PERFORMANCE ANALYSIS OF GATES IN WATER RESOURCES STRUCTURES

A DISSERTATION

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requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
WATER RESOURCES DEVELOPMENT

By
HARKESH KUMAR

WATER RESOURCES DEVELOPMENT TRAINING CENTRE
INDIAN INSTITUTE OF TECHNOLOGY, ROORKEE
ROORKEE - 247 667 (INDIA)
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this dissertation entitled "PERFORMANCE ANALYSIS OF GATES IN WATER REOURCES STRUCTURES" in partial fulfillment of the requirement for the award of the Degree of Master of Technology in Water Resources Development submitted at the Water Resources Development Training Centre, Indian Institute of Technology, Roorkee is an authentic record of my own original work carried out during the period from July 16, 2001 to February 24, 2002 under the supervision of Prof. Gopal Chauhan, Professor, Water Resources Development Training Centre, Indian Institute of Technology Roorkee, India and Shri D.K.Mehta, Director, Central Water Commission, New Delhi, India.

The matter embodied in this dissertation has not been submitted by me for the award of any other Degree or Diploma.

Place: -Roorkee

Dated: - February 24 , 2002.

Harkesh Kumar

(HARKESH KUMAR)

This is to certify that the above statement made by the candidate is complete and correct to the best of our knowledge and belief.

(Gopal Chauhan)
Professor, W.R.D.T.C
IIT, Roorkee.

(D.K.Mehta)
Director,
Central Water Commission,
New Delhi.

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Harkesh Kumar

(HARKESH KUMAR)

Place:- Roorkee

Dated: February 28 2002

SYNOPSIS

The regulation of water by means of hydraulic gate is an essential requirement of any Irrigation, Power-generation, Navigation, Flood-control, Industrial & Water supply project. Besides regulation of water, the hydraulic gates are also useful and essential for construction of hydraulic structures. Therefore, hydraulic gates & their operating mechanism are very vital component of water resources projects and thus requires specialised and expertise in regards to their selection, planning & design, manufacturing & erection and operation & maintenance etc. Any kind of laxity on the part of implementation of such schedules leads to handicapped, hazardous and catastrophic situations. There have been many incidents around the world, when the gates have malfunctioned, sometimes with disastrous result, beside loss due to wastage of water and high expenditure on rehabilitation, replacements etc. The causes for incidents of distress of gates can be directly or indirectly attributed to the deficiency of planning, structural design, hydraulic design, fabrication, erection, operation and maintenance. Vibration, cavitation, non-closure, corrosion, erosion and aging problems, improper selection of materials and neglect of lubrication of components have resulted in mal-functioning and even failures of gates in the past. It has been experienced that the designers normally take adequate care in proportioning and sizing the principal members of gates & hoists but the so-called minor details are often neglected both at the design and the fabrication stage leading to their non-performance.

In this thesis, an attempt has been made to analyse the performance of various gated installations in order to correlate the malfunctioning/ failure to specific aspect of planning, design, fabrication, erection, operation & maintenance etc.

Further, the process have been completed by arriving at specific recommendations pertaining to planning, design, fabrication, erection, operation & maintenance etc in order avoid the malfunctioning / failures of existing gated structures and also for evolving safe & satisfactory design for future installations.

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NOTATATIONS

DESCRIPTION	SYMBOL
UPSTREAM	u/s
DOWNSTREAM	d/s
WIDTH OF GATE SLOT	W
DEPTH OF GATE SLOT	D
THICKNESS OF PIER	T
PIER SPACING	B
FLOW RATE	Q
PIEZOMETRIC HEAD ON TOP	K_T
PIEZOMETRIC HEAD ON BOTTOM	K_B
RATE OF GATE OPENING	dy/dt
PRESSURE	p
METRE PER SECOND	m/s
GATE OPENING	y
HEIGHT OF OPENING	y_0
RADIUS OF GATE LIP	r
DEPTH OF GATE HORIZONTAL GIRDER	d
GATE LIP EXTENSION	a
GATE RECESSES	a_1 ,a_2
KILONEWTON	kN
TONNE	t
GATE AREA IN PLAN	A
OPENING WIDTH	b
GATE WIDTH	B
TOTAL HEAD	H
VELOCITY	v
GRAVITY	g

CHAPTER-1

INTRODUCTION

1.0 GENERAL

The hydraulic gates are moving facilities provided in Dams, barrages, hydropower projects, reservoir and river control. These are neither like concrete dam nor like other reinforced concrete hydraulic structure, which always remain stagnant. Therefore, the gates are more complicated and critical components than the dam proper and other hydraulic structures. Evidently, gates are of vital importance for water resources projects and should always be in smooth functioning. Their failure to fulfill the intended purpose can have devastating results, sometime may even endanger the safety of the entire project. While most recorded instances of unsatisfactory operation or failures of gates are due to hydrodynamic causes, however mechanical or electrical inadequacies can be just as serious because the structure does not perform as designed. In practice, shortcomings due to hydraulic or hydrodynamic factors are difficult to rectify, whereas mechanical or electrical faults can usually be repaired or improved.

Higher the head, the more serious the hydraulics problems. The larger the gate area, the more serious the structural problems and manufacturing difficulties. The larger the total dynamic pressure, the more serious the hoist problems. These three parameters, i.e. the water head, the gate opening area and the total dynamic pressure are the major indices, indicating the technical level of gates. It is necessary to consider the capability of design and manufacturing, the reliability of safety and the reasonableness of economics while designing the gated installations. These factors mainly depend on the potential of industrial background and the level of technical support. The expertise in design, fabrication and erection are important factors, which contributes significantly for the smooth and satisfactory operation of the various gated structures. However, some troubles and problems have been experienced, which required careful and painstaking effort in investigation, design, analysis and research.

1.1 PLANNING & DESIGN

Maintenance also affects the reliability and safety of any structures significantly. Therefore, the gated structures should always be designed and constructed with facilities for placing emergency, bulkheads/ stoplogs gates u/s of the main gate for attending to its maintenance requirements and as well as for closing /isolating the waterway in case of any emergency/ malfunctioning of service gate (Fig.1.1&1.2). The problems, which can occur in an emergency, can be taken from the failure of spillway gate at Folsom Dam. Stoplogs could not be installed because provision had not been made for them in the original design. The stoplogs slots were incorporated u/s side of the radial gates in hastily fabricated steel frames. Although, these frame provided a means for closing off the spillway bays, however, it is reported that these frames are disturbing the flow pattern and has increased the size of the vortices which form in front of the gates, especially, when the gates are operating at partial openings.

The need also arose to deign and install stoplogs for the rehabilitation of the spillway gates of a Barrage on River Indus (Pak). A floating bulkheads (Fig.1.3) may provide a solution in such circumstances, where the provisions are not made initially in the original planning for emergency closure of the bay by means of an emergency/ bulkheads gate but their requirement becomes important and the equipment or space is not available on the dam for handling them. However, the design of such floating bulkheads is complicated in regards to the control for their sinking. Orifice or tunnel spillways have submerged inlets and such structures are generally provided with two gates d/s gate for flow control and the u/s gate/bulkhead to serve as a guard gate in case of emergency or when the d/s gate requires servicing (Fig.1.4).

The installations having water head less than 30m, a Bulk head gate to be installed in the u/s of the regulating gate (slide or fixed wheel type) can be provided for maintenance purposes. Where as for water head more than 30m, an emergency gate of fixed wheel type for maintenance purposes and as well as in case of emergency shut off is preferable. However, the installation exposed to extreme higher head, two gates in tandem with similar construction is generally adopted (Fig.1.5).

In addition, special design of gated structures is required for combined operations of gates e.g. flood release combined with sediment flushing. Control gates for such applications are preferably top sealing radial gates and in some case vertical-lift wheel type gates. In either case the gates are designed for u/s sealing and the guard/ maintenance gate is usually vertical-lift type.

The crest gates for dams, barrages and open channels are designed generally to have U/s skin plate & adequate (at least 0.3m) freeboard between the top of gates and the normal water level. These provisions could reduce significantly, the maintenance requirement and the damages to the d/s structural members of gate. However, to avoid/ reduce the undesirable effects of hydrodynamic forces, velocities of approach for such gates should be restricted (preferably upto 4 m/s).

The parts of high head gates should also be stress relieved to resist the dynamic and fatigue loading resulting from vibrations. Stainless steel cladding of bottom lip of gate may also be advantageous to resist cavitation & abrasion under high velocity flow. The vertical lift gate (Fig.1.6) have a sloping bottom lip (generally 45^0 for high head) for ensuring a reduced downpull forces and also eliminate unstable flow reattachment in order to have vibration free operation of the gated installations. Bottom of the high head gate is subjected to the exciting forces, such as vortex shedding, fluctuating pressure and variable hydraulic downpull forces. Especially, during small openings, the gate is worst affected.

The high head gated installations (water head exceeding 20-25m) invariably suffer from cavitation and vibration problems resulting from either due to inappropriate design of gate slots or due to high velocity jet flow caused by serious water leakage. The appropriate design of gate slot is also an important factor for reducing cavitation/ vibration problems. Designs of bottom lip of the gate and ventilation (i.e. air supply) of waterway have significant effect in respect of cavitation and vibrations. However, it should be ensured that the inlets of the air vents should be located in such a manner that the high water levels, waves, debris, etc., do not interrupt the aeration. Other factors, effecting the cavitation phenomena are roughness of surfaces, distance between two adjacent gate slots, entrance shape of piers/ conduit and the location of gate slot. The factors responsible in respect of vibrations are configuration of the gated structure, flow pattern in the vicinity of the gate, sealing arrangement, strength & stiffness of the gate leaf, type of hoist adopted for operation of the gate, mode & sequence of operation of gates apart from provisions of air vent & air entertainment devices.

For high head outlets, the bonnet type gated installation is necessitated for satisfactory performance. In a bonnet type arrangement, the gate is withdrawn into embedded steel bonnet when fully opened. It is desirable to design the top 300mm of the embedded bonnets to withstand internal hydrostatic loads & imposed hoist loads without the aid of surrounding concrete. The bonnet covers should be invariably bolted down to bonnets or gate frames, so that the water load on the bonnet covers is distributed to the concrete surrounding through the bonnets and gate frames. Direct transfer of load from bonnet covers to the top concrete lift should be avoided for safety.

The intake for power tunnels and bottom outlets for high head are also provided with shaft type arrangement (Fig.1.7). However, in such cases it must be ensured that gate shafts should never be allowed to be submerged under water. The submergence of gate shafts may result in damages due to the vertical flows.

The rubber seals are provided generally for ensuring the water-tightness of gates (Fig.1.8&1.9). The seal design should not cause any flow irregularities in order to have safe and satisfactory operation of gates. The construction of seal assembly should be simple and should allow for easy installation and removal. The seal material and its mounting must be capable of transferring the initial stress (due to interference) to the seal. The seal fixture must allow the seal to deform/bend under the water pressure and must allow easy adjustment to take care of reasonable inaccuracies in sealing surfaces resulting from fabrication & erection tolerances.

For extremely high head purposes the metal sealing surfaces have been found to be more suitable in case of vertical lift gates. However, such constructions will require high degree of accuracy in manufacturing and erection.

In case the gate is intended for cracking opening, the top and side seals can be made effective only through this operation. Radial gate with specially designed sealing arrangements either using eccentric pivot hinges or adopting expansion rubber seal are capable to ensure water tightness for water head exceeding even 100m. The bottom seal of rubber having conventional rectangular section fixed to the gate, bearing on the stainless steel surfaces fixed at the bottom of waterway, is an arrangement frequently used. For ensuring the closure of gates, dependable downpull force can be expected for the d/s seal arrangement, in case the bottom seal is somewhat offset towards the u/s with reference to the top seal.

For top seal radial gates, it is important to design the top seals for the gates in a proper manner to avoid undesirable water jets during partial gate operation. It is usual practice to provide an anti-jet seal fixed on the embedded frame at the top in addition to the standard rubber seal fixed to the gate. The standard seal ensures water tightness when the gate is fully closed, whereas the anti-jet seal fixed to the embedded frame make reasonable watertight contact with the gate at partial gate openings. It is often preferable to provide a stainless steel skin plate suitably machined on the u/s side to provide a smooth surface for anti-jet seal contact.

1.2 OPERATING ARRANGEMENT

Oil hydraulics is being frequently used now a days to operate gates. The hydraulic fluid has to be environmentally compatible and suitable provision for arresting the gate and stopping delivery of hydraulic fluid in the event of the burst of a flexible hose or a pipe have to incorporated. A single cylinder for smaller span and twin cylinder arrangement for larger span is generally adopted. However, when lifting the gate from two points for twin cylinder arrangement, it is essential to synchronize the movement of piston of the cylinders to avoid distortion/ malfunctioning of gated structure. The development of accurate electronic piston rod position sensors built into the cylinder head has simplified synchronization and therefore has increased reliability of hydraulic hoists. From reliability considerations, an oil-hydraulic installation also offers the possibility of automatically interchanging the power packs so that one can act as a standby to another by incorporating a few additional directional control valves. Moreover, in order to avoid/ reduce the vibration problems, it is required that the high head gates be rigidly supported during their operation. Rigidity of supports are also required in case the gate is not capable of self-closing i.e. gravity closure by its own weight. Requirement of rigidity of suspension for high head gates can be fulfilled either by using a screw hoist (limited to small size gate) or by hydraulic hoists more often.

The hydraulic hoist can also meet satisfactorily the important operational requirement of controlled rate of closure to avoid or limit water hammer and also to slowdown further for the final 5 to10% of travel to avoid damage to the bottom of gate/sill in case of high head installation. Moreover, the rate of opening can also be critical, because it can initiate a reflected wave. Similarly, if used to operate the radial gates, the hydraulic cylinder must be properly hinged to ensure smooth gate operation without undue stresses in the stems and lifting mechanism.

The crucial & important load components, concerning design of hoisting arrangement for high head vertical lift gates, are the hydrodynamic (downpull) forces and the sliding/rolling friction. These two factors can vary appreciable for different installations and the problem is further compounded because of their variations throughout the length of the travel of the gate. In addition, the coefficient of friction may even vary from time to time, because of its dependency on state of sliding/rolling surfaces and lubrication provided. Model studies can be helpful for satisfactory assessment of hydrodynamic forces, but the accurate assessment of frictional forces is quite difficult in real life situations. Therefore, guaranteeing a satisfactory performance of gated installations in such circumstances is really a challenge. However, a conservative estimate of frictional force (sliding/ rolling, seals, guide etc.) is, therefore, imperative in design of hoist for satisfactory performance. In case of self-closing gate, it must be ensured that the submerged weight of the gates always exceeds the opposing forces during the closure operation by at least 20 percent.

As the coefficient of friction depends on the deposition of a lubricant film on the mating surface, therefore, the selection of the appropriate values is difficult. Also, the bearing surfaces in the gate slots are subject to high velocity flow and eddy circulation. Such forces can remove the lubricants and may increases the frictional coefficient, therefore, provisions for forcing grease between the gate and the gate seats by suitable means to prevent such eventuality are must to ensure smooth operation. In addition to such provisions, conservative estimate of required hoist capacity is made by assuming a higher value of sliding friction coefficient between the sliding bearing plate and embedded load bearing track plate, which are generally of stainless steel and bronze respectively.

1.3 OPERATION & MAINTENANCE

Consideration of reliability and minimum maintenance is an important aspect. The selection of suitable bearing surfaces, especially for underwater applications and trunnion bearings of radial gate plays a significant role in these respects. The bearings with lubricant inserts (self-lubricating type) for gated installations are being frequently adopted for satisfactory performance. One of the most important requirements in design of a radial gate is to ensure the satisfactory performance of its trunnion bearings even with a reasonable misalignment. Misalignment is likely to occur during erection, or during operation as a result of malfunctioning of gate, due to seismic/ flood loading, due to deflection of piers when an adjacent bay is dewatered. Self-aligning bearings are expected to ensure uniform loading of bearing surfaces and free moment under a reasonable misalignment across the span of the waterway. The vertical lift type control gates for outlets can also be provided with self-lubricating type bronze bearing plates attached to the gate leaf and slide on embedded track plate of stainless steel in order to reduce the frictional forces. Similarly, the wheel type vertical lift gates provided with self-lubricating bronze bearing & stainless steel pin are always preferable. However, it must be noted that the self-lubricating bushing should not have graphite inserts, as these have often given problems with stainless steel pin. Care should also be taken that the grease used is compatible with the bearings and is not detrimental. Designs of various components of the fixed wheel gates for high head also require careful attention, especially during the analysis of stresses in the wheels, tracks, and track beams, which carry heavy concentrated loads. Reliable bearing installations having a significantly lower coefficient of friction than the self-lubricating bronze bearings for the underwater uses can be engineered, but these type of arrangement rely completely on prevention of ingress of water /silt. Therefor, crucial factor for such applications is the sealing arrangement, because breakdown of the seals are likely to take place and cannot be expected to last longer.

The elastomeric side and top seals, plain or PTFE-faced (Fig.1.8) are satisfactorily used for achieving water tightness of gated installation exposed to water head ranging from low to moderately higher head. Rubber seals with PTFE cladding for gates operating under a head of upto 50-75m and metal sealing for higher heads are preferable. The top and side seals should preferably be effective throughout the travel of the gate to avoid undesirable water jets and consequent problems especially in case of high head regulating gates.

The seal material must have high tensile strength, high resistance against tear/abrasion, low water absorption, adequate resistance to aging apart from low coefficient of friction. For low head application plain rubber seal can be adopted, whereas the composite rubber seals with PTFE cladding (upto 2mm) having low friction coefficient is preferred for moderate to high head applications. The PTFE coating is found to be 3 to 4 times less resistant to abrasion than the plain rubber, it is therefore obvious that any contamination of the water by suspended abrasive material will have an influence on the erosion of the seals and thereby its life. By using two rows of top seal fixed on the gate leaf (in case of top seal radial gate one fixed to gate leaf and other fixed on breast wall) help to control the water leakage as well safe guard against the damages resulting from the emerging water jets from the sealing plane. Therefore, such measures could be very effective in smooth functioning of gated installations.

The regions where cavitation can occur are generally provided with steel lining, in some case even lined with stainless steel or high strength/hardened alloy steel. Steel lining of conduit is required for the portion in between maintenance and regulating gate in addition to some distance u/s of maintenance gate and d/s of regulating gates for installations subjected to water head in the range of 30-40m or more. However, complete lining of conduit is desirable for the portion of conduit passing through the dam or gate operating under a head of 100m or more. The conduit area at the gate location is generally kept somewhat lesser than the u/s conduit area to ensure positive water pressures for the fully opened position of the gate.

1.4 OTHER FACTOR

In the design of spillway gate for a dam/barrage, to a lesser extent river outlets & other low level sluice gates, reliable mechanical and electrical installations should take into account the possibility of common cause failures, such as seismic disturbance, extreme floods apart from fire, explosion, collision, and of course possible organizational, management, communication and forecasting weaknesses. The trunnions of the radial gates should be protected against corrosion and debris.

The mechanical and electrical considerations of earthquakes comprise precautions such as the rigid support for light fittings and long hydraulic hoist cylinders, where pipe couplings, gate position indicators, etc., can be affected. During a severe earthquake, electrical contactors/ main switches can be inadvertently operated and the operating cranes are liable to be derailed. The above factors may result in malfunctioning of gated installations or render them inoperative.

An essential requirement to avoid common cause failures is to provide atleast two opening for outlets and spillways and to separate their operating mechanism physically. In cases, where redundancy cannot be provided, working stresses are should be kept low enough to ensure safety, however, this provision can not guarantee satisfactory performance because operation of gated installations also depend on accurate alignment of various parts, avoidance of contamination of rotating/sliding faces, expansion/ contraction and of course maintenance as well.

For the safety of structures, dependence in regards to operation of gates by highly elaborate devices or computerized electronic equipment can be had provided that the system has proper feed back controls. The use of partly computerized system for flood routing may lead to malfunctioning of the spillway gates equipment by opening them suddenly, or it would equally well happen that when required gate may not operate, and therefore the dam is likely to be over-topped. In tropical conditions, the deterioration of electronic equipment can be rapid.

There is a considerable preponderance of failures caused by overtopping, especially in the case of embankment dams. Overtopping has generally occurred because the gate operator failed to react to the arrival of a flood in time, or because of power failure at the critical moment and thereby the gates could not be opened for passing the flood. Power failures are common in the area in stormy weather, and it is in just such circumstances that power failure to the gate operating motors would be most likely to happen at the time when it would be most important for the gates to open. Therefore, safety can be ascertained by such designs, which would facilitate the opening of the gate without fail at the right time, and by the right amount, and totally without dependence on power or operator.

1.5 OBJECTIVE & SCOPE

The objective of the study was to arrive at specific recommendations relating to deign, fabrication & erection, operation & maintenance in order to avoid malfunctioning / failure of the existing gated structures and also to evolve safe design practices for future installations. This required extensive study of literature relating to the various past & current design practices followed world wide, models study results, factors affecting performance of gated installations apart from case histories relating to malfunctioning / failure of different installations.

The various types of gates, operating arrangements and their suitability had been covered in Chapter-2. The Chapter-3 & Chapter-4 cover the problem relating to performance & design considerations for various types of gated structures. The case histories are presented in Chapter–5. A few innovations relating to planning & design, safety and economics etc. are discussed in Chapter-6. The conclusions & recommendations have been written in Chapter-7.

CHAPTER-2

TYPES OF GATES AND THEIR HOISTS

2.1 SPILLWAYS GATES

A wide variety of spillway gates have been developed and used through the history of dam design and construction, however, the most common are mechanical types. The radial and vertical lift type gates are extensively used except for few cases, where other types have been adopted. Provisions for installing the bulkheads/stoplog are generally made to facilitate maintenance of the main gate and for emergency lowering in some cases.

2.1.1 Vertical Lift Gates: - These gates are generally wheel type (Fig.2.1&2.6) except for small dam, where slide type may be used for economy. For surface spillways of a large dams these type of gates require a substantial overhead structure for their operation. Sometime a large gantry crane can be employed for operation as well as for removal for maintenance of the gates. Maximum sizes range to 20m by 20m. These gates are reliable for closure under full flow provided that the gate lip is properly designed. They require a rectangular section rubber seal across the bottom and music-note seals on the sides. Gate slots are required and therefore, they disturb the flow, which makes them somewhat less efficient than radial gates. When the vertical-lift gates are used on tunnel spillways, a rectangular section seal for the bottom and music-note seals are generally provided for the top and side seals. Two rows of music-note seals may be provided on the top of the gate in order to prevent severe vibration/ cavitation damages resulting from water jets emerging from the top of conduit when the gate is partially opened.

2.1.2 Radial Gates:- Radial gates (Fig.2.2) are the most popular being economical, requires lesser lifting effort than vertical-lift gates and their gate leaf is structurally strong. For surface spillways maximum size ranges upto 40m wide and more than 20m high. Radial gates have better discharge characteristics than vertical lift gates because of absence of gate slots. Generally, stiff rectangular section rubber seal across the bottom and L-shape or music-note rubber seal along the sides are provided. Top sealing radial gates is frequently used for flow control in orifice or tunnel spillways. However, it is not preferred to allow the flow to overtop large radial gates. In case a large flows pass over the gate, serious vibrations can occur which may structurally damage the gate. Also, where significant amount of floating material or trash accumulates u/s of the gates, a movable flap is sometimes provided at the top of the radial gate in order to provide a capability for passing trash.

However, it is preferable that the top of radial gates be fitted with a shaped overflow crest, because the hinges of these flaps require regular maintenance to ensure their operation. A radial gate must be structurally strong to resist any forces tending to rack the gate when it is being raised or lowered. Side guide wheels/ guide buffers are provided on each side of the gate in order to minimize the possibility of tilting the gate and thereby jamming.

2.1.3 Flap Gates:- Flap gates (Fig.2.3&2.4) are used on surface spillways when close control of water level is required and the operating head is relatively small. Maximum size range to 70m width. Because these gates require heavy lifting effort, therefore, height is limited to about 3m. Seals are continuous across the bottom and are effective from both sides. They are subject to severe vibrations unless provisions of flow splitters along the crest of the gate and adequate aeration below the nappe is provided. Their disadvantage is a weak structure to withstand high torsional effect. However, flap gates are excellent for passing a great deal of trash over them. These gates can operate automatically if the u/s water level rises. With the help of the counter weight, the flap remains in the raised position as long as moment due to weight exceeds the moment due to u/s water level. The counter weight also causes the flap to return to the closed position with the fall in the u/s water level. However, large sized flap gates provided on spillways are generally operated by hydraulic cylinders for reliability and safety of structures.

2.1.4 Segment Gates:- Segment gates (Fig.2.5) are composed of two independently operated gates. The gates are generally of vertical lift wheel type. Such gates provide much operational flexibility and are generally used for longer spans range upto 70m. The gate leafs and the hoisting systems are designed for a variety of operational conditions e.g. flow over the top leaf only, under the bottom leaf only, over the top leaf as well as under the bottom leaf simultaneously. These gates are ideal where large flows with a considerable amount of floating debris have to be handled. Therefore, they can be recommended for use on dams controlling the flow in a run-of-the-river scheme.

2.1.5 Automatic Gates: For improving the operation reliability, a number of schemes may require for automating the operation of gates. Automatic features can be provided by a system of floats and counterweights (Fig.2.7) for such installations, which require that the spillway gate should automatically open if the reservoir water level rises above a predetermined level. However, the float and counterweight systems may prove to be unreliable for handling such flow, which contains silt and carry floating debris. Also, the arrangement requires stringent maintenance for achieving the reliability. The radial gates with positive control i.e. with hydraulic cylinders and counterweight (Fig.2.8) have also been provided as a second line of defence at some project. The arrangement has been designed as fail-safe and opens the gate automatically in case the operation of gate by hydraulic forces fails.

Some automatic gates (Fig.2.9) for small sizes like Q-type, Godbole, top hinged flap type are being used. These types of gates have been found suitable for small sizes and require a little maintenance. For larger sizes drum / sector gates (Fig.2.10) have been provided at some installations. The operation of these gates is achieved by simple technology, based on hydraulic principles only and therefore requires neither gearing and lifting machinery nor any power supply. Therefore such gates are found suitable for remote and unattended sites.

Automatic gates swinging on horizontal axes have a number of other practical advantages, such as moderate maintenance requirement thus allowing for quite rough methods of handling; no necessity for large piers and steal trestles or bridges for the locating the hoisting machinery; little tendency for d/s scour because of the regulation by overfall only. Moreover the location of the swing axes allows for the transfer of a large proportion of the imposed hydrostatic/ hydrodynamic forces directly to the mass concrete sill. Their only disadvantages are complicated sealing arrangements and the phenomena of gate vibration.

Automatic hydraulic control gates, operating as a result of the difference in hydraulic pressure do not require any machinery or electrical equipment and are capable of operating well over a long periods without requiring any maintenance. Their operation is based on hydraulic principles only; as such there is no danger that their resting in the upper position will cause inundation because the hydraulic pressure causes them to swing downwards. Other advantage is its simple construction with high structural solidity. Moreover, these can be fabricated from locally available materials and therefore are suitable especially for the conditions of remote areas & developing countries.

2.1.5.1 Drum /Sector Gates are suitable for relatively higher heads than other type of automatic gates. As robust hollow structures, these gates act as a float, balancing the weight of the moving part; therefore only a small additional mechanical or hydraulic forces are needed for their operation. The counter weight, lifting gearing and the electro-mechanical equipment are thus dispensed with. The automatic operation of these gates is achieved with precise and elaborate equipment located in the piers. The drum / sector gates are unsuitable where water weeds and algae develop quickly or water contains considerable amount of sediments.

2.1.5.2 Flap Gates:- This type of gate is capable to control a water level by purely hydraulic means, without use of floats or pressure differentials that may be subject to malfunction. The bottom hinged flap gates are generally used for automations. However, top hinged flap gate having a counter weight with a certain length of lever-arm, at an angle relative to the gate plane have been developed. The specified weight allows simple, effective and economic level control for relatively small discharges in irrigation channels with these bottoms hinged flap gates.

Improved design of flap gates is now considered to be vibration free and stable under all operating conditions. Whereas, the old version of flap gates suffered from hydrodynamic instabilities.

2.1.5.3 Fuse Gate:- Recent development in automatic operation of spillway is the Hydroplus Fuse Gates, which are constructed of steel/concrete and are placed on a modified spillway crest. Individual fuse gates fail at predetermined reservoir water levels in order to prevent the overtopping of a dam during passage of an extreme flood and also thus avoid sudden / large spills. However, their disadvantage is that after the failure of these fuse gates shall need the installations of a new one each times.

2.1.5.4 Rubber Dams:- These inflatable dams are used as a gate primarily to control the u/s water level. Maximum sizes range to 100m long and upto 3m high. They are not able to pass a controlled discharge, because flow concentrates at the center instead of distributing evenly across the span. However, they are economical to install in cases where it is desirable to increase storage in the reservoir without increasing the spillway capacity.

2.2 HIGH HEAD GATES

The gate operating under water head exceeding 25-30m, used in dams, tunnels, penstock, or outlets fall under the categories of high head gates. The high head gates if required to operate under partially open positions for prolonged periods, as in irrigation / river outlets are known as 'regulating' gates and if operate only fully closed or fully opened, as in power conduits/sediment flushing are known as 'non-regulating' gates. Emergency and guard gates are also nonregulating types of gates. Power conduit or penstock gates are also required for quick shout off the flow to turbines in case of an emergency and also to facilitate maintenance of the conduit (waterways) and turbine valves. Gates capable of self-closing quickly even without electric power are provided at such installations. Bottom outlets are provided in a dam for irrigation releases, sediment flushing, and flood release or minimum river releases. Gates are installed either to regulate water releases or to serve as guard or emergency gates to shut off the flow and permit repairs or maintenance of the regulating gates or valves.

Based on past experience, performance and hydraulic model studies; the following types of gate designs suitable for high-head applications have been evolved. Some designs have become obsolete due to operational problems that developed after their installation and some of them have been improved in order to have for trouble free operation and satisfactory performance of the gated installations.

2.2.1 Slide Gates:- Slide gates (Fig.2.11) are the most common types of gates used for high head applications. Several modifications may have to be incorporated in their shapes and details to improve the performance for a specific application. These gates have the simplest and most rugged type of constructions. Slide gate has a leaf that consists of a rectangular skin-plate stiffened by vertical and horizontal structural members. These gates can be constructed of cast steel (small sizes), of fabricated welded steel, or of a combination of both. The gates can be either bonneted or shaft type(unbonnetted). A bonnetted gate has its hoist arranged in a gate chamber. The gate chamber is located in dam body just above the top (roof) of the conduit but much below the u/s reservoir level. Therefore, this arrangement requires bonnet cover to prevent water entry into the chamber. Where as, in case of shaft type (i. e. unbonnetted) arrangement gate has its hoist located above the u/s water level.

Tandem installation of slide gates is generally adopted for high head applications, the u/s gate serving as a guard or emergency gate and d/s gate as regulating type. The gate leaf has bronze or stainless steel sliding flats on each side that bear and slide on stainless steel seats fastened to the embedded gate frames in the gate slots. The top sealing and seating arrangement is similar to the sides. Flat rubber seal of rectangular cross section attached to the gate bottom and bearing on stainless steel surfaces at the invert of conduit is preferred arrangement for sill seal. High-head slide gate is a rectangular gate with an almost rectangular cross section in plan. The ends of these gates rest and move in narrow gate slots (usually 100-150mm) in order to minimise the flow disturbances. Steel liners are provided in the waterway (u/s and d/s of the gates) in addition to the gate slots so as to protect the concrete surfaces against high velocity turbulent flow, erosion, and cavitation. The conduits must be smooth without offsets or abrupt irregularities. Offsets or irregularities, if any, have to be ground to a smooth slope varying from 1:40 to 1:60 depending upon magnitude of flow velocities to avoid cavitation problems.

The high head gates are generally d/s sealing type and the gate leaf bottom lip has a 45^0 slope converging d/s smoothly to a narrow gate bottom. The sloping bottom of the gate is preferably provided with a stainless-steel overlay to resist corrosion and cavitation damage. The sealing arrangements of vertical lift gates are either effective through the entire range of gate travel or only effective for the fully closed position of the gate. For the regulating gates, sealing effective for entire range of gate travel is desirable. However, this provision will require the entire surface of the gate leaf coming in contact with top seal seat, to be machined smoothly. Generally, the slide gates are operated by hydraulic hoists except for those small sizes gates being operated by Screw-type hoists. Screw-type hoists have limited capacities and moreover can suffer damages from vibrations inherent in high head gate installations.

2.2.2 Fixed Wheel Gates:- Fixed-wheel gates (Fig.2.12) are also rectangular shaped like slide gate with the difference that sliding surfaces are replaced by wheels mounted on each side of the gate leaf to reduce the large frictional forces inherent in slide gates. In addition, the lower frictional forces in case of wheeled gate permit the gate leaf to be self-closing under gravity without requiring the downward thrust. The high loading imposed on the gate will require relatively large sized wheels and corresponding wider gate slots. The wider gate slots are hydraulically undesirable because these will result in flow disturbance, cavitation damage, and sometimes severe gate vibrations. These types of gates are not suitable for regulation under water heads exceeding 20-25m. Although they can be used as guard or emergency gates for head over 120m. As the size of the wheels dependent on wheel loads, therefore for higher head applications, accommodating the large sizes wheel assemblies on smaller gates may be impractical. In such case, roller-mounted or cater-pillar gates can be used. In spite of their increased maintenance, roller-mounted gates have the advantage of distributing the hydrostatic loads more uniformly on the tracks and the surrounding concrete structure. The fixed-wheel and roller-mounted gates are ideally suited as guard or emergency gates. These gates should be preferably operated by hydraulic hoists, although they can also be operated by Electro-mechanical type rope drum / chain hoists (if designed to close by self-weight) or by screw hoists. There is possibility that screw threads may damage due to vibration of the gates, therefore, use of screw hoists under high heads is limited.

2.2.3 Radial Gates: - Radial gates (Fig.2.13) have skin plates formed to an arc of a circle. Absence of gate slots renders radial gates hydraulically more suitable for high head outlets than the vertical lift slide and fixed-wheel gates. The necessity for large chamber located within the dam body for accommodating the raised gates is a disadvantage for their use. As such, these gates are located generally at the exit end of outlets. The top seal arrangement for the high head outlet gates requires special attention. Two seals are commonly used; one attached to the gate to serve as normal top seal effective in the fully closed position, and another fixed to the top lintel beam of the embedded frame to maintain contact with u/s face of the skin plate throughout the gate travel. The seal fixed to embedded frame is sometimes also called as "anti-jet" seal. Stainless steel skin plates are preferred to carbon-steel skin plates as the corrosion resistant paint layer is likely to be damaged by the antijet seal and thereby result in deterioration of skinplate. A rigid beam provided in the vicinity of the top seal of the gate minimizes the deflection of gate and therefore, ensures water-tightness. The top and side seals can be of music-note or J-type seals, however, the bottom seal must be a flat rubber seal to ensure a well-defined control point for the jet leaving the gate bottom.

2.2.4 Jet-flow Gate:- Jet-flow gates (fig.2.14) are basically slide gates except that they are installed in circular conduits. Their unique feature is an orifice formed by 45^0 truncated conical nozzle in the conduit just u/s of the gate leaf. This orifice constricts the flow into a circular jet, which is deflected away from the gates slots. Jet flow gates are cavitation free if designed properly. The free jet is fully aerated and free from gate slots disturbances normally present in slide and fixed wheel gates. When placed at the end of the conduit, a jet-flow gate offers a compact jet and a high discharge coefficient. At partial gate openings, the jet is likely to be deflected towards the walls of the d/s conduit and requires air grooves on the conduit wall to prevent cavitation damages. These gates are operated by hydraulic hoists and can be used for regulation in outlets for heads upto 200m or even higher. The u/s face of skinplate (stainless steel or cladded) maintains watertight contact with the seals fixed to the conical nozzle.

2.2.5 Ring-seal Gates:- Ring-seal gates are used as emergency or guard gates in circular conduits under high heads (Fig.2.15) and water load acting on the gate leaf is transferred to embedded frame through the wheels or roller trains. The rectangular gate leaf has an u/s skin plate that maintains contact with an u/s ring-seal fitted to the frame. Because of their high maintenance costs, these gates are rarely used.

2.3 HOISTING EQUIPMENT

The hoisting arrangements generally used for operating the gates are rope drum hoists & chain hoists hydraulic hoists and screw hoist. There are certain specific situations for which only one type has to be used. In the past, a gantry crane, or a mobile crane had been provided at some project to operate several gates apart from handling other equipment such as trashracks and bulkheads etc. The crane can only handle one gate at a time, its use is inconvenient and the process may be too slow at times when extreme floods need to be handled, moreover having only one hoist for several gates introduces unreliability. Therefore, the operation of spillway gates by such means is not recommended.

2.3.1 Rope Drum Hoist:- Rope drum hoists and chain hoist are frequently used for operation of spillway and other low head gates. For large span gates, two hoists one for each end of the gate has to be provided. The rope drum for such installations can be operated by independent electrical motors or by a single motor with a shaft connecting the two drums. In case two electrical motors are used, electrical synchronizing equipment is required to maintain the equal lifting speed/ force at both ends of the gate. If well maintained they provide reliable service with a long service life. Lifting ropes /chain are usually fastened to the bottom of the u/s side of the radial gates to provide maximum leverage and thereby require smallest hoisting force. Either ordinary steel or stainless wire rope can be used, however, the ropes/chains and lifting brackets are subject to the corrosion if provided u/s side. Operating requirements of a vertical lift gate, installed at the bottom of a tall gate shaft, are successfully met by a rope drum hoist. In case a hydraulic cylinder is provide for operation of gate for such installations, it would require a very long hoisting rod, apart from special equipment needed to lift the gate completely out of the shaft for maintenance. Whereas a rope drum hoist can be arranged to lift the gate completely out of the shaft without requiring any special equipment

Their disadvantage is that these are unable to dampen the vibrations in case the gate is subjected to high-velocity flow and also these types of hoists can provide only lifting force due to their flexible ropes/ chains. Also, the vertical-lift gates provided in tall gate shaft have experienced serious vibration problems whenever the gate was lowered into high-velocity flow due to the elasticity of a long rope. The rope drum hoist also requires a brake for controlling the lowering speed of the gate.

2.3.2 Hydraulic Hoist:-Hydraulic hoists are now used widely throughout the world for operation of all types of gates. They can be designed to provide practically unlimited hoist capacities and if designed as double acting these can affect the lowering with a downward thrust as well. Hydraulic hoists are preferred for gates with potential for vibrations since the hydraulic cylinder serves as an additional damper. For operation of top-sealing radial gate installed in bottom outlets and sluice /tunnel spillways, the hydraulic hoists are also frequently adopted. In case lifting a large span gate, multi cylinders are used in order to avoid the torsional effect in gate leaf. The synchronizing to maintain the equal lifting speed at all the lifting points is much easier in case of these hoists, moreover, the hydraulic cylinders also easier to maintenance.

2.3.3 Screw Hoist:- These type of hoist has limited capacities and are therefore, used for small size gates. The small size sluice and other free surface gates are sometimes provided with a motor driven screw hoist. This type of hoist also can affect the lowering with a downward thrust. Moreover these hoist require frequent maintenance for reliable operation.

CHAPTER-3

FACTOR AFFECTING PERFORMANCE OF HYDRAULIC GATES

3.0 GENERAL

The performance of the gated installations is affected by a number of reasons. However, the reliability of gate operation is one of the serious concerns in case of spillway gates. It may happen that the gate may not operate, when their operation is most critical. Special attention needs to be given to inspection and maintenance if the reliability of gates operation is to be assured.

Gates should be simple and rugged. Design should be conservative to avoid the consequences of overloading and fatigue failures. The proper selection of materials, well-defined flow conditions, and provisions of sufficient stiffness of gate leaf can avoid the vibrations. Oil hydraulic systems are more reliable than the mechanical hoisting systems in respects of vibrations. Conservative design for electrical equipment is also essential and multiple energy supplies should always be provided to ensure reliability & safety.

Defective design and construction can accelerate the process of aging. Light gate components can deteriorate rapidly because of overloading and fatigue. Structural weaknesses result from poor welding, particularly in older projects. Exposed electric circuits, poorly conceived automation system, fragile & improper seal fixture/ seals (Fig. 3.3 & 3.4), improperly chosen hydraulic shapes can induce vibrations. Such design features are frequently responsible for equipment deterioration at faster rates.

Accidents/ malfunctioning of gated installations have led to the improvement of design concepts. Adopting a conservative sections for gate leaf assembly will be helpful in dampening/ eliminating the vibrations by provide higher resistance/ stiffness, and therefore satisfactory performance can be expected.

Lack of articulation of the chain links (especially of Galle chains) has led to the replacement of this type of radial gate suspension by a more reliable and effective hydraulic hoists in some of the gated installations.

Leaking seals, unfavorable shape of the bottom lip of the gate, unstable flows separation (Fig. 3.1 & 3.2), and lack of stiffness of gate parts and suspension systems can result in hydraulically induced vibrations. Drowning of the issuing jet may also worsen the vibration phenomena. Insufficient structural stiffness, improper shapes for hydraulic passages and asymmetric openings also contribute significantly in respect of vibration and jamming of cylindrical gate in vertical intakes. Resonance may result for unsuspected combination of the natural frequencies of hydraulic and structural phenomena, particularly for slender structures.

Air can accumulate at high points of hydraulic circuits if ventilation facilities are not appropriate or not provided. Sudden releases of entrapped air can damage and dislocate the gated structure.

For surface spillways, radial gates are the best alternative for larger opening upto $400m^2$ or little more. The gate functions satisfactorily and has a long life. The operation by two synchronized hydraulic hoists is simple and reliable, and it is easily adaptable to automatic as well as remote control, whereas the rope and chain operated gates require regular inspection and maintenance. It is desirable to incorporate devices for stopping the hoist motor if the ropes/chain slacken during the lowering of the gate for safety. Gate seals have been developed that do not vibrate and ensure reasonable water-tightness apart from minimum maintenance requirements (Fig. 3.3, 3.4 & 3.5).

Bottom outlet gates are selected in line with the function they have to perform. Radial or slide gates are most suitable and effective for regulations/ partial openings. Absence of slots, efficient structural concept, small operating forces, and ideal hydraulic conditions are attributes of radial gates. For higher heads of about 70-100m or more, eccentric trunnion type radial gates can be used to achieve water-tightness as well to reduce the tendency for vibration. For water head upto 50-70m, inflatable rubber seals can be employed. Modern designs of slide gates ensures the vibration free operation of the gate and therefore is gaining acceptance due to their favorable geometry and smaller space requirement. The narrow and well-designed gate slots along with use of stainless steel for the most exposed parts reduce the risks of cavitation. Flow separation affected by conveniently designed deflectors can prevent the jet from striking the gate slots or prevent cavitation damages by keeping the vortex trail far away from the solid boundaries. Two slide gates operating in tandem are must for outlets which require continuous operation. In such gated arrangement, upstream gate acts as a guard gate and is kept open during normal operation, however, the guard gate should be able to be closed under the conditions of full head and full flow. The wheel type vertical lift gates are best adopted to perform as guard gates, also some of their sturdy designs are capable of being used for flow regulations as well.

Sturdy gate structure, simple geometry, smooth hydraulics, free flow conditions downstream of the gate, ensure the vibration-free operation of gated installations. For gates installed in slender concrete structures, like arch dams, an assessment of natural and hydraulically induced frequencies can be helpful in guarding against the resonance phenomena.

Adequate aeration is often essential for bottom outlets to perform satisfactorily. The required air discharge depends on gate opening, water flow conditions, and overall geometry of the project. The comparisons of the results obtained from the tests carried out on large-scale models and prototype help to assess the performance of future installations to a fair degree of accuracy.

Airflow velocities up to 50 m/s are generally adopted for airvent design. However, the acceptable limit of air velocity and the locations of airvent have to be decided keeping in view the safety of operating personnel. Serious accidents can be partially or totally attributed to faulty operation or inadequate maintenance. Maintenance is the routine work required to prevent and correct the consequences of deterioration.

Electrical and mechanical equipment are intrinsically more vulnerable to deterioration than are massive concrete works. Common processes that can cause deterioration are corrosion of metal parts, abrasion by sediment discharge, fatigue by repeating loads, cavitation and vibration caused by the water flow, deterioration of seals, and failure of electrical components. If preventive maintenance is provided, most of the aging processes may not evolve into serious incidents. The most frequent problems in equipment are defective sealing; guide misalignment; defective bearing rollers; deterioration of electrical systems; inadequate painting protection; structural weakness; deficient stoplog conditions. Leakage around the gate seals, guides, and through /around the second stage concrete of embedded parts may be serious nuisance. The cold climates further worsen this problem due to formation of ice.

Vertical lift wheel gates are sometimes more effective in cold climates where ice formation presents special problems. For lesser heights (upto 5-7m), and wider openings up to 50m or more, drum gates have been provided. The flap gates have been found suitable for lower height and are capable of discharging ice and floating debris. Flap gates are typically operated by hydraulic hoists and gate leaf should be designed to be sturdy. Spragging devices to prevent accidental opening can be used especially during the dry seasons.

Safe and permanent access to the gates during floods must be ensured in particular to the electrical and electronic parts. Computerized automatic gate operating system must provide reliable information about the gate conditions; prevent the unintentional closing or opening of gates, and should ensure safe operating conditions even under extreme circumstances. Gate opening indicators should monitor the actual gate position and not that of the hoisting mechanism. Automation is advantageous if sudden floods and rapid rises in reservoir level is expected. Alternate systems of energy supply are some of the precautions needed for reliable operation; so is the provision of continuous and competently performed maintenance.

Adopting stringent maintenance schedule and modern design practices can prevent malfunctioning of the gated installations. However, automatic or centralized gate operation may also result in malfunctioning of gate. The condensed moisture on the switch connectors activated the relay and therefore resulted in self-induced opening of a spillway radial gate at Mavcice dam. At Tarbela dam, the malfunctioning of one of the radial gate occurred when the gate dropped suddenly after getting stuck-up probably in the lateral guides during its closing operation; the operation was directed from the control tower located at one of the end of the spillway. The resulting accident demonstrates the importance of routine checking of working clearances between the gate components and embedded frame. Continuous surveillance of the actual gate movements even with automatic or remote control is important to avoid such mishaps.

Serious equipment deterioration that can lead to gate replacement is more likely in old bottom outlets. Bottom outlets become totally inoperative when not used for a long periods. In case of low level outlets, the access for maintenance/ repair work is often difficult, moreover, some parts remain submerged most of the time so even their inspection is difficult.

Graphitic corrosion of old cast iron parts is not uncommon, an intercrystalline process can slowly change the structure of cast iron, depending on chemical composition of the water. The iron content is reduced at the surface of the metal so that that the component softens and loses strength and therefore the replacement may be necessary.

Rate of corrosion of steel liners in waterway is usually negligible. However, the process may be aggravated by seepage behind the liner plates resulting from poor concrete placement and high-pressure gradients.

The broad reasons for which gate can suffer/ malfunction are classified as under:-

(a) Design deficiencies: - Unusual loading (Seismic, overtopping, vibrations), Design Details, Manufacturing & Erection.

(b) Deterioration: - Processes (Chemical, Hydraulic, Environmental or a combination), Operation & Maintenance.

(c) Hydrodynamic forces and vibrations (Discussed in details in chapter-4)

3.1 DESIGN DEFICIENCIES

3.1.1 Unusual Loading:- It is due to the failure to recognize all the loading possibilities for which the gated arrangement should have been designed.

3.1.1.1 Seismic:- Lack of consideration of possible seismic loading is the most important of such design deficiencies. Earthquake damage to gates is usually due to the effect of large dynamic forces that act on the gates during an earthquake.

3.1.1.2 Vibrations:- The second most common cause of design errors is failure to consider the possibility of vibrations of a gate. However, vibration problems can be avoided most of the time by adopting the standard designs, except for a few cases, which may require more detailed considerations. These special cases may involve unusual approach flow conditions, which do not appear to be important initially. Radial gates may be subjected to vibration particularly at small gate openings due to instability that arises as a result of faulty seal arrangement especially the bottom one. It is desirable that the angle between the upstream gate face and the profile of spillway crest be made as large as possible. It has been established that vibrations have played an important role in the failure of the spillway radial gate of Folsom Dam, when the gate was partially opened about 0.73m under a head of 12.2m. The stiffening of the remaining spillway gates was increased significantly and the replaced gate was designed to be much stiffer than the failed gate. Improper design of sealing arrangements especially of bottom seal may result in gate vibrations even without overflow. Music-note type seals are not suitable for bottom sealing, as their geometry tends to project the seal bulb into flow with consequent flow separation and reattachment of jet, thus inducing vibrations. Flat seal having larger X-sectional area, such as timber seal are also not recommended for bottom sealing. However, a thin rectangular X-sectional rubber seal adequately clamped to the gate bottom, presenting a sharp edge to the flow under the gate is most suitable configuration to eliminate/ reduce gate vibrations.

3.1.1.3 Overtopping:- The spillway gates may be subjected to overtopping in case not opened in time during the high flood. The impinging overflowing waters and trash will result in damages of gate members if not protected by a suitable arrangement. In such circumstances, a poorly designed gate may fail either by damage to its critical members, or due to severe vibrations caused by overflow/and underflow. However, the top of the gate provided with the ogee lip will permit flood overtopping without any damages in case the gate remains closed due to malfunctioning or otherwise. Although, for such installations, the hoist should be designed to raise the gate automatically as soon as the depth of overflow reaches a predetermined skimming depth of 0.5-1.0m for the safety of structure. Single rigid arm gate is also a solution for installations subjected to frequent overtopping. Spillway gates are also apt to incur unusual loading when operated to pass extreme floods. Operational problems can occur when the largest flood of record must have to be handled. The excessive flood may result in serious damages to gate, hoist, etc. Enormous amounts of debris may get lodged against the gates & stoplogs and can result in loading much above that for which the gated structure/hoists had been designed. Vibrations and as well as overloading may result in failure of the gates during overtopping if the top of gate is not streamlined or the nappe lacks aeration.

3.1.1.4 Impact by trash/boulders:- While flushing of trash/ boulders from under the gates, damage to the bottom rubber seal and erosion of bottom sill may take place. Presence of hyacinths and other such vegetation will further worsen the problem. Generally, for skimming the trash, the flap gates are provided on the top of radial gates. The flap gates mounted on the radial gates require careful & regular maintenance. Trash is likely to wedge into the hinges and seal areas of the flap gates and thus may result in jamming of the flap gate. Another disadvantage of this arrangement is that in case the flap gates are lowered during rainy season, there is always a risk that the radial gates may need to be opened suddenly to pass the flash floods, without having sufficient time to restore the flap gates to their closed position. In such circumstances, if the height of flap gates is large, the radial gates will be subjected to large overflow and underflow, which can cause severe gate vibrations. However, in such circumstances it is preferable to provide fixed ogee lip on the gate top instead of flap gates, which is almost maintenance free. During flood, the water will spill over the ogee lip and will also carry the trash away. For streamlined ogee lip gate, suitable side shields/flow deflectors are provided to avoid damages of gate member. Also provisions for adequate aeration of the overflowing jet is required to be made in order to avoid vibration of gate.

3.1.2 Design Details: Another common deficiency in the design of gates is failure to recognize the possibilities for corrosion of the gated structure. The design of the gates should be such that will facilitate easy detection of serious corrosion of gate/ hoisting arrangement and must permit inspection of all parts of the gate. Design should also not allow water to accumulate on erected gate structure and thereby accelerating corrosion of gate parts (Fig.3.6). Corrosion is one of the main problems encountered as the project ages. Also, the gates designed to operate in cold climates should not have any pockets where water can accumulate and thereby result in damages on freezing. Structural corrosion can also be the main cause of the failure. Fabrication and erection errors can also lead to malfunctioning or even failure of a gate. The lapses may be due to a lack of inspection at different levels. Therefore, the selection of qualified contractors and sub-contractors is vital for the fabrication and erection of various gated components of the project.

3.1.2.1 Friction:- It is believed that ordinary lubricants may not be effective in case the gate is not operated and remains submerged under high head for a long period. Therefore, while designing the hoisting arrangement for the high head gates, a provision must be made for adequate capacity to break the possible seizure of metals after the gate has remained closed under high head for a substantial period of time.

To illustrate an extreme case, at one installation there were three 12'-7" (3.835m) wide & 23'-5" (7.137m) high fixed wheel gates. These gates were used to shut off the flow in each penstock intake. There were twenty-two forged steel wheels on each gate fitted with chrome-plated SAE 1040 steel pin and the self-lubricating (considered to be maintenance free), bronze type bushings having graphite inserts. These gates were stored under water above the penstock intake openings. After being submerged for about 10years it was required to make an emergency shutdown with the help of these intake gates at nearly full flow conditions. The first two intake gates closed completely without difficulty because of the reason that there was little unbalanced pressure on these gates while closing, since the flow passing through the remaining opening was sufficiently large to supply water through the turbine. When the last gate was being lowered under almost unbalanced pressure conditions, the gate stem and operating crane started to vibrate at an opening of about two-third. The vibrations soon progressed to violent proportions as the gate continued further to close in jerks and the gate finally stopped to move downward with an opening of about 8' (2.438m) remaining unclosed.

The gate was later taken out completely to the surface for detailed inspection. An examination of all the twenty-two wheels indicated that only one of these wheels had rotated during the unsuccessful closure and that all of the other wheels had skidded on the track. By using pinch bars and sledgehammer blows, it was possible to free most of the wheels so that they could be made to turn. However, several of the wheels could not be freed at all and had to be disassembled. A similar condition of the remaining intake gates was observed at this installation. The failure of the intake gate to close under unbalanced head flow conditions was due to the failure of the wheels to rotate and roll on the track after having been submerged continuously for years together. As a remedial measures, the original self-lubricating bushes having graphite inserts were scraped off and grease fitting were installed on all wheel assemblies. Periodical greasing of the wheel assembly was recommended to ensure that the wheels would rotate during the gate operation.

Similarly, lack of lubrication & corrosion of surfaces of pin/bearing will increase the trunnion friction and may result in gate failure during the operation. Gate structure may fail because of excessive moments induced in the radial arms and their connections with hub/gate leaf, as has happened at Folsom Dam (USA). Increased trunnion friction due to corrosion and lack of maintenance is of concern especially for radial gates, provided with bush bearing & trunnion pins of the non-corrosion resistance material.

Method and type of grease used to lubricate the bearing surface also effects trunnion friction significantly. Automatic lubrication system, which gets activated whenever the gate is in operation, is most suitable for radial gates. However, it will be preferable/ safe to use stainless steel pins with self-lubricating bronze bushings to avoid above-mentioned problems. The provisions of self-aligning bearings for trunnion of a radial gate will be of great advantage, because of their capability to accommodate certain misalignment at trunnion, resulting from earthquake or some other accidental loading or from fabrication/ erection inaccuracies.

3.1.2.2 Drainage of gate structure:- Inadequate drainage (Fig. 3.6) will results in corrosion of gate members and if allowed to continue for long time unattended, the failure may takes place as has happened at a number of the projects. It is important to provide adequately sized drain holes in the strategic areas of radial arms, horizontal girders and other structure of the gated installations to avoid stagnant water puddles being collected on them due to rain or spray. The drain holes of adequate size (minimum 50mm wide and 100mm long) should be provided to effectively drain the structural members of gated installations.

3.2 DETERIORATION

Deterioration is defined as any behavior that may endanger either the safety or the performance of the gated installation. It is a gradual phenomenon and is the result of ongoing hydraulic, chemical and environmental processes e.g. cavitation, abrasion, corrosion, expansion of concrete, etc.

3.2.1 Processes

3.2.1.1 Chemical & environmental

3.2.1.1.1 Concrete deterioration:- Deterioration of concrete at spillways and outlet works is mostly related to cracking/expansion of concrete, potential corrosion of reinforcing steel, misalignment of openings and jamming of gates due to reduced spans, guide rail deformation, etc. The use of low alkali and pozzolan or flyash is the primary way to avoid problems related to Alkali-aggregate reaction. Designs of civil structure having open type joints may also prove to be helpful in some cases for reducing the effects of eventual expansion of concrete. Remedial measures shall include gate trimming & relocation/ remodeling of embedded parts to ensure operation, and the cuttings of slots in the civil structure to isolate the expanding bodies as also for temporarily accommodating the expansion.

3.2.1.2 Hydraulic processes

3.2.1.2.1Cavitation:- Cavitation in one of the most important cause of deterioration of high head gated installations (spillway and outlet works). Cavitation occurs in a liquid at a point where the pressure drops below a certain limit. Small gas bubbles or nuclei within the flow become unstable and grow rapidly due to vaporization. Nuclei, that may be very small (0.01mm or less), exist normally in water, in crevices and irregularities at solid boundaries. Critical conditions for instability and growth of vapor pockets occur at regions of lowest pressure /highest velocity in the flow. The bubbles are then swept away in the regions of high pressure and collapse there. The implosion of the bubbles leads to pressure shocks, noise and vibration. Damage to the walls may result if the collapse occurs near a solid boundary. The damage is not at the points of low pressure but at those places where the pressure has just risen. Serious damages may results in case these bubbles collapse repeatedly at the same spot.

Misalignments and discontinuities generally induce cavitation as a result of separated cavity flows that offsets into or away from the flow. Abrupt curvature or a boundary that slopes in or away from flow, extreme roughness, transverse grooves and protruding joints also promotes cavitations. Cavitation damage can also occur with very high velocities even if the surfaces are fairly smooth.

Shear flows can produce strong vortices and may originate from asymmetric gate operation. The deep water standing behind the closed gates is dragged towards the high velocity flow issuing from the adjoining bays. Shearing between the two bodies of water generates vortices along the interface of the two merging currents and creates a path along which low pressures occur. Cavitation damages from such vortices can occur even for heads as low as 20m. Cavitation damages in & around the gate slots are also similar. The vertical vortex in the slot is intensified by shearing effects as it is dragged by the main flow. Cavitation damages on the invert along the vortex trail occur especially during the critical gate openings (usually very small).

Bottom outlets discharging at the downstream face of spillways have suffered cavitation damages during the simultaneous operation of spillway and outlet. Vortices are again generated by shearing at the exit of the sluices with the merging of flows at different velocities. The induced low pressures are sometimes strong enough to cause cavitation. Damages take place generally along the vortex trails. Example of damage resulting from shear induced vortices is cavitation pitting occurring at locations immediately downstream of the gate shafts.

Adoption of simple shapes and well-defined separation lines are the design features that minimize the occurrence of cavitation. Steel lining is usually provided to resist the cavitation damages under most of the hydraulic conditions. Adequate thickness of the concrete cover shall minimize the chances of steel parts being exposed and damaged successively. Similarly thoroughly backing of the steel liner with concrete should be ensured to avoid their vibration & successive failures. Induced aeration of the high velocity flow can effectively prevent cavitation of structures. Aeration is also helpful in preventing the cavitation damages in the regions immediately downstream of high head.

3.2.1.2.2Abrasion:- Sediments carried by water can abrade the surface of gates and embedded parts. Such damages depend upon the concentration of solids, velocity of flow, hardness of particles and of course the duration of flow.

Damages from the abrasive effects of the sediments carried through waterways is unavoidable, however, can be reduced by the adoption of suitable design provisions related to the quality of the materials used. The sediments that are rich in quartz and flow at high velocity can result in severe abrasion damages. Abrasion damages to bottom outlets normally used for sediment flushing are most severe and therefore, the designs of such installations require careful considerations. Concrete surfaces are erodible and no lining material has been found totally effective to eliminate the abrasion. Piers, transition section, gate slots and other type of discontinuities in the solid boundary accelerate the erosion phenomena. Therefore, such susceptible locations should be avoided or otherwise suitably protected for satisfactory performance of gated installations. Protective linings also retard the abrasive process, however, limiting flow velocities & periodic maintenance will be important. The lining material shall be in line with the requirement of the facility. The selection will depend upon the abrasion resistance of the material given as under:-

Steel	:1
Polyurethane	: 3.7-5 times lower than for steel
Stone	: 15-20 times lower than for steel

High strength concrete : 300-400 times lower than for steel

3.2.1.2.3Sediment and floating material:- Progressive silting of reservoirs may cause deterioration of outlet facilities. The accumulation of debris can impair the operation of gated installations. Clogging is more likely to occur in outlet designed with small size gates and operated infrequently. The gate remaining closed continuously for long periods shall allow the openings to become completely obstructed and thereby may result in the complete loss of the facility. Silt accumulation in gate slot is a common nuisance to gate operation. Operation of spillway radial gates can be effected by silt accumulations in hoisting chain's links and similarly the drum gate can malfunction due to silting of gate chamber.

Floating debris can also hamper spillway operation. Small openings and inappropriate gate shapes aggravate such problems by increasing the likelihood of choking. Shorter spans can also be vulnerable as they help the accumulation of debris during floods. Wooden logs may accumulate at gate/ stoplog structure or in slots and thus may prevent the normal operation of the gated installations. The impact of logs may damage seals / gate leaf, concrete surfaces or the more vulnerable radial gate arms.

Proper design shall minimise the probability of major jamming problems. By adopting of bigger sized openings for outlet and spillway, the problem can be further reduced. It is advisable to have opening of $3m^2$ or more for satisfactory performance of bottom outlets. Free openings are always preferable. Provisions of sufficient distance between the tandem gate installations (i.e. guard and regulating gates) shall reduce the risk of jamming by floating debris.

If sediment is to be discharged on a regular basis, the outlet works should be studied with the help of hydraulic models to define critical parameters e.g. reservoir operation procedures, intake location and geometry, mode of sediment transport through the outlet, and surface protection requirements. Simple shapes and free openings, absence of gate slot, piers and other obstacles, shall effectively reduce the wearing. Double conduits and replaceable lining materials shall be provided for easier maintenance.

Floating debris can pass over spillways if openings are ample and gate is designed appropriately. Flap gates are ideal for passing floating material such as ice blocks and large trees. The spillways provided with radial gates, although depend on almost full opening of gate for disposing off the floating material, but have the advantage of large and free openings. The satisfactory performance of gated installations can be guaranteed if the floating materials are stopped & disposed off from u/s of gate on a regular basis. Hydraulic hoists are preferable to u/s located chains or rope hoists because they offer essentially no obstacle to the passage of solids.

3.2.1.2.4Uplift on embedded parts:- The common failure resulting due to uplift is buckling of steel linings under the pressure exerted on their embedded side (i.e. concrete side). As the guard or bulkhead gate is closed, stagnant seepage water will exert hydrostatic pressure on the impervious steel plates. Buckling may result if the steel lining is not self resistant or sufficiently anchored. Buckling of steel liners can be prevented by such designs that can adequately resist the external water pressure acting on either side for the worst combination of gate openings. This objective can be achieved if the plates are self-resistant between stiffeners and anchored to the concrete structure by suitable means. Such arrangements shall provide the requisite stability of embedded parts at all operating conditions.

3.2.1.3 Corrosion: - Corrosion manifests in different forms and it is desirable to know the form of corrosion that is taking place under given environmental conditions before adopting any remedial measures. Identifying the cause of corrosion, usually help in choosing the most effective method of preventing it. In most of failure analysis related to corrosion, it is imperative to identify the form of corrosion responsible for the failure. Corrosion is classified, on the basis of its mechanism, i.e. into electro-chemical corrosion or chemical corrosion.

3.2.1.3.1 Atmospheric corrosion:- Atmospheric corrosion of ferrous and non-ferrous metals is the most common form of electrochemical corrosion. The metallic parts of the gates and related equipment are worst effected by this type of corrosion, although, the effect could be uniform or localized. Moreover, the rates of such corrosion greatly vary and depend upon ambient conditions, such as temperature, rainfall, and wind conditions, atmospheric pollutants, etc.

3.2.1.3.2 Intergranular corrosion:-The great majority of intergranular corrosion problems are in austenitic stainless steels, such as AISI type 304 (18/8 stainless steel) and is related to metallurgical changes that occurs when these steels are cooled slowly during their manufacturing processes. Parent metals on the sides of welds, hot forged components are also susceptible to such attack.

3.2.1.3.3 Pitting corrosion:- It is the most destructive form of corrosion and results in sudden failure of equipment due to formation of holes. Stainless steel and aluminum are most susceptible to pitting corrosion. Pitting tendency is greater in martensitic and ferritic steels than in austenitic steels. Pitting resistance of austenitic (18/8) stainless steel is decreased on severe cold working. The pitting corrosion can be avoided in stainless steels by maintaining clean surface, by preventing stagnant conditions and by applying cathodic protection.

3.2.1.3.4 Crevice corrosion:- It is an intense localized corrosive attack and usually occurs within confined spaces or crevices formed by certain mechanical configurations (Fig. 3.7). The crevices are also created by surface deposits of corrosion product, scratches in protective paint layer, etc. Crevice corrosion usually occurs at very small openings and rarely with in more than 3mm wide grooves or slots. The components of metals and alloys which depend upon oxide films or passive layers for corrosion protections are especially susceptible to crevice corrosion.

3.2.1.3.5 Water line attack:- It is another special case of crevice corrosion, which occurs just below the liquid level on metals submerged in water.

3.2.1.3.6 Protection against corrosion:- Atmospheric corrosion is greatly accelerated when the atmosphere contains suspended dust particles of sand, salt, metallic oxides and chemicals. It has been observed for steel that paint films applied to rusted surface in winter have shorter life than the same paint applied in summer. Atmospheric corrosion can be reduced or eliminated by use of better alloys, by using corrosion resistant coatings (organic, inorganic or metallic) and by providing the cathodic / anodic protection.

In addition, it has been found that the use of metallic zinc-aluminum coating has a high corrosion resistance for steel equipment operating in atmospheric and variable water level zone in hydraulic structure. It has been reported that a service life of around 25years can be expected by providing such coatings.

One of the major factors responsible for the corrosion failure of any structure can be its faulty geometrical design (Fig. 3.6, 3.7 & 3.8). Complicated shapes having more angles, corners, edges and internal surfaces, will have a larger surface area exposed to the corrosive environment and will be difficult to protect by painting or other surface treatment. Also, to avoid the possibility of galvanic corrosion, different metals and alloys should not be jointed and especially when they are far apart from each other in the galvanic series. However, galvanic corrosion can be avoided by introducing an insulator, replaceable element or a paint layer in between the two metals.

Periodically wetted parts of steel structures suffer great damages resulting from atmospheric corrosions. The surfaces of the structure with seasonal / daily wetting are subjected to a high & constant rate of pitting corrosion. The underwater parts of steel structures are damaged by local corrosion. In still water, damages are in the form of small spots. Turbulent water results in more severe damages and with a larger number of pits, whereas the flowing water damages are maximum, with constant rate, and in the form of pitting. Cathodic protection is the most effective method for ensuring long life of steel structures in such case.

3.2.1.4 Aging:-The problems affecting the operation of the gated installations may also be a result of aging. Maintenance is particularly important to avoid aging problems that may arise with gate operation. Regular detailed inspections of the gates after construction are needed in order that aging problems can be detected and corrected well in time in order to ensure reliable operation as well as safety of structure.

3.3 OPERATION & MAINTENANCE

Most of the projects prefer to use rope drum hoists, because of their easier maintenance. If the wire ropes are inspected on a regular basis for broken strands or other signs of distress, and are periodically lubricated with suitable grease (generally Cadmium-D compound), the ropes shall last for a long. Otherwise, sudden break of wire rope during gate operation can lead to disaster. Stainless steel wire ropes are preferable especially in corrosive environment and may be economically attractive for some installations. Chain and sprocket hoists are difficult to maintain especially in silty water conditions. In case of Roller chains, bushings in the chain links are a critical component. Bushings tend to bind and freeze due to improper maintenance and corrosion. Hydraulic hoist is being preferred as a replacement for wire rope & chain hoist. This type of hoist can be useful in dampening the vibrations of gate. However, the location of hinges of hoist cylinder and the construction /material of hoist stem have to be engineered with adequate care.

Electro-mechanical equipment must be closely checked. Structural members, alternative electric supply systems, electrical circuitry, and electronic controlling systems are the main items for attention. Checking of gate clearances, which may decrease gradually to insufficient values and thereby become critical (as the result of thermal or concrete expansion) will help to prevent gate binding and consequent malfunctioning. Operational tests of gates prior to the flood season are recommended, however, the operators are often reluctant to operate bottom outlets gates because of the fear about the likely difficulties, that may arise due to vibrations and gate sealing on opening of high head gate. Although, the reliable operating conditions depend on having the gates that have been tested.

Power may fail in several cases. The failure to operate the gate may be due to the saturation of electric equipment, control cables that were submerged by the flood or due the fact that the access to the gates was cut off and in several cases key operational people were not available or could not get to the dam site.

Inspection and maintenance is a vital part for ensuring reliable and safe operation of the gates. Inspections are required to insure that the gates and the civil structure are in good operating conditions and to detect any conditions that may be or may become a threat to reliable operation. Different levels of inspections should be held regularly. The outside experts can provide experience from other projects and may observe items that the owner's operators and engineers may not be aware. The inspection should always review the maintenance program as well as the spillway and related equipment themselves.

Extensive abrasion of even stainless steel guide rails at one of the intakes had been detected. The embedded parts were seriously damaged. Major portions of the parts (upto 75%) were eroded and even disconnected in some locations. Some of the embedded parts were washed away, such that the gate operation was impossible. The damages were due the to the vortices, high velocities and impacts. The poor shape of intake and gate slots further accelerated the abrasive action by formation of strong eddy and flow separation.

The technical complexity and the inherent risk involved clearly restrict the use of automatic operation of gates for embankment dams, especially for such cases in which a high technical standard of maintenance can not be assured. Operators at the site should observe remote or automatic gate operation during floods.

CHAPTER-4

HYDRODYNAMIC FORCES AND VIBRATIONS

4.0 GENERAL

Hydrodynamic forces have two components namely mean and fluctuating. The fluctuating component is especially important because of the reason that they may excite structural vibrations.

4.1 SOURCES OF HYDRODYNAMIC FORCES AND VIBRATIONS

The sources for these forces/vibrations can be grouped with reference to the predominant excitation mechanism involved (Fig. 4.1) i.e. extraneously induced excitation (EIE), instability induced excitation (IIE), movement induced excitation (MIE) and excitation due to fluid oscillators (EFO). However, in some instances, the flow induced structural forces may be result of the combined effect of different sources.

EIE is caused by fluctuating velocities /or pressures and are independent of any flow instabilities originating from the structure. These are also independent of structural motion except for the added mass effects. Sluice gate excited by the unsteadiness of the submerged surface roller is an example of EIE (Fig. 4.1a).

IIE is due to the instability of the flow caused by the structure. Impinging free shear layer underneath a gate is an example of such excitations (Fig. 4.1b).

MIE is due to fluctuating forces that arise from movements of the vibrating structure. Changes taking place due to the transverse movements of rubber seal may result in flow induced forces, which in turn tend to enhance these movements. The induced vibrations are thus self excited (Fig. 4.1c).

The fluid oscillations may be due the standing gravity wave generated between a long piers and the walls of a flume, or a surging water body enclosed in a shaft d/s of a tunnel gate, if these oscillators set in motion, may induce large fluctuating forces and thereby seriously damaging the nearby structures (Fig. 4.1d,e).

4.1.1 Turbulence: - Pressure fluctuations of extremely large intensity may develop in a tandem gate arrangement, when one of the gates becomes stuck and the other one operated for affecting an emergency closure (Fig. 4.2a). The bottom of the d/s gate experiences extreme pressure pulsation under such circumstances due to impingement of the free shear layer separating from the u/s gate.

Apart from the fluctuating displacements of impinging shear layer, the high velocity jet alternately hits and misses the d/s gate leaf for certain gate opening ratios of these gates. In such circumstances, the pressure amplitudes ranging to the dynamic pressure ($\rho V_1^2/2$) and negative pressures even lower than the vapour limit may happen even if the space between the gates is adequately aerated, however, the aeration would help in minimizing the cavitation damages. The largest pressure pulsation during emergency closures may occur shortly before flow control point shifts from the service to the emergency gate (Fig. 4.2b). As the resulting dynamic loading of the d/s gate and cavitation are unavoidable for higher heads, therefore, it is advisable to close the emergency gate without stopping in-between.

4.1.2 Multi-Phase Flow:- Extraneously induced excitation may also arise due to multiple phase flows e.g. fluctuating forces induced by the flow of air-water mixture. Whenever there is flow of an air-water mixture through the conduits, the agglomerations of air bubbles or generation of large air pockets may take place. The entrapped air may escape by travelling either with the flow (blow-out) or against the flow (blow-back). The gated arrangement having u/s cylindrical & d/s radial gate is shown in Fig. 4.3a. In such installations, if the u/s cylindrical gate becomes stuck-up partial opened the air water mixture would enter the conduit provided the Radial gate also remains opened. With both the gates remaining open for considerable time, air cushions will form under the horizontal ceilings in the gate chamber (Fig. 4.3b). These cushions will blow out from time to time into the air vent, leading to pressure fluctuations behind the gate. However, such happening can be avoided by sloping the ceiling suitably. Model tests indicated that in case of gate operating partially opened and with free discharge, the air-water mixture flow can produce extremely large pressure pulsations on the u/s face of the Radial gate (Fig. 4.4). As the air accumulates in front of the gate, the pressure within that pocket reaches almost to atmospheric level. Thus, the air–water interface becomes accelerated toward the gate until it abruptly strikes on to the skinplate (Fig. 4.5), and thereby produces a water hammer like effect having pressure peak of several times that of the static pressure. The blowout processes (Fig. 4.4) are inherent to every outlet work having a pressurized conduit with air-water two phase flow. These phenomena can be prevented by adopting such measures, which allow the air to escape before it reaches the control structure. Otherwise, the gated structure should be designed to withstand such unsteady and unpredictable loadings.

4.1.3 Flow Instability:- Fig. 4.6 & Fig. 4.7 illustrates a few cases in which IIE can cause excessive loading or flow-induced vibrations of gated structure. Similarly Fig. 4.8 & Fig. 4.9 depicts some case which may lead to moment induced fluctuating force.

The steel lining of a gate installations was damaged near the spillway foot (Fig. 4.10) during the passage of floods. The steel lining at that location was not in contact with concrete and therefore, it acted like a membrane with extremely low damping, even under a flow depth of about 0.10m & average flow velocity of 5m/s. However, such damages would have avoided provided that the steel lining is properly anchored to the concrete (Fig. 4.10a). As the periodicity and the amplitude of the response grow substantially with a reduction of damping, the damage was therefore initiated by an extraneously induced (EIE). Once the lining started vibrating, additional forces due to the movement-induced excitation (Fig 4.9c) were exerted on it. If the lining assumes instantaneous geometry as depicted in Fig. 4.10 b&c, the streamline pattern of the flow get disturbed and a fluctuating force is induced which acts in the direction of the displacement of the lining. Ultimately, the lining got damaged(Fig. 4.10d) probably by fluctuating forces due to a combination of EIE and MIE. The example demonstrates the importance of adequate anchoring of steel linings in hydraulic structures.

4.1.4 Other Factors

4.1.4.1 Gate slot:- Flow turbulence within gate slots, and cavitation damage just d/s from gate slots, occur when the vertical lift wheel or slide type gates are operated at small openings under heads exceeding about 10m. There are many factors to be considered for designing such type of gates. The most important one is concerning to the gate slots in which the ends of the gates are supported. Unless the gate slots are properly designed, the turbulence and cavitation will result in damages to the gate leaf components, especially the flow surfaces & components lying in the gate slots. It is always preferable to provide a narrow slot to avoid hydraulic problems. In addition, gate slots also have effects the distribution of the piezometric head coefficient and thereby the downpull forces.

Various shapes of the gate slot for vertical lift gates are depicted in Fig. 4.11. Type-1 & 2 are only suitable for emergency / service gate operating under low head and low velocity, whereas the Type-3 & 4 are preferred for those gated installations which are exposed to water heads exceeding 25m or the flow velocity exceeds 25 m/s.

The preferred width / depth (W/D) ratio for the gate slot lies in the range of 1.6 to 1.8, however, the installations having the W/D ratios of 1.4 to 2.5 are not uncommon. The offset (Δ/w) at the d/s corners of the gate slot ranging from 0.05 to 0.08 has found to be preferable for high head installations. The chamfer slope (Δ/x) in the range of 1/10 to 1/12 is generally provided to avoid cavitation of waterway at the d/s of the gate. The relative radius of curvature (R/D) of d/s corner of gate slot as 0.1 & circular arc with 'R' varying from 30 to 50mm has been found to be suitable.

Hydraulically unsuitable gate slot configurations are responsible for a number of problems at some old gated installations. The arrangement (Fig 4.12) that forces the contraction of flow can be advantageously used to overcome the gate slot problems of such installations. This large contraction directs the jet away from the slot and thereby provides aeration. Where aeration can occur effectively, satisfactory operation of the gated structure can be ensured under free or submerged flow conditions. However, it is recommended that if a deflector is used for contracting the flow, it must continue without affecting the change in its shape until it reaches the u/s edge of the slot.

4.1.4.2 Distance between adjacent gate slots:- The pressure of the d/s slot will be lower than that of the u/s slot. Therefore, it is desirable that the space between two slots should not be too large, otherwise the increased friction losses and the decrease in the pressure near the d/s slot will induce cavitation apart from increasing the overall length of civil structure. Contrary to this, the pressure distribution of d/s slot is influenced by the u/s slot disturbances within a distance of about 1 to 1.5 times the slot width and beyond which the pressure distribution will recover to its normal pattern. Therefore, it is desirable that the center to center spacing between two slots should not be less than 2.5 times the slot width in order to avoid the disturbances from the u/s slot. However, the center to center spacing of 2.5 to 4.0 times the slot width is generally adopted for best performance of the gated installations.

4.1.4.3 Aeration:- When the gate of a high head outlet conduit is partly opened, a high velocity flow occurs d/s of the gate resulting in sub-atmospheric pressures. Theoretically, these pressures can be as low as the vapor pressure of water and may lead to structural damage due to cavitation and vibration. To avoid severe sub-atmospheric pressure the conduit is connected to the atmosphere through an air vent located d/s of the gate. The purpose of the air vent is to draw in air and thereby keep the pressures d/s of the gate at a safe level. Adequate supply of air is of vital importance for minimizing structural damage due to cavitation and vibration. The required quantity of air depends on the entraining & carrying capacity of the flow and the drop in pressure behind the gate is a function of the size, shape and length of the air vent. Therefore, the accurate determination of air demand is essential in order to provide adequate airvent size for maintaining pressures d/s of the gate within safe limits. The air demand is determined for gated installations by using empirical formulas developed on basis of laboratory and field measurement. The problem, however, remains still unsolved to some extent because of the fact that field measurements have indicated in some cases the higher air demand than those predicated from model tests or otherwise. The following flow conditions (Fig. 4.14) may prevail in a gated conduit and the air demand should be determined for the prevailing flow category for satisfactory performance of the installation.

(1) Flow of air alone i.e. under fully close gate condition there is no flow of water, but due to difference in temperature flow of air may take place in the reverse direction.

(2) Spray flow, at small gate openings, smaller than 10%, the jet issuing under the gate spray out into numerous small droplets and entrains a relatively large quantity of air.

(3) Free flow, depending upon the ratio of rate of flow of air to water, this may occur in the form of slug flow, or stratified flow.

(4) Foamy flow, the conduit section filled with almost uniform air-water mixture but still not flowing under pressure.

(5) Hydraulic jump followed by free surface flow.

(6) Hydraulic jump followed by pipe flow.

(7) Flow of water alone i.e. submerged or drowned hydraulic jump condition.

Further, the main considerations for deciding the maximum allowable velocity through the airvent are that it should not result in undesirable pressure drop behind the gate and also it should not create undesirable suction effect in the approach adit and the its surroundings. Therefore, the maximum velocity through the airvent should be adopted (not exceeding 60 m/s) keeping in view its adverse effects. Also, the air vent must be located at the top of the upper boundary of the conduit (Fig. 4.13) in order to avoid cavitation damage on it by the high velocity flow. In order to reduce the cavitation damages of conduit surfaces, the pressure in the conduit can be increased by gradually reducing the conduit area d/s of gate. For satisfactory performance, the ratio of Area of conduit at u/s of gate and Area of discharge end (N) can be adopted according to water head. When H<30m, N = 1.10 to 1.15; when 30m <H< 70m, N = 1.15 to 1.2 and when H >70m, N = 1.20 to 1.25.

It could be noted that in some of the gated installations, the part of air demand may be supplied from the d/s portal, because of this phenomena airvent provided in d/s of gate may turn out to be oversized. For tandem gates bonneted type arrangement, three air vent pipes, one each at d/s of service & emergency gate and the third a smaller one opening at the center of emergency gate slot may result in adequate aeration of the critical areas and therefore guarantee safe & satisfactory performance of the installations. But in case of high head gated structure of Beas Dam irrigation tunnel, the vibrations occurred during the initial operation irrespective of adequate aeration provided by a well designed arrangement.

4.1.4.4 Entrance-shape, pier thickness & others:- The entrance shape of piers also affects the cavitation. For the streamlined pier form (Fig. 4.15), the incipient cavitation number shall be equal to negative minimum pressure coefficient. Experiments have shown that beyond a distance of about 0.5 to 1.0 times the thickness of pier (T) in the d/s of the intersection point of tangency of circular arc, the effect of pier form curvature on the pressure distribution is negligible and can be considered as free from the influence of head shape of the pier. Therefore, it is suggested that the gate slot should be located at a distance of 0.5T behind the end of pier head curvature in order to eliminate the effects of head form of gate pier and also for satisfactory performance of gated installations. The ratio of pier thickness (T) and pier spacing (B) also influences the cavitation provided that this ratio (T/B) is larger than 0.05, because the pressure coefficient would have some variations as a result of the blockage effect. The curvature of crest of the spillway is also a factor that affects the cavitation. Whenever gate slot is located in the vicinity of the highest point of spillway crest, three factors will simultaneously induce the cavitation i.e. i) flow separation at the d/s corner of gate slot; ii) vortex formation within the slot; and iii) the pressure reduction at the surface of spillway crest, especially at the bottom. The pressure drop, which pushes the vortex out from the slot at the bottom, may induce the flow in the vertical direction in the gate slot. At the intersection of the curved surface of spillways, the vortex formations & the flow separation causes the pressure to drop sharply and thereby result in cavitation. However, on the other hand, the vortex can penetrate to the bottom and the self-aeration would take place in the slot provided that ratio of width and depth of gate slot (W/D) is small. The air content increases the pressure both in and around the vortex and thus reduces/mitigate the cavitation significantly.

At the top of conduit immediately u/s of the gate slot, it is preferable to provide a recess (Fig. 4.13). With such an arrangement, the water level in the gate shaft shall be immediately raised and significant downpull on the gate will be exerted near the fully closed position of d/s sealing gates. This will help to ensure satisfactory closure of the gate. The width of recess can be approximately taken as five times the thickness of seal.

4.2 HYDRODYNAMIC FORCES ON HIGH-HEAD GATES

The internal-type cylindrical gate (Fig. 4.16a) is located inside an intake shaft and consists of a cylindrical skinplate with an axisymmetric supporting structure. Since the horizontal forces act radially inward and are resisted internally by the gate leaf structure, therefore the forces transmitted on to the shaft (including frictional forces) are generally very small. The problem that may arise due to possible asymmetries in the approach flow is a lateral displacement of the gate between the guides and may produce instabilities especially at small gate openings.

For the cylindrical gate, the hydrodynamic forces in the vertical direction, produced during gate operation on the top and bottom seals, are also relatively small. Larger vertical hydrodynamic forces are brought about only if the water level inside the shaft changes too rapidly during fast gate movements. The axial flow through the inner space of the cylindrical gate can generate substantial drag on the ring girders.

The radial gate (Fig.4.16b) offers advantages of relatively small hydrodynamic hoisting forces similar to cylindrical gate, provided that the trunnion pin is located at the geometrical center of the skin plate. While evaluating the hoist capacity, it is required to consider the hydrodynamic forces (downpull) on the bottom girder & radial arms in addition to the some frictional forces due to the top and bottom seals. From the hydraulic considerations, the bottom horizontal girder should be kept as high as possible with respect to the jet emerging under the partially opened gate. The supporting arms and the trunnions should be installed such that they are not struck by the flow.

The large sized vertical lift gates (Figure 4.16c) are frequently used for flow regulation or emergency closure in high head installations as they offer number of advantages during construction and maintenance. However, from all types of high head gates, the vertical lift gate suffers the most in respect of hydrodynamic loadings. The vertical lift gate can operate either in a shaft or a gate chamber located within dam body (Fig.4.17a) or on the u/s face of a dam or an intake structure (Fig. 4.16c,d and 4.17b,c&d). In either of these cases, the pressure along the bottom of gate is reduced during operation as a result of high efflux velocities and thereby result in downward hydrodynamic force i.e. downpull, which may considerably exceed the dead weight of the gate. Therefore, accurate analysis of such downpull forces is crucial for the design of hoist and also for the safety of the entire project. The possible combinations of arranging top seal and skinplate are shown in Fig.4.18c, d, e & f. The feasible arrangement for face-type gates is that with seals and skinplate on the d/s side and similar arrangement is mostly adopted for tunnel-type gates. Gates with u/s seals offers the advantage of the reduction in downpull. However, such arrangement is used for relatively low heads only because of a number of problems inherited, especially those resulting from the extensive vortex action in the gate slots.

The major contribution for the downpull results from the difference between the pressure forces acting on the top and bottom surfaces of the gate. The forces acting on the seals and other protrusions of the gate may also be significant for certain installations. The prediction of the pressure forces effective on the top and on the bottom of the gate is essentially required for the analysis of the downpull forces.

4.2.1 During Underflow: - Two states of flow occur (Fig. 4.17& 4.19) in high head gated installations i.e. free flows (the space d/s of the gate is filled with air) and submerged flow (space is submerged and pressurized).

In case of free flow, the pressure head in the conduit just d/s of the gate ($\Delta p/\gamma \leq 0$) will depend on the intensity of air entertainment in the emerging water jet and the effectiveness of the air vent (Fig. 4.19). Whereas in case of submerged high head gate operations (Fig. 4.19a), the flow Q' and Q" affect the pressure patterns. In turn these discharges (Q' & Q") depend upon the piezometric heads in the reservoir and in the contracted jet d/s of the gate.

4.2.2 During Overflow:- The overflow in the vicinity of the gate shall make the analysis complicated due to the formation of corner eddies u/s of the gate (Fig. 4.19a & 4.20a). The three-dimensional eddies influence the flow and the downpull as they affect the loss in total water head (H_{ce}) along the conduit ceiling as also the piezometric head (h_T) in the gate shaft and the elevation (y_0*) of the uppermost streamline bounding the flow Q' immediately u/s of the gate (Fig. 4.19a). Therefore, it is y_0* (not y_0) which significantly effect the magnitude of the downpull coefficient k_B. With flow passing over the gate (Q"≠0), two counteracting effects on y_0* occur for any given ratio of y & y_0. First, an increase in Q"/Q' will reduce the elevation y'_0 of streamline dividing the streams passing over (Q") & under (Q') the gate. Secondly, increase in Q"/Q' will reduce the size of the corner eddy by an effect similar to boundary-layer suction, and thus has a tendency to increase y_0*.

The high velocity jet (Q") streaming down the skinplate changes the momentum of the jet (Q') issuing underneath the gate and thus affecting its vena contracta & the downpull coefficient (k_B). As the downpull coefficient (k_T) depends on head at the top, therefore the effect of overflow on a typical tunnel-type gate is always significant (Fig. 4.19d). The release of flow over the gate (Q") reduces the head on the top of the gate i.e. downpull. Therefore, it may be desirable in some installation to increase the rate of overflow (Q") in order to reduce the downpull and thereby hoist capacity.

4.2.3 Other Factors Affecting Downpull:- The hydrodynamic force or downpull, acting vertically in the direction of the hoist mechanism on high head gate with d/s top seal and skin plate is due to the difference of the piezometric head on the top surface (k_T) and the bottom surface (k_B) of the gate. Therefore, the magnitude of the downpull will depend upon width & thickness of the gate; thickness of the skinplate (Fig. 4.18); area of the horizontal projection of the top seal apart from the geometry of the gate bottom i.e. e/d, r/d, θ (Fig.4.18a) and the geometry of the bounding streamlines i.e. y/y_0, y_0^*/ y_0 (Fig. 4.19a).

4.2.3.1 Larger gate openings: - The effects of the velocity distribution u/s and the streamline curvature d/s of the gate cannot be neglected because of the fact that negative downpull (i.e.uplift) in such circumstances may inhibit the closure of the gate (Fig. 4.21). Although Q''/Q' is very small at large gate openings, still it controls the head in the gate chamber and influence the pressure distribution underneath the gate. To avoiding uplift in the range of large gate openings, recess can be provided (fig. 4.19d) such that the top seal would closes the gap (a_2') within the range of dangerous gate positions (Fig. 4.38).

While designing the bottom lip shape, achieving least downpull should not be the only criterion. Due considerations should be given for the possibility of uplift forces, unstable flow conditions and the cavitation (Fig. 4.22). While designing the gates having u/s seals and skinplate (Fig. 4.18), it is essential to arrange the bottom plate or girder such that the upper boundary of the jet emitting under the gate remains at sufficient distance to avoid substantial suction effect. Therefore, by adopting such measures (Fig. 4.45 & 4.46), the downpull can be reduced significantly. As the downpull will depend on the condition of overflow in such cases and therefore, the hydrodynamic forces acting on the hoist mechanism can be controlled as per the necessity by an appropriate design of the sizes of the overflow areas i.e.a_1 & a_2 (Fig. 4.19d).

This feature (i.e. Reduced downpull) may be reasons for adopting such an arrangement for a number of gated installations.

However, the disadvantages of adopting u/s seals and skinplate for high head gates are:

(1) Moderate downpull is always preferable to ensure safe closure of gate under emergency conditions, however, in this arrangement the downpull due to overflow reduces to zero as the top seal closes off the flow passage in the range of small gate openings i.e. ends when it is required the most shortly before gate closure.

(2) The higher the head, the more will be the problems associated with high velocity flow/ vortex action in the gate slots, including possibility of cavitation and vibration.

(3) It is impossible to avoid three-dimensional jet flow underneath the gate originating from the gate slots (Fig. 4.23). Component of this jet flow directed vertically upward is especially stronger for u/s skinplate gate and it reaches to its maximum strength as the gate opening approaches to zero.

(4) Among the other unfavorable effects of this jet flow can be uplift forces; closing off of the ventilation during free-surface flow leading possibly to cavitation; the generation of force fluctuations and thereby vibrations of gated structure.

4.2.3.2 Water holes:- The downpull reduces for submerged flow as shown in fig. 4.25 with the provisions of water holes in the lower most horizontal girder of a high head gate. Such holes are also useful to drain the water from the interior of the gate in its opened position.

4.2.3.3 Approach flow condition:- Recent studies have shown that the approach flow conditions, such as the intensity of free-stream turbulence have great effects on the downpull characteristics. The significant changes in the free-stream turbulence are encountered with intake gates on account of presence of trashracks or dividing piers u/s of the gate (Fig. 4.16c). These features, in turn, significantly effect the flow around the gates and thereby the downpull, especially, when the flow separates from the gate bottom either completely or partially. The roughness of the u/s face of the gate affected by either covering the horizontal girders by a smooth vertical plate u/s or leaving them open also effects the flow conditions significantly (Fig. 4.26). The lower most girders affect the streamline u/s of the gate by way of directing them slightly away from the gate bottom.

4.2.3.4 Gate movement and vibrations:- These effects the downpull significantly in case of the tunnel-type gates with overflow ($Q'' \neq 0$) especially in the range of large gate openings. The reason for this is the changes in flow pattern underneath the gate, u/s and d/s tunnel portions as well as in the space over the gate top. The water level in the gate chamber (hence the h_T and k_T) will adjust to the quasi-steady gate position at a rate which is controlled by the flow resistance within the gaps between gate and gate and gate chamber. The tendency for uplift forces is increased by the unsteadiness of a closing gate ($dy/dt<0$). Gate vibrations also produce an effect of unsteadiness on discharge and hydrodynamic force characteristics. The gate-lip vibrations can effect the free stream turbulence and thereby the shear-layer separating from the gate bottom will tend to assume a greater curvature due to turbulence. The effects of vibration on k_B is similar to the turbulence effects shown in fig. 4.26 & 4.27. As the high head gates will ever be free of tremors during gate operation, therefore it is recommended to ensure that the lip shape chosen should not be susceptible to large vibration effects on k_B.

4.2.3.5 Aeration and cavitation:- In free-surface flow past high head gates, the conditions of aeration through the air vent (Fig. 4.17 & 4.19b) effect the pressure along the free surface of the emerging jet and thus change the magnitudes of the rates of flow Q' and Q" and the hydrodynamic forces. The greater the air-flow resistance in the air vent, the more will be the under-pressure in the space d/s of the gate ($\Delta p < 0$) and also the more will be the jet velocity. The increase in jet velocity will, in turn, lead to larger downpull. An airvent of adequate cross-sectional area, located d/s of the gate, is essential for the safety of high-head installation. Free flow without sufficient aeration can be highly unstable, thus result in splashes against the conduit roof and gate vibrations. Some of the old installations having u/s sealing gates in gate shaft have not been provided with air vent. However, in such arrangement air will be sucked in through the gate shaft as a result of pressure difference at the top & bottom of the gate shaft and this phenomena may prove to be dangerous sometime, because the air while escapes during the gate closure may result in water hammers.

4.2.3.6 Gate recesses:- The gate chamber may designed with a recess on the d/s of the gate to allow overflow ($Q''\neq0$, Fig. 4.19) in order to reduce the maximum downpull (i.e k_T). However, in order to avoid the possibility of uplift forces, the d/s recess should be such that overflow takes place only for gate openings exceeding about 0.7m (Fig. 4.29b) because in the critical ranges of small openings (less than about 0.7m), the nature of hydrodynamic forces (i.e. from downpull to uplift and vice versa) may change drastically.

As far as the possibility of uplift forces is concerned, two ranges of gate openings must be analyzed accurately i.e. very large gate openings ($y/y_0 \rightarrow 1.0$ for $a_2' \neq 0$) and very small gate openings for u/s skinplate and sealing gated installation. The first range of gate opening can be made safer by allowing the top seal to remains in contact with d/s face of gate chamber (i.e. $a_2'=0$). Also, for ensuring safe closure during the last mentioned range, bottom seal can be offset toward the u/s face of the gate. In such design, any upward forces produced by the three-dimensional jets emerging from the two gate slots (Fig. 4.23), will be nullified by the forces resulting from the difference of F_T and F_B (Fig. 4.29).

In case of installation shown in Fig. 4.34, the uplift is avoided by increasing the height 'n' (from 300mm to at least 700mm) such that for large gate openings the a_2 is small enough. This change in design would also improve the unfavorable situation of the variable jet flow (Fig. 4.31& 4.33). Moreover, it will also eliminate the large variations in a_2 during gate operation and lead to a smoother change in downpull (Fig. 4.35).

4.2.3.7 Flows entering from top of shaft (i.e. vertical flows):

Example-1: A high head vertical lift type gate having d/s skinplate & sealing was used for emergency closure of the bottom outlet in an arch dam. The details shown in Fig. 4.36 (i.e. d = 1.31m, B =7.75m, y_0 =8m, r/d = 0.3, θ_{crr} =39^0) should be critically examined as for as hydrodynamic forces, cavitation, and vibration are concerned.

For a gated arrangement having gate shaft open to the reservoir, the most dangerous situation is depicted in fig. 4.37. Whenever the bottom of gate lies slightly above the conduit ceiling, the whole of the gate leaf will be surrounded by high velocity jets flowing through areas between gate structure & gate shaft at the u/s and d/s. The flow passing through the conduit underneath the gate will deflect the above mentioned water jets towards the d/s and cavitation will occur most severely at the highlighted areas (Fig. 4.37). Moreover, the jets will most likely flutter (especially the u/s one) and may give rise to fluctuating hydrodynamic force on the gate and thereby the vibrations. Also, there will be extremely large downpull acting on the gate because of sub-atmospheric pressure along the gate bottom. Remedial measures for these problems are shown in Fig. 4.38. The jet flows are sealed off till the gate bottom projects atleast 0.8m into the conduit. However the downpull will be extremely large even for larger openings in this arrangement. The large downpull and the problems of jet flow mentioned above can be avoided by isolating the top of gate shaft from the reservoir water completely under all circumstances.

Example-2: To supply irrigation water during the construction period of an earth-fill dam, the outlet was provided with a u/s sealing gate of sizes 1.83m x 2.44m (Fig. 4.39). The aeration of d/s of the gate was to be provided through the vertical gate shaft. As reported, this gate was operated about half open while the reservoir level rose due to flooding conditions. In spite of the best efforts, the earth dam was overtopped and thus failed. Detailed inspection revealed serious cavitation damages of the gate-leaf and the conduit d/s of the gate. Model studies concluded that the reason for this cavitation was the cut off of the air supply due to a closure of the gap between the gate and the d/s face of the gate shaft by water streaming down that gap. The problem was further intensified by the fact that the bottom girder flange was close to the top boundaries of high-velocity jets emerging from underneath the gate (Fig.4.23). Apart from cavitation, this resulted in severe vibrations of the gate, which could have significantly contributed to the settling of the earth dam and its subsequent failure.

Example-3: Crack opening of the intake gates (Fig. 4.40) were planned to be used for watering-up the scroll case area between the intake and the wicket gate. Compared to the bypass arrangement, this crack opening of gate requires lesser time and avoids the additional expenses on installation of the bypass. Uplift forces on the intake gates have to be kept small enough to avoid catapulting of the gates near the completion of the filling operation. As the space between intake and wicket gates becomes filled up with water during the watering-up operation, water start entering the gate shaft through the areas provided between the d/s side of the gate and the gate shaft. If this area is smaller than the effective gate opening area (during the filling operation), the flow into the gate shaft may be restricted enough to cause uplift forces which can catapult the intake gates high up into the gate shaft. For ensuring the safety against catapulting, an improved design shown in Fig. 4.40c was proposed for future constructions on the basis of Model tests result. However, for increases the safety against catapulting in respect of the existing arrangement, it was advised to crack open the intake gate with the greatest flow restrictions, i.e. gate ' F ' shown in fig. 4.40b for filling operation.

Example-4: Water for irrigation & power was being released through four intake shafts (Fig.4.41a). Each shaft consisted of two cylindrical gates 3.35m high, located at the upper and lower entrances. During the emergency closure of these gates the water surface inside the intake shaft drops, and large downpull develops shortly before closure, especially on the lower gate. Since this possibility was not envisaged initially at the time the gates and hoists were being designed. Therefore, in order to access the maximum downpull and the possible measures to reduce, model tests were necessitated. It was observed that during the closure as the gate bottom reaches near the sill, the flow passage between the gate bottom and the sill seat widens in the direction of flow thus forming a diffuser (Fig.4.42a). The angle of this diffuser increases gradually as the gate opening is reduced from about 0.3m to zero. Such unfavorable geometric conditions may lead to:

(1) Severe cavitation along the gate bottom accompanied by high-frequency vibration and noise at gate openings lesser than 0.5m;

(2) Local separation of flow from the gate bottom accompanied by large downpull as the diffuser angle is about 8^0 and above;

(3) Irregular and sudden changes in flow pattern between two bistable states of completely separated flow as the diffuser angle is further increased, accompanied by substantial, jerk-like changes in down pull and possibly surging of the water surface within the shaft.

However, by removing a part of the gate bottom (Fig. 4.42b) reduced the diffuser effect and thus substantially reducing the intensity of noise as also vibrations. After carrying out the modifications, the maximum down pull occurred at smaller gate openings and reduced to about 25% of that of the original design (Fig. 4.42c).

4.3 HYDRODYNAMIC FORCES ON LOW HEAD GATES

The hydrodynamic forces is one of the various loading which needs to be considered in the design of gate and their hoisting apart from dead weight, friction, ice, trash or mud, effects of temperature, settling etc. The design of the gate lifting device/ hoist mechanism is a challenge for such installation, which involve the hydrodynamic force. These forces have to be determined more precisely if the water load along the skinplate contributes to the force required to lift the gate for satisfactory operation of gated installation.

In case of gates with curved skinplate, it is important (Fig. 4.43a) that the resultant force, static or dynamic should always pass through the center of curvature of skin plate, if it is part of a circular cylindrical. By placing the trunnion pins of a Radial gate or a drum gate at this center, the moment of the hydraulic loading on gate leaf become zero. Similarly, the magnitude and direction of these moment can be changed to one that tends to either open or close the gate depending on the supporting pin location i.e. above or below the center of curvature respectively. Radial gates with low Mass-damping should not permit to have such closing moments because of the possibility of self-excited gate vibrations. However, such moment can arise even though the trunnion pin is located at the center of curvature because of the deflection of the skinplate under hydraulic load or due to fabrication /erection inaccuracies.

The sources of hydrodynamic downpull (F_y) depicted in Fig. 4.45 are as under:-

(1) The entertainment of fluid into the free shear layer which develops along the submerged jet below the gate, leading to a low-pressure under the bottom girder.

(2) The splitting up of the submerged surface roller by the bottom girder, giving rise to stagnation pressure above that girder. The smaller the distance of point 'E' from the shear layers the larger will be (F_y) due to an increase in the first mentioned effect. Therefore, the parameters like y_2/y, e/d, and apron slope are adequate to determine k_E. Also, by increasing the apron slope d/s of the gate sill, the k_E reduces because of the fact that the distance (e_{ff}) between point E and the shear layer increases with the increase of apron slope (Fig 4.45).

However, it would not be justified to conclude from Fig.4.46 that k_E always reduces with an increases in apron slope. It must be noted that if the inclination of the apron becomes too large, the emerging jet may separate from the floor and rise upward for moderate ranges of tail-water level (Fig. 4.47). With the upper jet boundary touching the bottom girder may result in substantially increase and fluctuation of hydrodynamic downpull apart from the possibility of gate vibrations (Fig. 4.54).

4.3.1 During Overflow:- Similarly, as in the case of gates with underflow, the flow rate must be known for determining the hydrodynamic forces for gates with overflow. The discharge can be either increased or decreased depending on whether the pressure under the nappe is lowered or raised. The pressure may drop to sub-atmospheric when the tail water is low and the ventilation under the nappe is cut off and it increases above zero when the tailwater depth comes close to or exceeds the height of the weir.

Fig.4.48 shows a simple double-leaf gate with overflow. Under various operating condition i.e. (1) the nappe separating from point 'A'; (2) the space between 'A' and 'B' is fully ventilated; and (3) the gap between the two leaves is sealed at point 'S', both area 'S' and 'U' will be under stagnation pressure, and there will be a vertical hydrodynamic force per unit width acting upward on the upper leaf composed of two parts, $F_y = F_{y1} + F_{y2}$ When point 'B' is approached by the lower nappe boundary, or when the nappe, separates form 'B' rather than 'A' (Fig. 4.49), the pressure between 'A' and 'B' will be controlled by the overflow and F_{yl} will change as a function, of mainly, flow geometry.

Two types of gated arrangement are shown in Fig. 4.50 i.e. a vertical lift gate with attached flap and the other one is a special type of double-leaf vertical lift gate. Both types can be operated with overflow; underflow; over & underflow simultaneously. The advantages of the double-leaf gate shown in Fig. 4.50b are that it can be designed for larger overflow depth (about 5m) and that, in comparison to the gate shown in Fig. 4.50a, the hydrodynamic downpull remains smaller during the entire range of overflow. The Fig.4.51 depicts the downpull forces for a particular gated installation having a span (B) of 24m and total height (y_0) of 12m . The vertical hydrodynamic force acting on the upper part of the gate with flap, evidently, is about four times large than for the special double-leaf gate. The vertical hydrodynamic force induced when the flap is in its lower-most position must be considered for designing the hoisting device for raising the complete gate. This force was found to be about 67t i.e. twice of the double-leaf gate (34t). However, if the radial gate (Fig. 4.52) is operated with overflow, an additional hydrodynamic load will also be exerted by the nappe striking the supporting arms, unless prevented by side shields.

4.3.2 During Underflow:- With an apron slope 1:1 below the gate, the flow, for a certain range of submergence, was found to be possible with both a rising and a falling bottom jet, similar to that as reported in Fig. 4.53. The rising jet (Fig. 4.54a) is associated with relatively large force fluctuations and large hydraulic downpull due to sub-atmospheric pressure developing along the gate bottom when the jet become reattached to it.

Also, it has been established that the bottom jet remains attached to the apron, provided that its slope does not exceed 1:1.8 (Fig. 4.55g). As the underflow with rising jet is dangerous and may result in gate vibrations, it is advisable to avoid apron slopes larger than 1:1.8, also for gates even with pure underflow (Fig. 4.47).

Other configurations which must be avoided in gate design are depicted in Fig. 4.56a and Fig. 4.57a&c. As shown in Fig. 4.56b, jet dividers with 50% obstruction may force the bottom jet to rise toward the gate even in case of small apron slopes of about 1:2. With bottom girder of the gate as low as the one shown in Fig. 4.56a, the underflow gives rise to relatively large force fluctuation and suction effect, similar to those depicted in Fig. 4.54a. The provision of holes in the bottom girder and a sloping upper surface of the jet dividers have proved to be the most successful remedies for reducing the gate vibration induced by the fluctuating forces. Holes having 6% of the total areas of bottom girder has provided adequate pressure exchange between the spaces above and below the girder so as to reduce the intensity of gate vibration by about 90% (Fig. 4.56c).

It should be noted that the above remedies do not work for such cases where the bottom jet strikes the girder or comes very close to it over the entire width of gate leaf. Fig.4.57 shows gates having the bottom girder construction of open trusses type. As seen from Fig. 4.57a, the girder can be hit by the jet for relatively small gate openings. A possible remedy for preventing such dangerous condition of hydrodynamic loading is shown in figure 4.57b. As reported, large force fluctuations may also arise when the trailing edge E of the open-truss bottom girder comes too close to the jet boundary (Fig. 4.57c). A satisfactory solution was obtained in this case by arranging the apron slope as indicate by the dashed line-2 in Fig. 4.57c; compared to the original design-1, the fluctuating force on the gate for small y/d (0.07) was thereby reduced by a factor of about 12. The hydrodynamic forces acting on an underflow gate with u/s skinplate may be negligibly small, especially when the lower most point E of the girder lies sufficiently high above the jet boundary.

4.3.3 During Simultaneous Under & Overflow:- Typical flow conditions for a gated installation are shown in fig. 4.64. For extremely low tailwater levels, the flow is unaffected by the tailwater. With rising tailwater, the depth y_2 behind the gate increases and causes the velocity V_j of the bottom jet to decrease (Fig. 4.58c); at some stage of increased tail water level, the ventilation of the nappe also ceases to contribute (Fig. 4.58c). At still higher tailwater levels, the upper jet finally changes from a plunging to a wavy surface jet (Fig.4.58d). However, in all of the above cases, the bottom jet remains attached to the apron unless its slope d/s of the gate becomes too steep. For an apron slope of 1:1 (Fig. 4.55h), there can be three possible patterns of the bottom jet, depending mainly on the parameters y/y_3 & $(y_0 - y_3)/y_3$ as shown in Fig. 4.53. However, in critical zones, two states of flow are possible for a specific installation (Fig. 4.53b), the jet pattern may be influenced due to some disturbance e.g. change in tail water level. However, the state of flow with the bottom jet rising toward the lower gate leaf should be avoided because it may result in excessive fluctuations of the hydrodynamic load (Fig. 4.59) which may give rise to gate vibrations. It is therefore, advisable, to limit the apron slope to 1:1.8 d/s of the gate sill (Fig. 4.55g).

In some circumstances, the fluctuating hydrodynamic force acting upward ($F_y < 0$) was found to occur in jerks, and the mean upward force increased when the ventilation of the overfalling nappe was stopped. Such uplift forces are resulted by nappe-induced vortices, which comes closer to the gate leaf structure. In absence of ventilation of nappe, the sub-atmospheric pressure are produced in between the gate leaf and the overfalling nappe and therefore the nappe tends to move toward the gate leaf.

The greatest upward force was also observed with non-ventilated flow while the greatest downward force occurs, in general, with ventilated flow. The corresponding value of k_E depends upon the shape of the lower gate leaf. For installations having apron shape-2, the gate shape of has significant influence only on the upward forces during non-ventilated flow. The greatest hydrodynamic forces as well as their fluctuations were observed for apron shape-3 (Fig. 4.59). Therefore, the apron slopes large than 1:1.8 should be avoided while designing the gated installations.

4.4 HYDRODYNAMIC FORCES ON MULTI-SECTION/ STOPLOG GATES

Multi-section and stoplog gates units (Fig. 4.60) are often provided to used as an emergency gate for spillways, that is to say these are placed u/s of the main/service gates. These multi-section gates, however, are designed to operate under static condition i.e. balanced head of water generally. In case these are attempted for installing these units under flowing water, then, as a consequence of turbulent flow, extreme hydrodynamic forces and severe vibrations occurs to such an extent that it becomes very difficult or even impossible to handle them. Situation shall be even worse, if these stoplogs are operated with underflow & overflow simultaneously. It is particularly difficult to calculate the effect of turbulent flow on such gates when not only the skin plates but also the frame work or parts of lattice girders and lifting beam come into a strong current and the discharge passes simultaneously under and over the gates units.

It is recommended that instead of using lifting beam for operating (Raising or lowering) these stoplog units, these should be provided with automatic grappling and ~~lifting~~ hooks for their operation. The skinplate & sealing for stoplog units should be kept on u/s side. Further, by stream lining the bottom & top of the gateleaf & lifting beam (Fig. 4.61 & Fig. 4.62) almost any flow condition coming into consideration can be mastered to a certain extent while operating these stoplog units. As such, the factor of safety of whole spillway is increased or even doubled. However for such operation, the crane capacity and weight of stoplog units should be liberally provided to be on higher side for safe and satisfactory operation.

4.5 HYDRODYNAMIC FORCES ON EMBEDDED PARTS

Hydraulic forces on the embedded track plate/ rails for high head vertical lift gates also need consideration in regards satisfactory performance of gated installations. The tracks and their fixtures are normally designed to resist the forces exerted on them by the wheels of a loaded gate leaf (Fig.4.63). Model test has revealed the nature of the pressure distribution on the surface of the embedded track and effect of penetration of water between the track and its mounting (Fig. 4.64). By virtue of the above phenomenon a significant force is exerted on the embedded parts and tends to lift the track from its mounting. Therefore, while designing gate tracks and fixtures, theses hydraulic forces must be considered to ensure safety of structure and satisfactory performance of the gated installations.

Under high velocity flow situations in lined canals and spillways, cases of failure of the concrete surface are known to have occurred as a result of the reconversion of velocity head into pressure head in joints and cracks. It is suggested, therefore, that a similar mechanism might apply to gate tracks especially when the gate is partially or fully opened under the effect of extreme higher head and flow velocities. The high pressures near the stagnation point affects both the outer edge and the back face of the track, while the high velocity vortex across the u/s face of the track created low pressures, possible so low as to cause cavitation.

The flow patterns can be such that high stagnation pressure, even approaching the full hydrostatic head, can be developed in the vicinity of the d/s edge of the slot where the gate track is fastened. Also, construction procedure will probably require tolerance for the erection /alignment of the track and the embedded parts to which it is fixed such that a small gap behind the track is unavoidable. Such a gap is likely to be large enough to allow the high stagnation pressures to occur behind the track. Simultaneously, the low pressure, even down to cavitating conditions, may also exist of the open face of the track near to the circulating eddy.

4.6 PREDICTION OF PRESSURES IN THE GATE SHAFT

Vertical lift gates in the tunnel type installations have experienced problems especially under high heads, because of unpredictable hydrodynamic forces on such gates during their operation. The problem include not only downpull and vibration of the gates, but also the gates failing to close in several installations, and even catapulting of gate into the gate shaft. The prediction of pressures in the gate shaft above the partly open gate is an important and often challenging problem.

Unbalanced vertical hydrodynamic forces are the result of differences between the downward force on the gate, because of water pressures in the gate shaft, and the upward force on the gate bottom. The net force is termed as downpull when it is in the downward direction and as uplift when it is upward. Uplift is primarily responsible for catapulting or non-closure of the gate. Hydraulic model tests for an individual installation can predict such hydrodynamic forces reliably.

Fixed wheel or caterpillar-type vertical lift gates are generally used in the tunnel-type gate installations for high head operation. These types of gates are provided with rubber seals on the d/s face of the gate leaf for ensuring water-tightness. In order to have perfect sealing, the gated arrangement force the rubber seals to get compressed against stainless steel seating fitted to the embedded frame, when the gates are in their fully closed position. As the gate is raised, the top seal breaks away from its seal seat and the water flows down through the resulting gap between the d/s face of the gate and the seal seat. In some installations provisions is made to permit reservoir pressure to act behind the top and side seal, and the pressure is cut off by a valve prior to the raising operation of the gate. Some leakage will then occur through the side seal, but its effect on gate shaft pressure will be insignificant. When the gate is fully closed, the pressure in the gate shaft is hydrostatic and is equivalent to the u/s reservoir head. As the gated is raised, pressure in the gate shaft is reduced because of flow velocity at the gate and the discharge of water from the gate shaft into the d/s conduit. The width of gap 'a_2' between the embedded seal seat of the gate shaft and the d/s face of the gate is generally kept smaller than the u/s gap 'a_1'. The gap 'a_2'and the head in the shaft thus determine the quantity of water being released from the gate shaft.

4.6.1 Sudden Expansion in Gate Shaft:- Generally, the widths of gaps 'a_1'and 'a_2'are small as compared to the gate shaft sizes. It is, therefore, reasonable to assume that the entire velocity head of the jet flow issuing thorough the u/s gap is lost because of sudden expansion. This assumption is based upon the fact that during partial gate openings the jet issues through the u/s gap vertically upward, suddenly expands and mingles with the water present within the gate shaft and loses it velocity head prior to flowing down through the d/s gap.

When the gates are fully closed, 'H_G' is obviously equal to '$H-Y_g$', where 'H' is the total u/s head acting on the gate sill and 'Y_g' is gate height (Fig. 4.65). When the gate is raised, stagnation pressures should occur on the u/s corner areas of the partly opened gate. Also, the experiments had indicated that the pressure 'H_G' gradually diminishes as the gate is raised. This is because of the effect of corner eddies on the stagnation zone, caused by the velocity of flow beneath the zone.

The process of estimating the pressure in the gate shaft is complicated because of indeterminate energy loss u/s of the partly open gate. Moreover, significant errors could occur as a result of losses at the entrance and as well losses at the uncovered face of the gate leaf with projecting horizontal girders, especially for those installations having d/s skinplate & u/s vertical flow.

4.7 VIBRATIONS

4.7.1 Vibrations of Gates During Underflow:- The bottom of the high head and as well as low head gates are exposed to hydrodynamic forces that may excite vibrations in the vertical or horizontal direction whenever these gate are opened to allow underflow. The vibration response of a gate significantly depends on the bottom shape and the relative gate opening i.e. y/d, (where 'y' is the height of the opening & 'd' is depth of horizontal girder or the thickness of the gate). The excitation may also be induced by the impinging leading edge vortices, (ILEV).

The excitations are caused by submerged underflow or by a separating free shear layer that impinges on or passes near the trailing edge 'E'. If the u/s edge of the gate bottom is rounded (Fig. 4.66b), the shear layer forms closer to the underside of the gate than for a square-edged gate bottom and therefore, as a consequence, the maximum amplitudes of vibrations occur for larger gate openings for rounded bottom. Also, if the skinplate is extended a small distance say 'e' as shown in Fig. 4.66c, the feedback process inherent to ILEV is strengthened and remains functional over a larger ranges of y/d. However, if the extension 'e' is larger than some critical value, the shear layer remains stabily reattached to the bottom of the gate and the excitations are avoided.

Therefore, the susceptibility of a gate with a given bottom configuration to excitation by impinging shear layers depend significantly on the distance (d*) between the mean shear-layer position and the impingement edge 'E'. This distance in turn, depends on the position of the separation streamline below the gate. This distance (d*) can be approximated as (a_s-e^*) (Fig. 4.67a). Here, e^* is the vertical distance between the point of flow separation 'S' and point E, and a_s is the vertical distance from 'S' to the point at which the separation streamline intersects the vertical through 'E'. For practical purposes e* can be taken equal to 'e + r' for the bottom shapes depicted in Fig. 4.66.

In order to protect a gate against flow-induced vibration in the vertical direction, including the self-excited type, it is desired either to provide sufficient damping or select a shape of gate bottom from which the flow remains unseparated or stably reattached to the gate bottom for all operating conditions i.e. e*/d must exceed the largest possible value of a_s/d.

This recommendation is more easily fulfilled for a tunnel gate (Fig. 4.67a) with limited u/s depth of flow (y_0) than for an intake gate of identical cross-section but having large u/s depth of water (H). Moreover, a tunnel gate with a given ratio of e*/d becomes safer as far as flow-induced vibrations are concerned, because the ratio of tunnel height (y_0) to gate thickness becomes smaller. In order to eliminate the possibility of vibration excitation, it is desirable to adopt a value of e*/d well above the upper range-boundaries for a vertical lift gate as shown in Fig. 4.22.

For high head gated installations having one degree of freedom (i.e. in the vertical direction), the improvised bottom shapes have been evolved that can prevent flow-induced vibrations irrespective of the stiffness and damping capability of gate. The bottom lip of gate is designed such that either the flow never separate or it remains stably reattached under all operating conditions to the bottom of the gate. Also for stability of flow e* should exceed a_s for all operating conditions by some 10% to 20% except for those gates having flow separation from u/s (Fig. 4.68) and gates with two degrees of freedom (Fig. 4.69a).

A high head gated installation is shown in Fig. 4.68 in which the separation of flow u/s of the gate took place and thereby resulted in vertical vibrations of gate despite the fact that e* was greater than a_s. The corner eddies generating u/s of gates may also result in unstable flow separation from the conduit ceiling (Fig. 4.19a). However, such eddies may be absent only if boundary layer suction, generated by the flow through the gate chamber inhibit their formation. In the case shown in Fig. 4.68a & b, field tests had revealed that the gate vibration in the ranges of larger gate openings i.e. $0.7 < y/y_0 < 0.9$ (Fig. 4.68d) due to reduced horizontal force and the thereby small frictional damping in these ranges. The circumstances under which there is possibility of ILEV-induced gate vibrations are also depicted in Fig. 4.6. If a tunnel gate is withdrawn into the gate chamber with its lower edge close to the tunnel ceiling, it can still be excited to vibrate by impingement of the shear layer as shown in Fig. 4.6i. Frictional damping is ineffective in such situations because of almost no horizontal load on the gate leaf; as a result of this phenomena, the gate can develop into a bang-bang type gate performing more or less random movements in the gate chamber. Also, the favourable source of such excitation is pressure fluctuation within the gate slot (Fig. 4.6e & Fig. 4.70c), unless the d/s edge of the gate slot is offset adequately.

Pressure fluctuations of extremely large intensity occur for a tandem gate installation (Fig. 4.6h), if one of the gates becomes stuck-up and the other affects the emergency closure. Along with the fluctuating displacement of the shear layer originating at the bottom of the u/s gate, the high-velocity flow alternately hits and misses the skinplate of the d/s gate for a certain critical range of gate openings; this phenomena can results in serious damaging forces & cavitation in the gated installations. The provisions necessary in these cases is an instruction for the operator not to interrupt an emergency closure near a critical gate opening.

The gate design having bottom girder close to the free shear layer as depicted in Fig.4.57a may also excite a long span to vibrate. The remedies for such problems is to slope the apron (maximum 1:1.8) d/s of the skinplate location as shown in Fig. 4.57c_2 or to incline the bottom girder (Fig. 4.57b).

The fundamental or super-harmonic resonance with impinging leading edge vortices (ILEV) can lead to vibrations of a under flow gate both in the horizontal and vertical directions, because the regions close to the vortices are associated with low pressures. The ranges of horizontal gate vibration are adjacent to the ranges of vertical vibration, therefore their excitation requires different pressure distributions i.e. within the ranges of vertical gate vibration horizontal excitation is impossible. The horizontal gate vibration involves flexural movements of the skinplate at relatively high frequencies and it may occur if the dampening of the skinplate in gate construction is inadequate. Also, the resonance in such circumstances is restricted to very narrow ranges of relative gate openings, therefore, such excitation are significant only for those gates meant to regulate the discharge within that critical range.

The stable lip shapes shown in Fig. 4.71& 4.72 are difficult to achieve because of structural limitations. However, since ILEV-induced excitations of gateleaf are limited to a narrow range of gate openings ($y<2d$, Fig.4.73b), therefore it is required to design the bottom lip of the gate with as small thickness 'd' as feasible and ensure that the gate passes quickly through the dangerous ranges of gate openings. However, the stiffening of the gate bottom, which will form the part of the skinplate/ gate lip will result in increase of the critical vibration zone (Fig. 4.74e). Therefore, any strengthening to augmentation the structural dampening shall also helps to attenuate the vibration. The greatest destructive vibration can arise from simultaneous action of the movement-induced excitation & ILEV, therefore, the possibility of such excitations should always be eliminated by carefully designing the gated structure.

4.7.2 Vibrations of Gates During Simultaneous Over and Under Flow:- Shell type long span gates with relatively large overflow and simultaneous underflow at small gate openings can develop self-excited vibrations even in the absence of an inclined u/s face. For a gate with a vertical u/s face, however, it is only the hydrodynamic force acting on the crest of the gateleaf that may induce coupling mode of excitations. Any gate vibration in the direction of flow may initiate substantial added-mass flow which, in turn, produces pulsations in the rate of overflow. With these pulsations, the hydrodynamic forces on the gate crest will fluctuate and forces the gate to vibrate vertically. As a result of this phenomena, the rate of underflow will fluctuate and thereby generating horizontal force fluctuations that amplify the initial streamwise vibration of the gate. Also, the alternate shedding of vortices can also excite the gates while, operating under simultaneous over and underflow.

The instability-induced excitation of a multiple leaf gate, provided for emergency closure of a intake in case the turbine attain runaway speed is shown in Fig. 4.75. The combined hydrodynamic and friction load acting vertically on the first of three gate leaves during closure under runaway discharge, shall be nearly periodic & fluctuating that start from the centered position of the leaf as indicated in Fig. 4.75d. The maximum force amplitude (6.35t) was almost sufficient to cause the lifting ropes to become slack and these forces fluctuation subsided only when, the lower edge of the first leaf was 0.6 to 0.9m from the sill. During lowering of the second leaf gate, a hydraulic uplift equal to its weight were also experienced, and the downward movement stopped when the leaf was at a position about 2m short of closure. From test with several cross-sectional shapes of gate leaf, the one shown in Fig. 9.50c did not cause slackening of ropes and closed safely. Although, vortex excitation persisted with maximum amplitude of about 5.5t. The variation of the excitation frequency and the dependence of the force amplitude on both the sizes of the handling beam and its distance from the leaf gate are shown in Fig. 4.76.

A double leaf gate arrangement of the free surface type, designed for both over and underflow is shown in Fig. 4.77a-c. During simultaneous over and under flow, the hydrodynamic force acting vertically on the lower gate leaf fluctuated. The maximum magnitude the force excluding buoyancy and hydro-elastic effects is shown in Fig. 4.77e. The force fluctuations acting upward occurred in jerks, and the mean upward force was substantially high in case the overflow nappe is not ventilated. The uplift forces were generated by vortices from the underside of the nappe; these vortices come closer to the lower gate leaf when the under pressure, for the non-ventilated flow, displaced the nappe in the u/s direction. Both the force amplitudes and the mean upward forces for non-ventilated flow were smaller when the upper and lower sides of the lower leaf had larger inclinations. Obviously, a cross-sectional shapes as shown in Fig. 4.57b is the most favorable also with respect to instability-induced excitation resulting from simultaneous over and underflow for the lower gate leaf. However, the provision of an effective air vent is essential for all cross sectional shapes.

4.7.3 Vibrations of Gates and Gate Seals involving Flow Rate Pulsation:- The most dangerous mechanisms for movement induced excitation of gates and gate seals are those involving coupling with fluid-flow pulsation. For a vibrating skinplate, such pulsation can occur if the skinplate is inclined with respect to the apron in such a way that it behave as a press-shut device (Fig. 4.8a). Moreover, the movement-induced or self-excited vibrations may arise even if the underflow is not submerged, merely due the coupling of fluid inertia effects with skinplate vibration via flow-rate pulsation and the gate becomes unstable if either its stiffness or its opening 'y' are reduced; or if the velocity 'V' or the angle of inclination 'α' is increased.

The self-excited gate or gate seal vibration can occur if a seal arrangement gives rise to flow through a leak channel with an u/s constriction as shown in Fig. 4.78a. The remedy is to eliminate such a constriction or move it towards the d/s end of the flow passage. The originally diverging flow passage resulted in not only cavitation but also severe vibrations of skinplate due to flow pulsation generated by the fluctuating gap and the modified design helped to eliminate these vibrations. Violent vertical gate vibration of a similar type origin, accompanied by cavitation and extreme downpull, occurred when the cylindrical gate (Fig.4.78d) reached an opening of 1.6mm. Such vibration, cavitation and excessive downpull could have been avoided, had the 'leak channel' at small gate openings not been divergent. Modification of gate-bottom or seat geometry is required or damping device capable of suppressing self-excited gate vibration at such small gate opening (As shown for a reverse radial gate in Fig. 4.79) can be provided for safety.

Fig. 4.78e depicts a top seal arrangement for which self-excited seal vibration is almost inevitable because fluctuations in gap width near the flexible seal are unavoidable. The modified design shown in Fig. 4.78f can eliminate such vibration for moderate heads ranging up to about 25m, by means of fixing the gap width and reducing the rate of gap flow. However, for ensuring satisfactory performance of gated installations, a more effective and preferable solution to such problem is depicted Fig. 4.78 i.e. adoption of seals having less flexibility.

A gated installation provided with a cylindrical gate is depicted in Fig. 4.78b, in this arrangement the gap between the gate bottom and gate sill seat formed a diffuser at small gate openings of less than 300mm. Sudden changes in flow pattern between two bistable states were taking place thus resulting in severe vibrations & irregular changes in downpull, because of large diffuser angles at small openings. To ensure satisfactory operation the design of gate leaf was recommended for modifications as shown in Fig. 4.78c in order to substantially reduce the intensities of vibrations/noises, and downpull.

The lower face of the gate shown in Fig. 4.69a has an inclination that makes it a press-shut type device and therefore, such gate construction would be stable only if it had one degree of freedom. The low-head gates of this type having span-to-height ratios of about 15 to 20 or more will have relatively large bending flexibility in both the vertical and the horizontal directions. The coupling of the vertical and horizontal vibration modes can lead to movement-induced excitation especially at small gate openings in such installations. Moreover, when such gates undergo horizontal deflections, the corresponding fluctuation of the hydrodynamic forces acting on the inclined lower face produces vertical gate deflections that, in turn, cause flow rate pulsation. These pulsations generate additional force fluctuations and reinforce the initial horizontal deflections under certain conditions.

For dynamic stability of such gated installations, the ratio of the in water horizontal vibration frequency w_x to the natural in water frequency w_{ny} of the gateleaf structure should be smaller than unity; and the ratio of w_x to the in air vertical vibration frequency w_{ay} of the gateleaf should be larger than a limiting value of (w_x / w_{ay}) 1.5. In case either of these criteria is violated, self-excited gate vibration will set in, irrespective of the fact that the underflow is submerged or not, unless the mass damping of the gate is large enough.

For typical shell type long span gates, the natural frequencies of vibration in the first bending modes in air are almost equal for the horizontal and vertical directions. In water with only underflow, the frequency of horizontal vibration is significantly lower that that of vertical vibration because of added-mass effects. As such, the self-excited vibrations during underflow can occur provided the gate is suspended with flexible wire ropes because the frequency of the vertical vibrations in the rigid-body mode in such arrangement will lesser than horizontal-bending mode frequency. However, if the gate is subjected to substantial overflow simultaneously with underflow, it's added-mass for vertical motion will be much larger, and the stability criterion may also be violated for vertical bending mode vibrations. Severe self-excited vibration of a shell type gate during simultaneous over and underflow had been reported, inspite of the fact that nappe was broken by spoilers and the space underneath was fully ventilated. However, during pure underflow there were no vibrations in that installation.

CHAPTER-5

CASE HISTORIES

5.0 GENERAL

The data in respect of malfunctioning/ failure of various gated structures was collected for carrying out the analysis. The case histories have been grouped on basis of the major factor responsible for the malfunctioning/ failure of respective gated structure and are presented as under: -

5.1 SEISMIC & FLOOD LOADING

5.1.1 Kilmorack & Marun Dam

5.1.1.1 Seismic evaluations of spillway radial gate (Kilmorack Dam):- A gated structure requires adequate strength for specified level of ground motions resulting due to earthquake. Design should take care of such an extreme earthquake event liable to occur at least once during the expected life of the structure. However, the flood loading is not to be included in the seismic analysis and the gated structures should be analyzed for earthquakes under their normal operating condition, i.e. open, closed or both. The post-earthquake operability of gates depends on many factors including:

(1) Damage or permanent distortion to the gate's structure, potentially causing jamming.

(2) The response of other structures carrying related equipment.

(3) Damage to equipment related to the gate's operation.

(4) The blocking of gates caused by fallen overhead objects or structures.

(5) The loss of electrical power off and on site and failed standby power systems.

In many cases, the risks to the functioning of gates can be mitigated by strengthening the gated structure, restraining/ improving the control, standby equipment, gantries, simply supported beams and other heavy objects that may damage nearby equipment.

The seismic response of a radial gate has been observed with help of FEM model & 2-D static model and it is found that not only the gate properties but also the response of its supporting structure plays important role.

During the earthquake, as the gate moves towards and away from the reservoir, the gate leaf is exposed to considerable hydrodynamic and hydrostatic forces. These forces will be transferred to the trunnion bearings through the axial loading of the radial arms. In such circumstances, there will be a great risk of buckling of the radial arms and damage to the trunnion bearings/pin and their anchorage, apart from the gate leaf itself. Also, the cross-stream seismic loading may cause damages as a result of pounding between the gate and the spillway piers. The out of face vibrations resulting in differential seismic inputs at the two trunnion makes the situation even worse.

The seismic evaluation of Kilmorack dam radial gate of size 7.9m wide x 8.2m high was carried out considering the gate in closed position. Observations were concentrated on the structure of the gate and its response with a peak ground acceleration of 0.24g. Gate leaf consisted of skinplate supported on vertical stiffeners; and two horizontal girders. The inclined radial arms connecting horizontal girders and the trunnion hubs were converging at trunnion bearings. The gate, however, was not designed for the seismic loading.

FEM model indicated cross-stream displacement of the gate to be 9mm (max.) and this was less than the designed clearance at the gate's sides, therefore, pounding of gateleaf against the pier walls was unlikely. The effective load on the gate during the earthquake can increase by about 85% compared to the static, thus exposing the gate to a load almost twice of that for which it was designed. The normal water load on the trunnion bearing was about 1250KN.

For stream-direction seismic loading only, the equivalent-static analysis (1450 KN) indicated 26% higher reactions at the trunnion bearings, compared to the 3-D dynamic analyses (1155 KN). Also, the equivalent static analysis yielded axial forces in the radial arms up to 34% higher for the upper arms, but within 10% either way for the lower arms. For cross-stream seismic loading, the equivalent-static analysis gave significantly higher bending moments.

5.1.1.1.1 Conclusions:-This result suggests that the gated structures designed without contemplating seismic effect are vulnerable to extreme earthquakes. Moreover, the gated structure designed with consideration of only static effect of seismic forces may not be capable of resting the most dangerous dynamic forces during the earthquake. The damages to the gated structure can take place as result of the arching action of the stiffened skinplate (i.e. bending about the minor axes of the horizontal girders) and by buckling of radial arms (Fig.5.1). The may result in damages because of pounding of gate leaf against the pier walls. The most vulnerable component of gated structure in respect of safety and reliability of operation are radial arms and the trunnion. The radial arms being slender may initiate failure, where as misalignment of trunnion can effect the operability of gate.

5.1.1.1.2 Recommendations:-The trunnion of radial gate can be designed to have self-aligning bearings for reliability of operation. The design of arms and anchorage should conservative. Also, during transverse moment (i.e. in cross-stream direction) and possible displacement of piers, the radial gate may become wedged or suffer local buckling due to close tolerances between gate leaf & piers. Therefore, it is recommended that in order to counter the effect of cross-stream horizontal forces, the side seal arrangement may be designed such that it will deflect or buckle under severe impact (Fig. 5.5a). Similarly for ensuring the safety of vertical lift gate against the seismic forces spring loaded guide wheel (Fig.5.5b) capable of absorbing shocks may be provided to counter the horizontal accelerations.

5.1.2.2 Radial gates overtopping (Marun Dam):- The hydraulic model result showing the pressure exerted on the arms of the spillway gates, in case the radial gate remain closed and its overtopping occurs during the flood. The pressure forces induced by the falling jet were studied for the water depths of overtopping from 2.5m & 4.0m and are shown in Fig.5.4 The concentrated mass due to overtopping depth of 4.0m was calculated to be about 3.0t hitting on the arms of the gates directly.

5.1.2.2.1 Conclusions & recommendations:- It is concluded that during the overtopping of gate, the forces exerted on radial arms shall be significant and therefore, should be considered for the design of radial gate arms and their connections along with the hydrostatic loading. It is suggested that such force / load due to the maximum possible overflow depth should be considered in design. However, such loads can be avoided if gate arms are suitably protected from overfalling jet by an arrangement of side shields/deflectors etc.

5.1.2 Sefidrud Dam

5.1.2.1 Incident:- An earthquake during 1990 took place and as a consequences of this, the spillway radial gates were damaged.. The detailed inspection and operational test were carried out post earthquake in respect of the gated structure of dam including spillway radial gates. It was observed that although the recorded earthquake peak ground accelerations were much higher than the design value of 0.25g, but there were no failures in the gated structures of bottom outlets, power and irrigation intakes. However, the spillway radial gates were seriously damaged to such an extent that their operation was impossible

The Sefidrud dam of buttress type is 100m high. Two radial gates of sizes 7.5m (height) x 7.05m (width) control spillway of the dam. Three bottom outlets of sizes 6m(width) x 10m(height) at elevation of 191.30m and two irrigation outlet gates at elevation of 193.80m are also provided.

The spillway gates were closed at the time of the earthquake and the reservoir water level was at 265.5m, i.e. 6.15m below the normal water level (271.65m). After the event, it was estimated that the earthquake had generated accelerations having magnitude of about 0.6g. As a consequence of the earthquake, the severe hydrodynamic forces were generated that resulted in buckling of the web of the right upper arm beam of a spillway radial gate and thus caused the gate to leak (Fig. 5.2). The steel base plate of the trunnion hub of the another radial gate having thickness of 40mm developed a 20mm deep crack.

5.1.2.2 Analysis:-The analysis of damages sustained by these radial gates, confirms one of the likely failure modes predicted by 3-D F.E.M model & 2-D equivalent static models generated for Seismic Safety Evaluations of the Kilmorack Dam's spillway radial gate. In one of the failure mode predicted for certain frequency, the hydrodynamic forces can results in axial loading (compressive/ tensile) at the end supports of gate, apart from bending of gate leaf (Fig. 5.1). Also, as predicted the magnitude of forces can be higher in upper arms as compared to the lower ones. Therefore, it could be understood that the hydrodynamic forces acting on the gate leaf induced excessive axial compressive load in the upper arm of the radial gate and thereby resulted in its buckling. Similarly, the base plate of the trunnion hub of the another radial gate was pulled by the excessive axial tensile forces and thereby resulting in cracking of its trunnion hub base plate.

5.1.2.3 Remedial measures:-For rehabilitating the spillway radial gates, the bent section of the buckled radial arm beam was removed by cutting out and replacing the damaged portion of beam with a new one having same cross-section (Fig. 5.3 & Fig. 5.2). The cast-steel base plate of the trunnion hub of the another gate was restored by cutting a v-notch and backfilling by welding. The repaired base plate was tested by X-ray and stress relieved for the safety of structure.

5.1.2.4 Conclusions:-Considering that the reservoir water level of Sefidrud buttress dam during the earthquake was about 6m lower than normal water level, and the bottom outlets, irrigation and power intake gates did not suffer any damage, it seems that such gates can sustain earthquake forces of much higher magnitudes. Moreover, it could be assumed/ understood that the bottom outlets might have provided with vertical lift gates which are restrained in both directions comparably better than the radial gates. Also, sealing surfaces (especially rubber seals)of vertical lift gate are arranged such that these act as insulator and dampen the shocks to some extent during the earthquake. Moreover, because of their deep locations, the magnitude of static load is higher than the more dangerous dynamic loads.

5.1.3 Matahina Dam

5.1.3.1 Incident:-The Matahina dam located on the Rangitaiki River (New Zealand) is a zoned earth and rockfill embankment dam 80m high and has a crest length of about 400m. The dam owner undertook a detailed review of the potential impact of the future seismic safety of the dam and decided to strengthen spillway radial gates of sizes 8.5m (wide)x 12.5m (high). During the earthquake ground accelerations of about 0.4g were recorded at the dam crest. The spillway gates operated reliably even after the earthquake and the post earthquake inspection also revealed that there were no damages to the gated structures.

5.1.3.2 Seismic evaluations of gate:- The maximum total load on a closed gate during the earthquake was calculated to be approximately 17MN (1700t) horizontally, and 2.4MN (240t) vertically. The vertical component could be resisted safely by the gateleaf, arm and trunnions being negligible. On the other hand, the horizontal load is considerable and is more than double the original gate design load of approximately 8 MN, therefore, require strengthening of gated structure in order to ensure reliable operation and safety of the installation.

In the cross-stream direction, accelerations acting on the gate mass would induce sideways deflection of the gate arms. These forces would largely be resisted by the side guide arrangements. The gate trunnion rests on high strength stainless steel pins and spherical roller bearings. There are three side guide rollers on each side of gate leaf which bear against embedded stainless steel side plates.

Structural analysis for the SEE condition indicated that during earthquake, the gate would be overloaded and the damages are likely to occur especially in the following areas of the gated structure:-

i) The skinplate lower panels between horizontal T-beam stiffeners.

ii) Central vertical girder at the upper support and at the 'dog-leg' cantilever section.

iii) Mid-span of the horizontal beams of the portal frames at the central vertical girder supports; and the mid-way along the gate arms.

The spherical roller bearings of the trunnions were not expected to be damaged beyond their ability to function inspite of the fact these may be loaded to more than twice their rated static capacity. The originally designed gate anchorage arrangement was having sufficient capacity to safely resist SEE loading.

The analysis indicated that the overloaded gateleaf would tend to collapse within itself at the centre of its span and between the upper and lower arm frames. Moderate to severe distortion would occur in the vertical girders and portal frame beams. The gate arms may bow and distort and prevent free movement of a gate after the event, despite the trunnion bearings remaining functional. Distortion, leading to dishing of the skinplate panels between the T-beam stiffeners may occur in the lower half of the gateleaf.

5.1.3.3 Structural strengthening of gate:- For ensuring the safety of gated structure as also of dam, the following strengthening measures (Fig. 5.6 & Fig. 5.7) for the safety of spillway gates were carried out by:

(1) Introducing two new vertical girders between the existing three girders to reduce the amount of load shared by each vertical girder and as also to provide a more uniform distribution of loads onto the horizontal portal beams.

(2) Adding flat plates to the web of horizontal portal beams and gate arms to increase their shear and bending capacities.

(3) Increasing the number of side guide roller assemblies on the gate leaf to absorb any transverse loading with minimal damage.

Strengthening of the skinplate to prevent dishing would have involved extensive welding and paint repairs. Such work was considered more detrimental than beneficial. Instead, it was accepted that localized deformation of the skinplate could occur and would not affect structural integrity or operational reliability of the gated structure.

5.1.3.4 Other safety measures:- The precautionary measures included, to force open the gate by a pairs of hydraulic cylinders installed at the bottom corners of each of the radial gates (Fig. 5.8). This arrangement was devised to partial open the gate so as to take care of the eventuality of all the three spillway gates jammed due to earthquake. The reservoir level would rise rapidly and would soon overtop the spillway gates even if a small flood comes shortly after the event. In such situations, the above mentioned arrangement will force open the gates by about 1.5m. In the event that the gate cannot be moved using the forced jacking then the jacking force can be progressively increased, by relief valve adjustment, until either a maximum force reached, or the gate structure fails.

5.1.3.5 Conclusions:- From the analysis of this gated installation, it can be concluded that sturdy & conservative design of spillway gate in always preferable. Self-aligning bearings, quality and tested material/ components can withstand to certain extent, the unusual/ unpredictable hydrodynamic loading resulting from earthquake or any other extreme loading.

5.2 CONCRETE DETERIORATION

5.2.1 Kamburu Hydroelectric Scheme(Kenya)

5.2.1.1 Problem:- The spillway of the Kamburu hydroelectric schemes (Kenya), built in 1974, began to show some unusual deformations after about eight years of its construction. Extensive cracking and deformations affected by alkali-silica reaction prevented the operation of the spillway radial gates. The side seals of the radial gate were strongly compressed and the guide wheels were tightly in contact with piers. Measurement of the clearance between the gate and the piers indicated that the piers were distorted and the deviation from the vertical was ranging upto 40mm.

The concrete spillway consisted of three 13m x 13m size radial gates and their trunnions are supported by prestressed tendons embedded horizontally in piers. The spillway of the dam (Fig. 5.9) is flanked by two stoplog stores.

5.2.1.1 Remedial measures:-The radial gate was trimmed by about 140mm off the sides adjacent to piers for effecting its free movements during operation. The arrangement of the side seal and the embedded stainless steel sealing face was also modified as shown in Fig. 5.10. After, ensuring the free movement of gate by carrying out the above modifications, the alignment of the gate arms and trunnion bearings were checked. The minor adjustments were made to relieve stresses induced because of misalignment of the gate resulting from the expansion /deformation of piers.

5.2.2 Hiwassee Dam (USA)

5.2.2.1 Problem:- The spillway radial gates of Hiwassee Dam (Fig. 5.11) were having binding problems because of the growth of the concrete piers and non-overflow sections. The concrete growth has resulted in distortion of the embedded side seal frames. The two end piers have suffered the largest amount of concrete growth, thereby reducing the width of the two end bays by about 100mm.

5.2.2.2 Remedial measures:-The sides of the radial gates have had to be trimmed several times, to ensure their free movement during operation and ultimately further trimming was not possible without compromising the structural integrity of the gates. Therefore, the modifications were proposed which could accommodate a reasonable future growth without requiring any appreciable modifications in gate leaf or the embedded parts. The concept of modifying the spillway radial gates to alleviate the pier growth problem was evolved from the way slots are provided into the piers for supporting and operating the vertical lift gates (Fig.5.13). The modification involved replacement of the existing side seal arrangement on the radial gates with an arrangement similar to that used for vertical lift gates, and replacement of the existing side seal embedded parts with new embedded parts to match the modified new side seal arrangement (Fig.5.14). The slots in the piers will have to be cut radially to accommodate the new side seal arrangement. This feature will provide sufficient clearances between the pier wall and the gate to accommodate future concrete growth. The gate trunnions will also have to be modified (Fig.5.16) to facilitate adjustment in case of future concrete growth at the trunnion location and to incorporate this feature, width of the gate will have to be reduced (Fig.5.12) such that the hoisting arrangement remain unchanged. The proposed modifications will be possible without moving the gates from the spillway, i.e. by rotating the radial gate almost 180^0 to provide room for cutting of new side slots in the piers.

Reduction of gate width was determined keeping in view the future growth of concrete and also the existing clearances between parallel arms & piers. The proposed reduction shall ensure the operational reliability of the radial gate over a long period i.e. concrete growth will not interfere with gateleaf or with the radial arms.

As an alternative to modifying the radial gates, it was considered that they be replaced with vertical lift gates. However, the proposed modifications of the existing gates were preferred being economical.

5.2.3 Rihand Dam (India)

In this project, problems in attending to the maintenance/repair of power units were experienced, because the Penstock gates were not closing fully. Moreover, the stoplog units for Penstock gates could not also help in this respect because of heavy leakage through them and thus the maintenance of Penstock gate itself became a problem. There was bulging of concrete piers due to expansion of concrete, which resulted in jamming and thereby non-closure of some of the spillway radial gates and Draft-tube gates.

5.2.3.1 Problem of penstock gate's hoist:- Penstock intake gates are located at a depth of about 60m below FRL and are operated by 60t hydraulic hoist mounted at the top of the dam. Expansion of concrete has resulted in increase of the dam height and thus the top elevation of dam has changed. As a consequence of this phenomenon, the bottom & top seals of the penstock gates were not coming in contact with their seal seats and a gap of about 100mm was observed even after lowering the gate completely. Due to this, heavy leakage through these penstock gates was taking place and therefore, the maintenance of power unit was not possible.

5.2.3.1.1 Remedial measures:- This problem could be solved either by increasing the length of the hydraulic hoist stem rods or by modifying the hoist supporting arrangement so as to lower the hoist. However, lowering the level of hoist was found to be simpler and accordingly, the hoist support beam were modified as shown in Fig 5.17a.

5.2.3.2 Problem of penstock stoplogs:- The stoplog units were provided with wooden blocks at their ends to transfer the water load, as also to affect sealing. The wooden blocks were spoiled and become non-functional as a result of their storage for a long time in the open i.e. on top of the dam. In addition, expansion of concrete resulted in heavy cracks in the 2nd stage concrete and also separation/ misalignment of guide tracks both in vertical and horizontal directions. Therefore, lowering of the stoplogs for facilitating the maintenance of penstock gates could not be taken up.

5.2.3.2.1 Remedial measures:-The following modifications (Fig. 5.18) were carried out in order to make the stoplogs operational:

(1) The wooden blocks (Fig. 5.18a) attached to the stoplogs were replaced by machined mild steel plates & rubber seals of rectangular cross-section on the sides were added. Also leaf spring type guides were also incorporated. The originally provided J- type bottom rubber seals were also replaced with rectangular type seal for perfect sealing at the corners (Fig.5.18b).

(2) However, it was desirable to completely remove the 2nd stage concrete and the embedded parts for redoing the alignment. As the removal of parts and concreting again was not possible, therefore, the guide/ tracks clogged with heavy deposits of silt, mud etc. were cleared off the foreign particles thoroughly. The off-sets in guide tracks were ground to the extent possible to improve upon their alignment. By adopting the above modifications, the stoplog units could be operated with reasonable water tightness.

5.2.3.3 Problem of penstock gates:- Due to non-functioning of stoplog unit, maintenance of the penstock gates could not be carried out since their installation. After the stoplogs were made operational, the penstock gates were taken out completely from their slots and inspected thoroughly, the following defects/problems were observed:

(1) Wheel assemblies were provided with two spherical roller bearings but neither the wheels nor track plates were crowned.

(2) Gate was getting stuck up during its travel because of misalignment of guide/ tracks. The cracking of the 2nd stage concrete and expansion of concrete resulted in misalignment of embedded parts horizontally and vertically over the entire length.

5.2.3.3.1 Remedial measures:- The wheels were crowned to a radius of 3000mm (Fig.5.17c). The spherical roller bearings of wheel assemblies were found to be in order. The seals of the wheel assemblies were found to be damaged and therefore, replaced. Wheels were reassembled and the fresh grease was filled in the wheel assemblies. The off sets in horizontal direction of guide tracks were grounded to provide smooth movement of the guide shoes. The guide shoes were also machined to increase their clearances (Fig.5.17b) with guide track to avoid possible jamming of the gate during its travel. The guide-tracks alignment was also improved by making elongated holes in the direction of flow. This was possible because of their removable type bolted connections with embedded base plate.

5.2.3.4 Problems of draft tube gates: The expansion & consequent cracking of concrete resulted in misalignment of all the embedded parts and thus made it impossible for the draft-tube gates to lower. Face to face distance of the side guide tracks, have become non-uniform over the entire length of gate travel due to bulging of concrete. Tracks were having offsets both in horizontal and vertical directions.

5.2.3.4.1 Remedial measures:- In order to maintain the requisite working clearances, the distance between face to face of guide tracks have to be made uniform by means of cutting off the thickness of the guide track about 10mm for the entire height. Further to improve upon the offsets in thickness of guide tracks, it was decided to cover the offsets with weld metal having a slope of 1 in 5, so as to allow smooth movement of guide angles/ spring guides. The ends of projecting legs of guide angles fixed on the gate are also to be cut by about 10mm & rounded off to avoid interference with bulged concrete and to allow smooth movement even at the off-set points of the guide tracks (Fig. 5.19).

5.2.3.5 Problem of spillway radial gate:- There are thirteen spillway radial gates of size 40'(12.19m) by 30'(9.14m). The gates are not operating properly for several years and almost all the gates are getting jammed during their operation at different elevations because of interference caused by concrete growth. To ensure operation of the gate and thereby the safety of the dam as also of gates, the project engineers are resorting to trimming the sides of radial gate leaf/ removal of guide-rollers whenever these get stuck-up. Other measures include grinding and even cutting the wall plates to allow the free movement of the gates. The radial gates also require frequent replacement of seals, which were getting damaged invariably whenever gates are operated. Serious vibrations during the operation of the gate and the frequent tripping of the hoist motors due to over loading are also reported.

5.2.3.5.1 Remedial measures suggested:- For spillway radial gates similar modification can be carried out as in case of Kamburu(Kenya) and Hiwassee Dam. The proposed measures, if adopted for rehabilitation of the spillway gate shall be not only a long term solution, but will also take care of vibration as well hoist motor overload problems (Fig. 5.10 & Fig. 5.13).

5.2.4 Friant Dam (USA)

5.2.4.1 Problem:- The Friant dam 55years old is located in California (Fig. 5.20a) The dam is concrete gravity type having a height of 97m, and stores water for irrigation and drinking purposes.

The spillway is equipped with three number 5.5m (high) by 30m (long) drum gates. Alkali-aggregate reaction has resulted in the expansion of concrete and seriously effecting the outer bays. Therefore, the drum gates of these outermost bays are having problem of binding in their piers and thus their operations have been impaired.

5.2.4.2 Remedial measures:- As a remedial measures the outer drum gates have been replaced with rubber dams and the inner drum gate was rehabilitated. Rubber Dam i.e. Obermeyer Pneumatic Spillway Gate System comprises high strength steel gate panels, connected to the crest with the help of a reinforced elastomeric hinge. The gate panels are shaped to match closely with the curvature of the existing drum gates to avoid any flow disturbances (Fig. 5.20b).

5.3 DESIGN DEFICIENCIES

5.3.1 Itaipu Project

5.3.1.1 Incident:- The stem rod (Fig. 5.23) of right hand side hydraulic hoist of one of the spillway radial gate was broken on July 14, 1994, thus impeding the operation of the gate. The gate was in operation over a period of 12 year before this failure. For attending to the periodic maintenance/inspection, the gate was opened completely with the stoplogs installed in their slots i.e. no flowing conditions (Fig. 5.21). After carrying out the maintenance, the lowering the gate was initiated and the right side hydraulic hoist stem broke just after a little downward movement of the gate. The gate remained open about 16m supported by the left side hoist alone. The gate was stopped from closing to avoid any further damage. However, the design provided that even the single hoist would be capable to close of the gate, but the closure operation of the gate was resumed only after undertaking the special precautions at a much reduced speed of 50 mm/min.

5.3.1.2 Analysis:- On detailed inspection, significant corrosion was found on the surface of the broken section in the vicinity of the edge of the stem. It is know that stainless steel surface is affected by pitting corrosion, in case it remains in contact with rust-prone bodies, or remains without being cleaned. For accessing the safety of the remaining hoists, theoretical & by F.E.M. analysis were carried out and the following observations were made:-

It appeared from the scrutiny of designs that the bending stresses, resulting from the friction in the hinges (i.e. end socket bearings) and due to the weight of the hoist itself was not considered in the original design. Also, increases in the stresses due the stress concentration were not originally contemplated by the manufacturer. Further it could be established, the stem adequacy of only 250mmϕ portion was checked, the tensile stress in stem due to gate weight alone was 121Mpa

(1210 Kg/cm^2) i.e. well with in permissible limit of 138Mpa(1380Kg/cm^2). However, at the socket end the stem was reduced to 190mmϕ (Fig.5.26), tensile stress in that portion due to gate weight alone works out to be about 220Mpa(2200 Kg/cm^2) i.e. surpassing the permissible, but this again is well below the yield point of the stem material.

However, the fracture occurred in the transitions region lying at the ends of the 190mmϕ stretch, which was prone to stress concentration. Therefore, if along the gate weight, the friction in socket bearing and stress concentration factors (K_t= 3.8074, K_f = 4.101) are taken into consideration, the induced working stress is estimated to be about 901.8Mpa(9018Kg/cm^2) i.e. reaching almost to ultimate tensile strength of 924Mpa (9240Kg/cm^2). The phenomena of stress concentration that induces high stress locally can result in cracking and thereby progressive failure, which in this case happened after 17years of the installations. Moreover, the pitting of outer surfaces can also act as a stress concentrator and thus may initiate local failure.

Another factor, which might have probably contributed to the increase in the bending stress of the hoist stem, could be the increased play in the end guide bearing resulting from normal wear & tear. A small amount of increase in play/ clearances at guide bearings can result in abnormal rise in bending stresses in the stem.

5.3.1.3 Remedial measures:- The replacement of the hoist stem was made by a newly manufactured stem with construction details differing from the original deign. The new stem comprises of higher cross-sectional area and freedom from such details that concentrate stresses (Fig. 5.25). Ceramic coating on the stem have also been incorporated, in order to obtain greater longevity with a reduction in maintenance cost and as also to protect the stem surfaces from pitting corrosions.

For the remaining hoists, as a safety measure a new geometric shape in the critical region have been incorporated (Fig. 5.26) so as to reduce the stress concentration factors (K_t=2.207). By adopting this modification, it was possible to reduce the induced stresses in the critical region. It is calculated that the stresses will reduce from 901.8Mpa((9108 Kg/cm^2) to 547.5Mpa (5475 Kg/cm^2), resulting in a safety factor of 1.68, therefore permitting the re-use of he existing stems. Elimination of the existing inter-crystalline corrosion by machining 4 mm from the 190mmϕ diameter and achieving a surface finish of 1.6 microns (μm) for the safety against the progressive failure initiating from the cracks, was the other remedial measure proposed.

5.3.2 Nangal Hydel Channel

5.3.2.1 Incident:- During a stormy night, waves in the channel were formed which activated the floats, thus lifting the by-pass gates by about 0.60 to 0.75m. At about 9.30 P.M., the regulation staff heard a thundering sound and in split of a second, before the regulation staff could locate the cause of sound, they found that central radial gate was missing from its position. On detailed inspections, it was found that the right side trunnion pin of the radial gate had sheared. In addition, it was also observed that the right side float-stopper, its thrust bearing, rope pulley & turnbuckle had been damaged. On the left side of the failed gate, the trunnion pin was found intact in position, however, the turnbuckle was found damaged.

The radial gates of the bypass channel are of automatic type, however, these can also be operated with the help of electro-mechanical type hoist as well as manually. All the bays have provision of stoplog grooves u/s of radial gates for facilitating the planned maintenance of main gates. The general layout of the scheme is shown in Fig. 5.27

5.3.2.2 Analysis:- It was felt that the failure of the pin is basically due to non-homogeneous and coarse grained material of the pin and that with the passage of time some fine hair cracks might have developed due to fatigue over a period of about 33 years. Although induced stresses in the trunnion pin seems to be well with in permissible limit against the hydrostatic load, counter-weight and self-weight of gate arm (i.e. adequate factor of safety was available). At the bearing end, trunnion pin was reduced from 9"ϕ (225mm) to 7"ϕ (175mm). Moreover, at the transition zone of 7"ϕ (175mm), a slot had been cut (Fig. 5.28a) and their edges can act as crack, thereby stress concentration takes place. It appears that in the original design of pin, the manufacturer must have not contemplated this factor. Because of such susceptible geometrical shape of the component, the stress concentration induces high stresses locally, which can be several times the static load stress. It is likely in such circumstance that the material in the critical transition zone may start yielding and thereby, the effective cross-sectional area goes on reducing progressively until a sudden failure of the component takes place. At the time of failure, the gate opening was very small and vibrations in such situation can't be ruled out. The gate might have struck-up at very small opening due to jamming of float or malfunctioning of wire rope and pulley systems etc. In such circumstances of small gate opening, the gate is exposed to severe hydrodynamic loading/ vibrations and these phenomena can accelerate the already initiated local failure as result of fatigue loading under such circumstances.

Another reason in this case, which could attribute increased stress in the pin, is adoption of spherical bearing having shorter length, than the originally provided bush bearing. This change could also result in increased bending stress in the pin.

As reported about the deficiency in quality of pin material, there could also be reduction in ultimate tensile strength of material. However, pin has sustained for about 30years before yielding to the failure and the pin at the another end was intact, therefore it can be concluded that the culprit is the notch at the transition zone which resulted in stress concentration, thereby progressively leading to failure all of a sudden.

5.3.2.3 Remedial measures:- The new gate has been installed with pin having some modifications (Fig. 5.28b) in its geometry to adjust the spherical bearing length. Material adopted for pin is stainless instead of mild steel originally provided.

5.3.2.4 Conclusions & Recommendations:- Stainless steel can suffer from stress corrosion and pitting corrosion in case its surfaces not maintained properly. Therefore, it is recommended for safety of the system that the stainless pin surface should be kept clean to avoid pitting corrosions. Also, the geometrical shape at the transition zone should have preferably modified to eliminate/ reduce the possibility of stress concentration. The trunnion pins of all the other gates should be tested ultrasonically immediately, in-situ, to detect any hair cracks/discontinuity of material. Permanent approach to trunnion pins location should also be provided for carrying out regular inspection to avert such eventuality in future.

5.3.3 Manganti Dam

5.3.3.1 Problem:-The spillway of the Manganti dam on the Citanduy River in Indonesia is equipped with six large sized fixed wheel gates of the two-tier type (Fig. 5.29). Each gate has a 10.5m width and a total height of 7.6m. As reported, the gates vibrated severely and excessive leakage from the gates was observed during their testing.

5.3.3.2 Analysis

5.3.3.2.1 Vibrations:- The gates had rectangular wooden seals (Fig. 5.30) having cross-sectional area of 200 mm x 200mm, attached to their bottom. These wooden block for affecting sealing were held by a horizontal beam (200mm deep channel), placed at the bottom of the skin plate, and about 100mm of this beam was projecting u/s of skinplate. In addition, a 160mm deep channel section was welded to the skin plate horizontally on the u/s side i.e. a short distance above the wooden blocks. The horizontal beams projecting u/s made the bottom configuration of the gate hydraulically unsuitable especially for partial gate openings and therefore severe vibrations were induced (Fig.5.31) due to the following: -

(1) Flow separation and intermittent reattachment of the water jet under the flat and wide wooden seal at the gate bottom.

(2) Flow discontinuity and turbulence above the bottom channel.

(3) Flow turbulence above the upper channel and possible shear layer deflection of trapped water.

In addition, a flat bottom gate not only has excessive downpull but the magnitude of this can vary considerably over a small vertical movement of the gate and thereby result in vertical oscillations of the gate. To eliminate these problems and to ensure streamlined flow under the gate, it was necessitated that the gate bottom configuration be modified. However, It was desired that the modifications be carried out without excessive fieldwork and adversely affecting the structural integrity of the gateleaf. Also, the capacity of the existing hoists should not be increased.

The weir gates being low head structures, vibrations may not be as serious as in case of high head installations. However, the possibilities of fatigue failure of some of the gate components, weld, and even of concrete around the gate slots can't be ruled out as consequences of dynamic loading/ vibrations. In case the gates became jammed as a result of any of these problems, and could not be opened during floods, the entire weir structure would be in danger. It was therefore decided that measures to minimize or eliminate the vibrations should be adopted.

5.3.3.2.2 Leakage:- The factors which contributed to the leakage problem were poor quality wooden & rubber seals, lack of corrosion resistance material for the seal seats and the imperfect alignment of seal seats and sills, resulting in excessive clearances.

5.3.3.3 Remedial measures:- The proposed remedial measures for minimizing leakage had to take into account the fact that any inappropriate shape of the gate bottom in general could contribute to vibration. Hydraulic model studies in the past, as well as the prototype performance of several gates, have confirmed that the gates having d/s skin plate and streamlined 45^0sloping bottoms ensure positive pressures on the entire gate bottom at all gate openings. The 45^0 sloping bottom lip eliminate vibrations; reduces downpull significantly as compared to the flat bottom; and minimizes variation of downpull forces for small gate movements. Further, such a configuration of bottom lip could easily be obtained on these weir gates by providing merely a sloping cover plate i.e. without excessive modification work, and without adversely affecting the structural integrity. This would eliminate most of the flow disturbances at the gate bottom. To avoid silt accumulation in the trough formed by provision of the sloping cover plate on the u/s side, a top cover plate was considered necessary. Suitable openings with removable cover were provided on the top cover plate to provide access into the trough for periodic maintenance and painting. As the downpull was likely to be reduced significantly as also the hoist capacity required to raise the gates and moreover, the buoyancy of the hollow trough will also be of some help in reducing the hoist load.

It was desired to remove wooden seals and use vertical flat rubber seals at the bottom for reducing the leakage apart from replacing all of the poor quality rubber seals with high grade rubber or Neoprene seals and specially moulded corner seals. Other provisions were: i) Machined stainless steel seats fixed on the embedded gate frame, ii)ensure a requisite pre-compression of all seals when the gate is closed, iii) additional seals between the top and bottom tier gate, and iv) provisions of guide rollers with proper clearances to minimize lateral movement of the gates, were the other features desired for satisfactory performance of gated structure.

5.3.3.4Conclusions:- As a result of above said modifications, all the gates operated smoothly without any vibrations, and the leakage was reduced to acceptable limits.

5.3.4 Arkansas River Dams

5.3.4.1 Problem:-The spillways of series of dams on Arkansas river are provided with radial gates having 18.29m width except for the four dams where width of radial gate is 15.24m. The heights of radial gates are ranging between 6.40m and 14.0m. During the initial operation severe vibrations were experienced in the spillway gates of these projects. Operating personnel detected vibrations by hearing humming, fluttering, or roaring noises; by feeling vibrations in the spillway walkway; and by observing the oscillating movement of the gate members and, in the more severe cases, a ripple wave pattern that developed on the upper pool surface just u/s of the skin plate of the radial gate. In some of the gates, the vibrations were so severe that due to fatigue cracks in the steel members and their welded connections were resulted and thus impairing the structural integrity of the gates. These spillway gates were operated with bottom lip submerged by the d/s water.

5.3.4.2 Analysis:-The four types of bottom lip designs were used for the spillway gates (Fig.5.32). In the type-A lip design, the bottom base plate is parallel to the gate sill and the rubber J-bulb seal is flexibly mounted on this plate. In the type-B lip, the base plate is perpendicular to the skin plate and J-bulb seal is rigidly mounted to this plate. In the type-C lip, the base plate is perpendicular to the gate sill and forms a sharp control point for underflow. The type-D lip is the same as type-C, except for the addition of a rectangular rubber type seal on the base plate. The gate leaf of the higher height gates were supported by three horizontal girders and smaller height gates had two horizontal girders.

Model tests were carried to ascertain the sources of the vibrations and thereby devising the methodology for their elimination.

With type-A lip design, severe vibrations were observed under similar flow condition as in the prototype. These vibrations occurred at gate opening of 1.0m and less. With the bottom seal removed from the gate, the range of gate openings at which the gate vibrated was shifted slightly and the severity of vibration seemed to be somewhat reduced; however, vibration were still significant.

With the Type-B lip design, vibration did not occur with conditions simulating those in which vibration of the prototype gate was observed. However, with lower tail water elevations (almost like free flow conditions), vibration of the model was both visible and audible with openings ranging from 0.61 to 3m. The skin plate, top of the gate, and the top girder vibrated in the same manner as observed in the prototype. However, when the bottom seal was removed, vibration disappeared.

With types-C and D lip designs, the vibrations were not observed at all. Therefore, the lip designs were safe for all the gate openings and flow conditions.

The major causes of gate vibrations were found to be the faulty bottom lip design and bottom seal arrangements. The bottom lips of the gate not only effect the magnitude of vibrations but also the operating zones where vibrations occurred. The factors responsible for the vibrations were; Shifting of the flow control point between the skin plate lip and other bottom members of gate; the flexibility of the rubber seals which causes them to flutter when subjected to flows; and the pressure fluctuations resulting from Von Karman vortex trails which form in the d/s of the lip control point & react against the bottom members of the gate.

Later on, it was found that the rubber side seals (Fig 5.36a) on some of the gated installations were not in continuous contact with the seal plates and therefore, humming and roaring sounds apparently could be the results of side seal fluttering in gates having type-C lip design. The resulting gap between the side seals and the seal plates would set up pressure fluctuations believed to be caused by the difference in static and dynamic forces acting on the side seal.

It was also observed on some gated installation that if gates are set at the same opening, series of adjacent gates starts vibrating. However, staggering the openings by just a few feet on adjacent gate helps to break the harmonic similarities of the gates and vibrations stop automatically. This phenomenon could be the result of resonance.

5.3.4.3 Remedial measures:- A close inspection of type-D gate lip design revealed that the backup plate was 1"(25mm) thick and the rubber seal was only 15/16"(24m) thick thus prevented a tight clamping of the rubber seal (Fig. 5.32). Therefore, the backup plate thickness was reduced by 1/8"(3mm) and this modification in the bottom seal assembly resulted in elimination of the gate vibrations. The type-A lip design was to be modified as shown in Fig. 5.33. The spillway gates having type-B lip design were to be modified by removing the bottom seal and keeper bars and also by adding additional stiffeners at the bottom of the gate (Fig. 5.34).

5.3.4.4 Conclusions & recommendations:- It was recommended that the type-D lip design should be used in future applications and also ensures a positive clamping force on the rubber seal (Fig. 5.35). A proposed modification in the shape of the side seal section to provide greater flexibility (Fig. 5.36b) was also recommended to take care of probable gap resulting from construction inaccuracies, gate skewness, temperature shrinkage and expansion of gate, and normal structural deformation. Consideration should also be given to provide bottom rubber seal in the embedded sill bearing plate, however such seals will be more difficult to maintain than gate-mounted seals. Gates lip aeration always helps in dampening the pressure fluctuation under the gate therefore can be considered as measures to eliminate / reduce gate vibrations.

5.3.5 Feistritz Power Plant (Austria)

5.3.5.1 Problem:-The top seal radial gate weighing 45t (Fig. 5.37) for the outlets of the Feistritz Power Plant on River Drau are of the sizes 5.60m (height) x 15.00m (width). These gates are operated by means of a single 68t hydraulic hoist located at the center of the bay. When these gates were put into operation, severe vibrations were observed, probably because of the inappropriate shape of the sill (Fig. 5.39a).

5.3.5.2 Analysis:-As reported that a similar shape of sill was also adopted for the 15m (wide) x 17m (high) radial flap gates at Edling Project (Fig. 5.38). However, in case of Edling radial gates no vibration were observed because of such a sill shape. It is mentioned here that not only the sill shape but the dispositions of bottom girder/ radial arms and bottom lip of gate leaf has significant effect on flow induced vibrations. As the sill shape was not streamlined, therefore occurrence of low pressure and vibration of the gate structure is eminent. The clamping arrangement adopted for the rubber seal can also make lot of difference in respect of functioning of gated installations. Because of different height of gates at the two mentioned locations, it can be understood that gate having higher height will have bottom girder / arm located at comparatively higher position from the sill.

Another significant cause of vibrations could be the water head. It can be assumed that at Edling project the radial gate is on the surface spillway whereas in case of St. Feistritz, radial gate is installed on orifice type sluice outlet i.e. operating under higher water head. Third reason, which influences the vibration, is the dampening and natural frequency of vibrating structure. It could be noted that the weight of the Edling project radial gate was considerably higher than the Feistritz Power Plant thus mitigating the occurrence of vibrations. The weight of Edling gate will be around 2-3 times the St. Feistritz. Moreover, the number of hydraulic hoist (acting as damper) might be two instead of a single hoist as in case of St. Feistritz. Fourth reason could be the tail side water level being significantly higher in this case might induce vibrations.

5.3.5.3 Remedial measures:- The sill shape and seal arrangement was modified as shown in Fig.5.39b. After carrying out the modifications in bottom seal/sill, satisfactory functioning of the gates free from vibration was achieved. Further, it was advised that the small critical openings (about 20mm) susceptible to danger of vibration should be automatically passed through during the gate operation (i.e. while raising /lowering of the gate).

5.3.5.4 Conclusions:- It could be concluded that by using a similar type of sill shape performing satisfactorily at one installation (i.e. Edling Power Plant) can not guarantee vibration free satisfactory functioning of radial gate of this project (i.e. Feistritz Power Plant) because of the fact that the operating conditions and equipment details differs a lot at these two installations. The modified sill shape made it possible to avoid reattachment of the issuing jet with the gate bottom except for extremely small opening, which could be safely crossed quickly.

Further, in the modified arrangement, bottom seal assembly has been removed from gate leaf thereby resulting in sharp edge of skinplate for flow control point. By modifying the sill shape, a gradual change in direction of flow has been achieved and therefore possibility of occurrence of negative pressures near the gate sill was reduced. Therefore, as a result of these modifications, the satisfactory and safe performance of radial gate could be achieved.

5.3.6 Seals Problem of Gates

5.3.6.1 Problem:-Outlet works, in which partial opening of control gate is required for regulating the water releases under high head, damages to sill, bottom of the gate and seals are imminent especially at very small opening because of cavitation/ low pressure and impact of strong water jet.

Fig. 5.40& Fig. 5.41depicts the arrangement of bottom sill, which are likely to be seriously affected due to their strategic location. Water jet issuing below the gate bottom will result in low pressure and thereby ripping / squeezing out of flexible rubber seal from its fixture may happen apart from damages to the surrounding concrete.

5.3.6.2 Remedial measures:- However, such damages and malfunctioning of the gated structure can be avoided by carefully designing / shaping the hydraulic surface, bottom sill and sealing arrangement as shown in Fig. 5.42. Other preferred arrangements of bottom & side seal are depicted in Fig. 5.43 & 5.44.

5.3.7 Beas Project (Power Tunnel Fixed Wheel Gate)

5.3.7.1 Problem:- At the Pong Dam in Beas Project, there was also damage to the double stem rubber seals of emergency gate in one of the power tunnel. The gate is capable of self-closing under its own weight and is designed to shut off the power tunnel in case of any emergency within two minutes under full discharge. However, the normal operation of the gate is under balances head only. The gated installation designed for a head of 110m (Fig.5.45a), comprises fixed wheel gate of size 3.048m x 6.401m with u/s skin plate and double stem Teflon cladded rubber seals. A single acting 150t capacity hydraulic hoist, located at top of the gate shaft is provided for the operation of this gate.

When the gate was lowered for the first time under a head of 65m, there was considerable leakage across the closed gate and subsequently increased all of a sudden rapidly. Therefore, the gate was taken out, on inspection it was found that the side & top seals have been damaged and some of the guide shoes were missing. The cavitation damages were so severe that the water jets emerging from the sealing surfaces made a hole in the 25mm thick skin plate.

5.3.7.2 Analysis:- The reason of failure of originally designed seal assembly (Fig. 5.45b) was predicted to be its inability to withstand the hydraulic forces. The seal was clamped to the gateleaf by means of 12mm thick clamp plate with the help of 12mm diameter screws spaced 100mm apart. The arrangement was structurally inadequate and the clamp plate was not capable of holding the seal securely in its place.

5.3.7.3 Remedial measures:- Based on findings of a full-scale model test of 1.0m length of the seal assembly, a new arrangement was evolved for satisfactory performance of gate and safety of structure. From the test it could be concluded the seal when subjected full design head, had a tendency to get laterally displaced under the water pressure. The modified sealing arrangement consisting of increased thickness of clamp plates & increased size of screws, was capable of clamping the rubber seals with sufficient force, thereby preventing its lateral displacement by virtue of increased friction between the rubber seal and seal base. The sharp edges of clamp plate were also turned/grounded to avoid damages to rubber seal and stopper block to help in holding the seal in place was added in the seal assembly (Fig. 5.45c).

5.3.8 Ramganga Project (Cylindrical Gate)

5.3.8.1 Problem:- Similar problem in respect of double stem, plain rubber seals, installed around the top edge of the cylindrical intake gate was also encountered at Ramganga Project. The gate is located at the top of a vertical shaft (Fig. 5.46a&b) and normally operates under balanced head with the help of a single acting hydraulic hoist of 135t capacity. However, the gate is also capable of quick closing under a head of 69m in case of emergency.

5.3.8.2 Analysis:- Initial operations after the commissioning of the gate was satisfactory, however, later on excessive leakage developed around the top seal at increased reservoir level. In a attempt of closing the gate under a head of about 35m, it was found that the gate could not closed fully i.e. leaving a 35mm unclosed opening.

The reservoir was depleted to clear the gate sill for carrying out the inspection and to find out the causes of the malfunctioning of the gate. It was observed that the top seal (Fig. 5.46c) had been displaced and sheared off past the seal screws at a number of places. At some locations the seal was also found to be ruptured. Some of the seal screws were sheared off while some were missing. The seal arrangement appeared to be over-flexible and thus lacked rigidity / strength to sustain the hydraulic forces. The seal bulb was not solid type and therefore, the hydraulic forces can easily displace the seal. The edges of the clamp plate were not properly rounded and were biting into the rubber seal. The top sharp edge of the clamp plate damaged the seal while the latter was riding over the seal seat during the downward travel of the gate. Also, the seal screws were not tightened adequately.

5.3.8.3 Remedial measures:- The sealing arrangement was modified to have newly moulded rubber seal with a rigid & strong solid bulb (Fig. 5.46d). The original seal screws were replaced by new counter-sunk stainless steel screws having hexagonal socket head heads for achieving effective tightening. The sharp edges of the clamp plates/seal seat were also rounded smooth to avoid damage to rubber seal.

5.3.9 Bikou Hydropower Station (China)

5.3.9.1 Problem:- The cavitation damages also occurred on the steel linings of breast wall of the radial gate installed on the flood discharge tunnel of this project. A service radial gate of size 4m x 3.15m has been installed at the entrance and is designed to operate under a head of 90m. The gate is operated by a hydraulic hoist and has two rows of top seal of rubber. When the gate was operated partially opened (20-50 %) under a head of about 70m serious damages on the top seal seat occurred. The stainless steel lining was worn off and some of the fastening bolts were sheared off, while some of them were cut down and washed away. The portion of seals was also torn, The rubber seals were again damaged, when the gate was put on service after carrying out the repair and was operated at an opening of about 50%.

5.3.9.1 Analysis:- It was reported that during the course of commissioning of the gate, water leakage at the top seal was found, forming a high velocity water jet. Also, it could be established that the damages were occurring because of the top and side rubber seals at the corner were not fixed on the same curved plane of the gate leaf, thus subjecting the seal corners to stress concentration. The seal at the corner was acted upon by a larger tearing force under the high water head. Seals after being torn off and produces high velocity jets, which result in cavitation damages on the flow boundary and also vibration damage on the gate leaf / embedded parts.

5.3.9.3 Conclusions:- The corner seals should be designed with due care in regards to its strength. Planning & design of sealing surfaces and seal fixtures should be such that these shall avoid the undue stressing of flexible rubber seals. The carefully designed arrangement shall guarantee the satisfactory and safe operation of gated structures.

5.3.10 Talarn Dam

5.3.10.1 Problem:- The Talarn dam (constructed in 1916) is located in the North Eastern Spain and is 84m high, gravity type with curved shape of 300m radius. Maximum normal water level is 540.90m and minimum useful water level 510.00m (Fig. 5.47 & Fig. 5.48). The draining facilities of the dam in addition to the spillways, are steel lined tunnel for power generation and the irrigation outlets. For attending to the maintenance of steel lined tunnel; main valve of powerhouse and other equipment, the tunnel was emptied with intake gate closed. Because of some of the existing damage in civil structure, the water penetrated between the metallic lining and the backing concrete. This under-pressure produced excessive loading of the lining, thereby, resulted in breaking off the surrounding concrete, uprooting of the embedded metallic guide rails and part of the lining (Fig.

5.49). After the incident, the intake gates were opened and the penstock was immediately filled as a precautionary measure.

5.3.10.2 Remedial measures:- The cause of the concrete failure in the gate seating was its inadequate strength to bear the imposed loads as also the poor design of embedments of gate frame. The failures in wedge of the seating concrete had already taken place on three of the four existing gates. Therefore, it was desired to modify the design of the embedded gate frame (Fig. 5.50) in order to avoid the repetition of such type of failures. New design also incorporated the reduction of the gate span so as to reduce the loading of the seating /concrete, increasing loading capacity in the seating zones apart from changing the location of gate, because of the fact that concrete at the existing location of gate was fissured.

5.3.11 Tungabhadra Project Overtopping of Vertical Lift Spillway Gates

5.3.11.1 Problem:- The project consisted of 33 number of 12.83mx6.10m size vertical lift spillway gates operated by chain drum hoists. It was reported that the provision of free board over the vertical lift spillway gates was inadequate resulting in exposure of top main horizontal girder and struts to continued wetness and development of undesirable lateral forces besides rusting and pitting of gate members. The wave splashing also caused a loss of substantial storage through the spillway when the reservoir was at/near the FRL.

5.3.11.2 Analysis:- In order to prevent overtopping of the gates, the following alternative proposals were examined:

(i) Wave deflectors/flow splitters.

(ii) Gate hood.

Provision of wave deflectors was likely to impose additional water thrust on the gates, besides increase in gate weights and hence the hoist capacity. This alternative was not considered for adoption because there might be a tendency to store water upto top of wave deflector thus over-stressing the structural components of the aging gates. Likewise, provision of flow-splitters was also not pursued further because of likelihood of causing vibrations in the aging structures, unless the spacing of flow splitters could be designed very precisely.

5.3.11.3 Remedial measures suggested:- Provision of gate hood was finally suggested for adoption so as to direct the flow away from the immediate downstream gates' components (Fig. 5.51). It was proposed to design a stiffened gate hood plate to be butt-welded to the existing gate leaf over the entire length within the existing gate height.

5.3.12 Mahanadi Birupa Barrage

5.3.12.1Problem:-The barrage was equipped with eight number 18.00m x 5.35m size fixed wheel type under sluice gates operated by rope drum hoists. It was reported that silt-laden water entered into the spherical roller bearings causing jamming of the bearings of wheels. This resulting in sliding of wheel of instead of rolling during the gate operation, thereby leading to gate operational problems.

5.3.12.2Analysis:-One of the wheel assemblies was taken out and dismantled. It was observed that the bearing was in totally broken condition with dislocation of its rollers and deposition of silt and clay inside the bearing. Double lip retainer oil seals and rubber 'O' rings were found to be badly damaged. It was noticed that the oil seal on one of the sides was oriented in the reverse manner and that the 'O' rings were located on the outside of the counter-head screws thereby allowing water to enter into the bearings through the threads of the screws (Fig. 5.52).

5.3.12.3Remedial measures:-The sealing arrangement of roller bearings was suitably modified by changing the location of O-rings and by fitment of oil seals in correct orientation. Besides, the size of 'O' rings and nos. of fixing screws, size of grease holes were also increased from the existing provisions, apart from other improvement in gate structures.

5.3.13 Ranjeet Sagar Project

5.3.13.1Problem:-The project was equipped with two number 5.0m x 9.0m size fixed wheel type penstock emergency gates design for a head 140m and operated by 500t capacity hydraulic hoist. It was reported that the emergency gate shaft got filled up to about 73m head probably on account of flow of water through the hole left un-plugged in the air vent shaft while the gate was in closed position. On a subsequent occasion, the shaft again got filled up to about 50m head.

5.3.13.2 Analysis:- After de-watering, the inspection was carried out and it was found that there was a 15mm wide crack at the interface of 2nd and 3rd stage concrete in the bonnet chamber concrete floor on the u/s side of bonnet cover. After removal of bonnet cover, it was observed that the upstream welded joint of the gate bonnet body had opened at a height of 1.30m above the gate and also that the u/s liner had bulged towards d/s up to a maximum of 146mm at this particular location causing profuse leakage through the opened out joint. (Fig.5.53)

5.3.13.3 Remedial measures suggested:- On site inspection, it was suggested that upstream bonnet plate be replaced and damaged concrete backing (in particular 3rd stage concrete of 650mm thickness) removed and recast after creating dry conditions. The additional provisions of anchors in u/s body liner and effective keying by angle stiffeners etc. were made from safety considerations. Further it was decided to carry out the following for the safety:-

(1) Recheck the design of bonnet plates (with stiffeners in longitudinal as well as transverse direction) for withstanding full external pressure with a permissible stress of 80%of yield point of the liner material.

(2) Check adequacy of bonnet body anchorage with concrete with the assumption that there will be hollows behind the liner in which water can seep and exert water pressure.

(3) Check whether the stiffening ribs are provided with large enough openings for good concreting.

(4) Check provision of adequate grout holes in the bonnet plate to grout any hollows that might be created during concreting operation or subsequent shrinkage. Fill the grout holes with plugs welded in place and surface ground smooth. Also consider provision of perforated grout pipes extending into second stage concrete.

(5) Check provisions of adequate dowel bars at suitable intervals between second & third stage concrete.

(6) Check that coarse/fine aggregates proposed to be used are non-reactive in ASR.

(7) Check that the concreting behind the liners is carried out in as small a lift as possible limited to a maximum of 1.0m in a single lift.

(8) The floor of bonnet chamber be made water tight by providing a suitable finishing coat to prevent any ingress of water particularly into the interface of different stages of concrete.

5.4 HYDRODYNAMIC FORCES & VIBRATIONS

5.4.1 Cowlitz Falls H. E. Project

5.4.1.1 Problem:-Cowlitz project is a run-of-river scheme on the Cowlitz River in Washington. The configuration of the gates, the low-level conduits, the gate slots, and the gate chambers are shown in Fig. 5.54 & Fig. 5.55. Releases through the low-level sluices are controlled by two number 16' (4.88m) high and 12' (3.66m) wide, vertical lift type u/s sealing fixed wheel gates. The gates are operated with the help of hydraulic hoist (Fig. 5.55). During the testing of these gates under full reservoir level, loud banging noises were heard when the gates were in the fully opened position and the therefore, the tests had to be stopped. In an attempt of closing the fully opened gates, it was found that one of the gate became jammed 64% open and another at about 4% open position.

5.4.1.2 Analysis:-Detailed inspections were carried out subsequently and it was observed that the gate wheels, embedded rails, and the concrete on the d/s side of the gate chamber had been extensively damaged. It was understood that the gate vibrations had resulted in the severe banging noises and thereby derailing and jamming of the gates.

Out of the twelve stainless steel wheels, four of them i.e. two on top and two on the bottom of the gate were designed to have flanges. Spring-loaded guide rollers were also attached to the each side of the gate at the top and bottom on the u/s face in order to limit the gate movement toward u/s and thus to keep the upper as well and lower gate wheels in contact with the rails whenever the gate is partially opened. The u/s guide rollers were supposed also to counter the hydraulic force on the gate that creates a moment and thereby tends to rotate the top of the gate u/s. With the partial opened gate, the water flows upward along the u/s side then passes over the gate and finally returns to the conduit d/s of the gate.

It was noted that all of the wheels of one of the sluice gate were off the guide rails. However, in case of another gate only top flanged wheels were off the guides and the gate was cocked in the guides, with bottom two flanged wheels still on the guide rails.

5.4.1.3 Remedial measures:- The front guide wheels assemblies were revised to have an arrangement that would prevent the gate from excessive movement in the u/s direction and the side bumpers were incorporated to limit the lateral movement of the gate.

5.4.1.4 Conclusions & recommendations:- The pressure within a rectangular slot rises in the direction of the flow in the conduit (i.e. flow direction outside of the slot) in all cases (Fig. 5.56), and may be serious enough during the larger opening, especially for the fully opened position i.e. when the gate rests in the gate chamber. The pressure along the u/s face of the gate that rests inside the gate chamber will tend to be lower than on the d/s face. Therefore, the fully opened gate will no longer be acted upon by horizontal force pressing it d/s and if the lower edge of gate rests close to the conduit ceiling in such circumstances, the gate may develop into a 'bang-bang gate' performing random pendulum movements in the gate chamber (Chang & Hampton, 1980). These forces can be large enough to damage the wheels as also the u/s guide rollers and gate leaf, if not adequately designed to withstand such forces. Also, as a consequence of damages sustained or dislodgment of the gate leaf, the resistant to gate movement may become so large that it become difficult to operate the gate.

For safety of the gated installations, it was desired to have the gate bottom a little above the top of conduit when the gate is in fully open position. In order to avoid reattachment of flow to the bottom of the gate during fully open condition of gate, a slope in the top (i.e. roof) of conduit should be provided u/s of gate slot. The suitable slope can be determined with the help of model studies (Fig. 5.57). The excessive slack in gate components such as guide wheel hoist links etc should be avoided. Where clearance between gate leaf & embedded parts are unavoidable, it is desired that the component be preloaded. The pre-loading arrangement for guide wheel of a gate leaf is shown in Fig. 5.58

5.4.2 Liujiaxia Project (China)

5.4.2.1 Problem:- The Liujiaxia Hydropower Station, located in Yondjing County (China) has a 147m high concrete gravity type dam. The low level outlet gates are of fixed wheel, vertical lift type having sizes of 3m width x 8m height and are designed to operate under a head of 70m. When these gates were put to operation, the gate started vibrating severely even under a head of about 24m. This resulted in cracks on all of the cast alloy steel wheels.

5.4.2.2 Analysis:- On investigation, it was found that the roughness of the concrete surface of the breast wall caused water leakage in the form of jet from the top seal thus formed a large cavity in between the u/s breast wall and the skin plate of the gate leaf. Consequently, the water hammer and pressure oscillation in the said cavity induced vibration of the gate. Especially, during larger gate openings, the cavity was comparatively longer and the water hammer phenomenon became more serious.

5.4.2.3 Remedial measures:- However, after adding two rows of top seal of J-shaped rubber seal on the gate leaf, the hydraulic oscillation system have been controlled. It has also reduced the water hammer effects and as well the water leakage. The said measures were very effective in smooth functioning of gates.

5.4.3 Chukha Hydel Project

5.4.3.1 Problem:- There were two number 1.50m x 2.00m high head silt flushing fixed wheel gates operated by rope drum hoists. When one of the gates (with upstream skin plate & sealing) was partially operated at high reservoir level, it was noticed that the gate was not closing.

5.4.3.2 Analysis:- The main cause was identified as impinging of water jet on the bottom girder, thus creating uplift on the gate resulting in non-closure.

5.4.3.3 Remedial measures:- (1) Modification of gate bottom involving cutting of bottom inclined plate such that the issuing jet was at about 45° to the horizontal.

(2) Provision of 45mm wide plate on the upstream side of the gate causing additional down thrust on the gate thus facilitating gate closure.

(3) Replacement of rubber seals by Teflon cladded seals in order to reduce the frictional resistance.

5.4.4 Mahi Bajaj Sagar Project

5.4.4.1 Problem:- The project was equipped with two numbers of 3.30m x 4.20m size vertical lift fixed wheel type intake service gate designed for a head of 32.60m and operated by 45t hydraulic hoist.

It was reported that one of the Intake gates was malfunctioning. Detailed inspection revealed that the gate had catapulted to a height of 8.60m and lodged itself on the dogging platform. The hoist stem rod had completely buckled and the guide shoes sheared. The operating criteria provides for balanced raising of the gate to be achieved by crack opening (maximum 150mm) or by combination of crack opening and bye-pass arrangement.

5.4.4.2 Analysis:-The problem was analyzed and it was revealed that during balancing by crack opening, the penstock portion between the gate and turbine got filled up and the pressure nearly equal to reservoir head started acting at the bottom side of the gate while the pressure at the top remained equal to atmospheric pressure. It was also found that the gap between the gate body and downstream wall was small thus restricting the flow of water through this gap. The pressure developed at the bottom side of gate was of such a high magnitude that the gate was catapulted. The development of such high upward thrust might have also been precipitated by failure of limit switch or mal-operation with the result that the gate did not stop at crack opened position. On detailed inspection following observations were made:

(1) All the hoist links were badly twisted towards the u/s and d/s sides (Fig. 5.59).

(2) All gate assemblies got twisted, maximum twist being 55mm.

(3) All seals bases were bent by about 4 mm at the centre of gate.

(4) Left-hand sides guide shoes and lock plates of wheel assemblies were damaged.

5.4.4.3 Remedial measures and suggestions:- The gate was rectified and strengthened. The damaged hoist stem was replaced. It was decided to carry out model studies in order to find out the exact reasons for the mishap and thereby evolve a safe design for the future installations. The following factors were also proposed to be observed on the model in order to find out the remedial measures and as also the safe filling operation for this installation:-

(1) Relationship between the crack opening and gap between the gate body and downstream wall.

(2) Typical back of gate opening configuration.

(3) Effects such as catapulting height, uplift forces and pressures on the system during unbalanced operation.

(4) Effect of speed of opening of gate.

On the basis of model study result, the guidelines concerning safe procedures of achieving balanced head, the amount of crack opening, suitable design of back of gate orifice were evolved. Also it was decided to installation timer and electrical interlock in the electrical circuit for safety.

5.4.5 Tungabhadra Project

5.4.5.1 Problem:- The project was equipped with two number 1.829m x 3.658m size vertical lift fixed wheel type service and emergency gates designed for 25.30m head and operated by electric hoists. The service gates are provided with upstream sealing and skin plate whereas the emergency gates are having downstream sealing and skin plates. It was reported that the gates create difficulty in closing besides vibrations, cavitation problems and profuse leakage past the gates.

5.4.5.2 Remedial measures:- It was suggested to redesign the bottom lip slope of the service gate in such a manner that the flow jet cleared the gate leaf body on the downstream side ensuring aeration of flow. It was proposed to provide an angle of 35° or more with the horizontal between the controlling edge of the gate and downstream edge of bottom-most girder (Fig. 5.60). Likewise for emergency gate, the bottom lip shape was proposed to be modified to provide for convergence of the flow passage so as to achieve positive pressures on the gate bottom.

5.5 AERATION, CAVITATION & AIR ENTAPMENT

5.5.1 Beas Project (Diversion Tunnel)

5.5.1.1 Problem:- The Problem of air entrapment and damages due to air blowouts happened at Beas Project, probably due the vertical flow of water through the closure shaft of diversion tunnel (Fig. 5.45a). The diversion tunnel has three shafts i.e. a closure shaft, an intake shaft and a shaft for the vertical lift gate. The closure shaft was provided for enabling a 3.048m x 6.401m sizes bulk-head gate to be placed so that concrete plug could be laid on its d/s for the diversion tunnel closure. When the tunnel was closed by lowering the vertical lift gate for the first time with reservoir at El. 401m, surges in the form of fountains rising above the water surface were noticed.

5.5.1.2 Analysis:- During the diversion stage, the flow passing through this tunnel was entering at the inlet portal and the top of the intake shaft remained closed with the help of a flat bulkhead gate. However, the top of the closure shaft was covered by a grating, still some flow was entering the tunnel through this shaft also.

As the whole of the tunnel was fully submerged, therefore, it was conjectured from the location of these fountains that the surges came out from the inlet portal and the closure shaft. Also, large pieces of the tunnel liner plates were found in the d/s channel supposed to have come out from the portion of the tunnel near the closure shaft, when no flow conditions were achieved by the successful closure of the vertical lift gate. Detailed investigations of closure shaft also revealed that there was considerable damage to the bulkhead gate grooves, therefore closing the tunnel by lowering the bulkhead gate was not possible. The grating at the top of the closure shaft was also damaged and purpose of the closure shaft was thus completely defeated.

The flat bulkhead placed at top of the intake shaft, which remained closed during the diversion stage also, malfunctioned. Two numbers plates attached to stiffeners of the flat bulkhead gate of the intake shaft were also recovered for the d/s channel. Under-water probe by divers revealed that this gate had been displaced and had slipped into the intake shaft probably due to blowout forces induced by the entrapped air, which got compressed in a space below this flat bulkhead gate. It was found that this flat disc-like bulkhead gate (Fig.5.45d) had a air pipe which was closed. Therefore, the entrapped air could escape only through a vent pipe whose inlet was located about 2.40m below the bottom face of the bulkhead gate and there was no arrangement for escaping the air, entrapped between the bottom of the gate & above the inlet of vent pipe.

5.5.1.3 Conclusion:- It was established that appreciable downward flow through the closure shaft was taking place, because of its remaining always open. The vertical flow while turning through a right-angled bend at the tunnel (Fig.5.45e) resulted in low pressures at the tunnel roof. This phenomenon caused extensive cavitation damages to the roof and to a lesser extent to the floor. This phenomenon was also reproduced on a model and it was found that with the closed vertical lift gate, the pressure surges traveled u/s & up through the intake shaft. Thereby, the entrapped air got compressed and the forces exerted by air blowouts caused the gate to be blown up for a considerable height. During the free fall, the gate damaged the bottom piece of the cylindrical gate and fell into the intake shaft.

5.5.2 Krasnoyarsk Project

5.5.2.1 Problem:-The bottom outlets of Krasnoyarsk project (USSR) were designed for operation at head up to 70m. These outlets were equipped with two gates: a vertical lift gate on the u/s side for emergency as well for attending to the maintenance of service gate and a radial gate on the d/s side for regulation of flow (Fig.5.61). These gates are capable to sustain a static head of 100m.

Metal lined outlets having a length of 26m are constructed with a tapered rectangular cross section. The section at inlet is 6m x 6m and at the end reduce to 5m x 5m. Change in the cross-section of the conduit is achieved by sloping the ceiling and narrowing it laterally. The passage from the metal-lined portion to the concrete-surfaced outlet is with a 50cm expansion on each side. To eliminate low pressure and cavitation, air is delivered to the chamber of the radial gates by two 2m x 2.5m ventilation galleries. Air is delivered to the stream of water through a 600mm-dia pipe, whereas a metal box with holes deliver air to the sill of the regulating gate.

The most severe operating conditions are created when the regulating gate is operated with opening of 1/2 to 3/4 of the height of the exit section. With complete opening of the gate, the air could effectively penetrate around the stream from the chamber of the radial gate. However, with partial opening of the gate, side gaps provided for ventilation are completely covered with water spray and the entrance of air under the stream from the chamber of the radial gate is completely blocked.

It was also found that the concrete side surfaces of the conduits have roughness and projections up to 4cm. Inspection established that the metal linings, embedded seats, and metal structures of the gates were in a normal condition. However, in some places the rubber seal was torn away and at some places even together with the fixture (hold-down straps). The hoses delivering water under pressure to seals were also torn. Severe water leakage through the seals of the radial gates was also observed. In the hoisting arrangement, the articulated gate shoe mechanism of the majority of radial gates was also severely damaged. Portion of the perforated box for delivering air to the sill was partially torn away, the concrete side surfaces abutting the lining were scoured in the form of furrows 1 to 1.5m wide and up to 1m deep thus exposing the reinforcement.

5.5.2.2 Analysis:-It was found that the water jets issuing underneath the gate strikes the concrete mass supporting the trunnion of the radial gates. The pipes delivering air under the stream were severely clogged with ice. It appeared that the damages of the concrete surfaces occurred due to inadequate aeration because of insufficient expansion of the outlet (i.e. inadequate side gaps) beyond the embedded side seal seats of the radial gate. The half-meter side gaps could not provide sufficient delivery of air to the flow for its aeration. In addition, during the winter, ice forms in the ventilation galleries and bottom outlets, which reduces the delivery of air considerably.

5.5.2.3 Remedial measures:-In addition to rehabilitating the surfaces of the outlets and putting the mechanism and seals of the radial gates back into operating condition, it was decided to install deflectors on the ceilings of the outlet to direct the flow away from the trunnions in order to avoid damages in future.

5.5.2.4 Conclusions & recommendations:-The irregularities and projections on the concrete surfaces also promoted cavitation erosion of the concrete. Location of trunnion was also observed to be at relatively lower position. Length of the radial arms also seems to be lesser so as to avoid water splashes on the trunnion assembly. Adequate factor of safety in designs, protection & use of corrosion resistance material should be recommended for all the machined components of the hoisting arrangement because these are subjected to constant water splashes apart from the dynamic loads due to vibration etc.

The size and location of the air ducts must be determined so as to provide the maximum possible aeration of the flow in the bottom outlets. Sufficient aeration of the flow reduces the cavitation effects of high velocity flows considerably. The ventilation galleries must be situated such that water does not enter them. For more reliable operation and reduction of leakage it is desirable that the rubber seals of the gates be pressed against their seating mechanically rather than relaying on the water pressure. In the trunnions, it is expedient to use roller bearings instead of the sliding bearings.

5.5.3 Curnera Dam

5.5.3.1 Problem:-The layout of the bottom outlet is shown in Fig. 5.62. The originally designed aeration system of the bottom outlet of the Curnera arch dam (constructed in 1966) was found to be inadequate during the gate operation. This resulted in considerable vibrations and noises.

5.5.3.2 Remedial measures:- The aeration channel was directly connected to the access shaft of the gate chamber and the galleries of the dam in order to improving the performance of gated structure. The aeration system of the bottom outlet of the outlets is shown schematically in Fig. 5.63 & Fig. 5.65. The original aeration channel supplies the partial airflow (Q_{a1}). The three additional openings can allow an additional airflow (Q_{a2}). Therefore, the bottom outlets can be aerated with the airflow Q_a (= Q_{a1} + Q_{a2}) for satisfactory operation of gates. However, by closing one, two or all three openings, air supply can be varied. The detailed arrangement of the additional openings is shown in

Fig. 5.64. After carrying out the above modifications/ remedial measures, satisfactory performance of the gated installations was achieved.

5.5.4 Ramganga Project (Auxiliary Intake)

5.5.4.1 Incident:-The intake shaft for the auxiliary outlet (Fig. 5.66a) in the Ramganga dam has at its top a trash rack structure consisting of vertical trash racks (for the flow entering form sides) and a hemispherical trash rack (for the flow entering form top) (Fig. 5.66b). The Howel Bunger valve installed in the auxiliary outlet tunnel regulates the flow. Under deep submergence (i. e. adequate head of water), the tunnel as well as the intake shaft could run full under pressurized condition. The malfunctioning of the gated outlets took place at the decreased reservoir level.

5.5.4.2 Analysis:-Under the conditions of low submergence of the intake, the outflow capacity of the valve exceeded the inflow passing through the trash racks. There were vortex formations around the entrance and thereby allowing the air to be sucked in and creating mixed flow conditions in the tunnel. Subsequently, when the Howel Bunger valve was closed, the intake shaft and the tunnel started getting pressurised and in turn compressed the accumulated air, which escaped through the shaft causing violent surges. With the blowout forces of air the sides trash panels jumped up as also the hemispherical dome-like trash rack which was blown up and fell into the intake shaft (Fig.5.66c). Thereafter, due the rise in water level, the discharge increased through the valve, which forced the trash rack to be sucked in further in the tunnel.

The phenomenon was later on simulated on a model in order to find the reasons of mishap and also to guard against a similar disturbance due to air entertainment / blowouts in future. **5.5.4.3 Remedial measures & suggestion:-**It was advised to provide heavier hemispherical trash rack with larger open area. It was also suggested to operate the outlet with restricted discharges whenever the water level in reservoir fall below the critical level in to avoid air entrapment.

5.5.5 Guatape Project (Colombia)

5.5.5.1 Incident:-Similarly at this project also, two extreme violent accidents in the intake tower happened due to strong air blow-outs. The cylindrical gate was seriously damaged in these accidents and also there was significant damage to the overhead crane, concrete roof, trashracks, etc. The layout of intake is shown in Fig. 5.67a.

5.5.5.2 Conclusions & recommendations:- Air had been apparently drawn into the cylindrical intake by strong vortices, which were intensified by the partial obstruction of the trashracks. Both the accidents happened at times when the reservoir was at the low level. Subsequently, the dam height was raised by 30m in the second stage of construction of the project. With the increase in dam height, deeper submergence of the intake constituted the main defence against air entertainment, and therefore no such accidents happened due to sudden air releases after the second stage of construction was completed.

Increasing the submergence of intake inlet as much as practicable can prevent the accidents described above. Increased submergence also decreases the strength of air entraining vortices apart from reducing the movement of debris towards trashracks. A trap (Fig. 5.68a&b) and vent shaft should be constructed at appropriate location to let out the trapped air so as to ensure satisfactory performance and the safety of gated structure.

5.6 OPERATION & MAINTENANCE

5.6.1 Tarbela Project (Pak.)

5.6.1.1 Incident:- The service spillway of the dam consists of seven number 15.2m x 18.6m size radial gates (Fig. 5.69). The gate trunnions are supported by reinforced concrete girders projecting beyond the side face of each pier at its d/s end. Hoist platforms are located at the top of the spillway piers d/s of the bridge (Fig. 5.70).

The gate leaf is made of Plate Steel assembled by welding. Skin plate is of varying thickness and is supported by curved vertical T-beams stiffeners. The side seals for gate are of solid bulb music note types. Three bronze faced guide buffer (Fig. 5.72) on each side of the gate leaf are provided to limit the lateral moment of the gate while operating.

Each gate is operated by rope drum hoist with the help of two groups of nine number corrosion resistant steel wire ropes fastened to brackets attached at the u/s bottom face of the gate on each sides. The ropes wind spirally in separate grooves at the two drums.

The incident of malfunctioning of one of the gate took place on June 23, 1992, while lowering the gates from their fully opened position with the help of remote control and the reservoir level was at 460.2m. As reported, the hoist motor of gate No. 7 tripped when the last step of 0.6m travel in lowering operation was started and a thumping sound was heard resulting probably from the free fall of the stuck up gate. The gate was found stuck up at an opening of 112mm and thereby resulting in a high velocity discharge-taking place from the small-unclosed opening between the bottom of the gate & sill. Apart from the above, the operator also found that the drive shaft coupling had disengaged and the hoist Platform had rotated toward d/s. The hoist ropes were also found to jumbled.

A detailed inspection of the damaged gate equipment was undertaken later on and the following were also noted:

(1) Shearing of the 19 out of 24 foundation anchor bolts & displacement of right side hoist platform in anti-clockwise direction.

(2) Disengagement of drive shaft coupling.

(3) Pulling out of a rope from its socket at right side and breaking of strands of a rope close to the hoist drum at the left side.

(4) Shearing of all the four bolts of left side bottom guide buffer bracket & a green scratch mark starting from the bottom buffer guide position (when the gate closed) and extending upwards for a length of 4.67m on the left side seal plate.

5.6.1.2 Analysis:-From the mechanism of failure, it appears that the gate might have stuck up because of insufficient clearances between the embedded side sealing plates and the guide buffers/side seal assembly mounted on the gate (Fig. 5.71). The jamming of the gate due to insufficient clearance, could be the result of insertion of a foreign material between the moving gate components and the embedded side plates, thermal expansion of gate, concrete growth or the progressive outward movement of side seal assembly in the oval shaped clamping holes. It could be understood that during the lowering operation, a considerable length of the ropes might have unwounded from their respective drums even after the gate got struck-up. Thereafter, the gate fell down freely by its own weight, when freed by vibrations or the contraction of gate leaf resulting from lowering of ambient temperature /cooling effect of water.

5.6.1.3 Conclusions & recommendations:- It has been observed by hydraulic/ mathematical model, that significant hydrodynamic forces (Fig. 5.85) act on the gate leaf when the flow is suddenly interrupted by it. The freely falling gate result in blockade / cutting of the nappe all of sudden due to uncontrolled lowering speed and thereby results in generation of large hydrodynamic forces. These forces alongwith impact of moving body (gate leaf) resulted in damages of ropes, hoist components/ supporting structures etc. The magnitude of hydrodynamic force depends upon the height from which the gate fall (i.e. velocity of falling gate). In this case, incidentally the flow was not blocked completely, due the fact that the gate got stuck up leaving a small-unclosed opening. Therefore, the gated structure was not exposed to the severe (momentary quick rising peak) of the hydrodynamic forces, which generates at the time of sudden and complete closures due to the simultaneously occurrence of compression on the u/s & suction effect on the d/s face of the gate leaf. Otherwise, the extreme hydrodynamic forces would have resulted in more serious damages as has happened in case of spillway radial gate of Picote Dam.

Frequent maintenance & inspection of the gated structures be carried out, also all the clearances critical for gate operation be checked & rectified in order to ascertain safety as well reliability. In case of gate operated by chain/ rope hoist, the position indicator capable of monitoring the actual position of gate leaf during operation should be installed on the installations.

5.6.2 Folsom Dam

5.6.2.1 Incident:- On July 17, 1995, at Folsom Dam, one of the spillway radial gates having a width of 13m & height of 15.2m (Fig. 5.74 & Fig. 5.75) failed during the raising operation, thus resulting in an uncontrolled release of water.

5.6.2.2 Analysis:-Prior to the failure, there had been no indication of any structural deformation in the gated installations. Although concern had been raised about corrosion damages taking place on the spillway gates. After the failure, an intensive inspection of the gates was taken up and it was observed that due to inadequate drainage of the arms/gateleaf, various bolted and welded connections were structurally compromised as result of severe corrosion. However, this was not considered the primary reason for the failure.

Based on the theoretical and the failed gate configuration analysis, it could be established that the first diagonal brace between the two lower right arms failed; thereafter, the remaining diagonal braces on that side failed due to excessive loading. With the loss of bracings, which had provided vertical fixity of radial arms resulted in failure of these two lower arms by buckling about the weak axis. With the failure of two lower arms, the structural integrity of this side was lost and resulted in deformation/ failure of the remaining gated structure. Historically also, although, there had been only a limited number of radial gate failures, but they all were due to minimal arm bracings /vibrations.

From the markings on the wall plates, it appears that initially on raising the gate, the left bottom corner of the gate moved laterally thus making contact between the side seal clamp plate and the wall plate (Fig. 5.76). As the gate continued to be raised in the tilted position, vibration of the gate occurred resulting in the circular and oval markings on the left side wall plate. After the primary failure of the right arm, the skinplate moved u/s on the left side as evidenced by the rubber markings, and the top right side of the gate dug into the concrete pier as it moved d/s.

Initial lateral movement of the gateleaf toward the left may be attributed to three things. The major cause could be the non-uniform friction at the trunnion bearings. It was found that the right side trunnion had twice the friction of the left side trunnion. In case, the right trunnion had the higher frictional resistance, the tendency would be for the left side to be raised first because of its lower resistance, thus moving the gate to the left. The higher resistance on the right side would also lead to higher loading on the right arm, causing it to fail first.

Another reason for the lateral movement is the relatively low lateral stiffness of the arms. The third source of lateral movement of the gate could be the unequal chain lengths. The freezing or binding of links of hoisting chain can take place because of corrosion of adjacent links. Therefore, the original equal lengths of the chains, changes due to the fixed angularity between some of the links.

5.6.2.3 Remedial measures & structural strengthening: -The provisions for stoplogs were not made in the original planning, so they were designed, fabricated, and installed within a very short time after the incident in order to carry out installation of new gate as well for taking up remedial measures in the other bays (Fig.5.79). Therefore, the first stage of remedial works involved fabrication of steel frames with grooved sides and bolting them into the concrete piers of adjoining spillways bays. The steel stoplogs 15m long x 2.5m wide were than dropped three at a time into the grooves. The wooden wedges were placed under the stoplogs with help of divers to prevent the leakage through the stoplogs for facilitating the erection of new gate.

The inherent weaknesses in the original gate design (Fig. 5.78) were corrected i) By welding additional plates on the arm flanges, ii) By adding stiffeners between the arms near the trunnion end, iii) By incorporating additional diagonal bracing between the two upper arms, iv) The connections for both vertical and diagonal braces modified to obtain a more rigid configuration by welding the attachment plates to the flanges instead of the web, v)Diagonal tie rod bracing were added between the left & right side arms (i.e. in the plan Fig. 5.77) in the region u/s of the trunnion tie beams, vi) Modified bracing arrangement between girders to prevent rotation of the girders in the vertical plane at arm connections and vii) To lower trunnion friction, the pins were rotated by 180^0 so that the un-corroded surface would be in contact with the bushing.

5.6.2.4 Conclusions & recommendations:- The structural design of gate leaf & radial arms should be conservative. The rigidity & stiffness of the gateleaf shall prevent the formation of an eccentricity between the skinplate center of rotation and the trunnion pin center and therefore will reduce the occurrence of coupled mode of vibrations apart from withstanding overloading.

Therefore, the conservative design will ensure safety and reliability of gated installations. The trunnion bearing should also be designed with adequate care. Self- aligning & self-lubricating bearing alongwith provision of corrosion resistance stainless steel pin can be made for ascertaining the safety & reliability.

5.6.3 Picote Dam:

5.6.3.1 Incident:- The Picote dam in Portugal (Fig. 5.80) is an arch dam having a height of 100m above the foundations. The spillway of the dam is equipped with four 20m(wide) x 8.60m(high) radial gates (Fig.5.82). The radius of the skinplate of the gates is 11.70m. The hydrostatic load acting on the gate leaf is transmitted to the trunnion girders by radial arms. The trunnion girders are fastened to the concrete piers by four sets of embedded anchors consisting of 20 numbers, 38mm ϕ steel rods. The gates are operated by "Galle" type chains, attached to the bottom of the gate in the u/s side. The hoisting chains are connected to a system of two electric motors and synchronizing shaft installed on the top of the piers.

During a flood, when the gates were being opened by the remote control, there was an accident in one of the spillway radial gate. From the investigation, it appeared that the accident resulted because of lack of articulation in the chain links, probably due to the accumulation of debris or some other foreign material. This led to overriding of the chain and overloading of the left side electric motor and thereby resulted in yielding of the bearing of the output shaft of reducer and warping the gate owing to the lack of support on that side. As each motor was capable of lifting the gate alone, the gate continued to rise by the effort of the right side motor alone. However, the excessively increased hoist loads resulting from the friction, jamming of the tilted/ warped gate, brought about the yielding of the bearing of the reducer's shaft of the that motor also and thus the gate was freed completely from both the ends.

The moment, both of the hoists failed, the gate started to descend on account of its own weight and thereby blocking the flow with an increasing speed. The hydrodynamic load, to which the gate was exposed, caused the trunnion girders to be torn from the anchors, thus dragging the gate with trunnion girders along the flow (Fig. 5.83). This accident put the gates of the adjoining bays also out of use due to lack of trunnion support at one of the end.

5.6.3.2 Analysis:-It could be noted here that the maximum hydrostatic load under normal water level is 389.9t on each trunnion for the fully closed position of gate. However, it was estimated that an accidental hydrodynamic force of more than 1700t would have lead to the failure of anchorage.

Further, the tests on the Hydraulic as well the FEM models were carried out to determine the magnitude of forces to which the gate was exposed during the accident. **5.6.3.2.1 By hydraulic model:-**The tests on the Hydraulic model indicated that the forces acting on the trunnion increase with the height of fall of the gate. The situation under which, the accident occurred it is possible that a force of about 1665t might have been exerted on each trunnion, which corresponds to about 4.3 times the normal maximum hydrostatic load on them.

The tests also showed that a rise of the water level of the order of 1.9m to 2.4m at the entrance of the bay and about 2.9m to 3.4m near the gate could be expected. Further, it was also observed that the induced forces acting on the trunnions increase with the increase of rate of flow. For the flow of 8210 m^3/s (maximum flow tested) which is lower than the maximum discharging capacity of spillway i.e. 10,400m^3/s, the induced forces attained a values of about 2840t, which amounts to about 7.3 times the maximum hydrostatic load on each trunnion. 5.5, 6.3 and 6.4 respectively were observed from the hydraulic model.

5.6.3.2.1 By FEM mathematical model:- The values non-dimensional peaks of hydrodynamic force observed from this model were 5.1, 5.66 and 6.94 (Fig. 5.84 & Fig. 5.85) respectively for three heights of fall of the gate, with its lower edge at elevations 468.00m, 470.70m and 473.40m. The model also indicated that the peak of force depends upon the height from which the gate fall (i.e. velocity of falling gate) and the flow rate as observed from hydraulic model.

5.6.3.3 Remedial measures:- For reinstalling a new gate, it was not possible to re-use the existing embedded anchors, therefore eight pre-stressed cables, having a capacity of 190t each, were used.

5.6.3.4 Conclusions & recommendations:- It was concluded that the non-dimensional pressure force rises very quickly to the maximum when the flow was suddenly interrupted (Fig 5.85). The maximum non-dimensional forces in the above test were 4.49(compressive) on the u/s side and -2.45 (suction) on the d/s side (Fig. 5.84). The occurrence of these values was simultaneous. The suction force on the d/s side of the gate accounted for a substantial part of the total impulsive load nearly 1/3. As these forces are several time of the static loading, therefore these can result in severe damages to gated structure as also to the surrounding civil structures.

Some of the gates are handled by means of gantry cranes & lifting beam/blocks, with the help of the hooks attached to the gates or lifting tackle. These type of hoisting (hooks and pins) arrangement permit carrying out the operations of suspending the gates at the required elevations, disengaging / engaging the gates under water. The crane operator depends upon the series of signals received by him to accomplish all these operations. The signals convey to the operator about the status of the desired gate handling operations. In case of malfunction of the system of automatic devices and signaling system, unsafe positioning of the hook on the pin or latches may occur, with the result that the gate may slip past the support and fall swiftly on its sill. Such accidents may induce substantial hydrodynamic forces on the gated structure and surrounding civil structure. The hydrodynamic impact loading, which may several times not only the normal load, but also the ultimate strength of the civil structure and gate structure. Therefore, in such circumstances, immediate destruction of the gate and supporting structure is imminent.

Also, the strengthening of the gateleaf in such case would be pointless, since the falling gate could destroy the supporting civil structure. Therefore, handling of the gates by such means at the important hydraulic structures, whose failure can leads to disaster, may be allowed, provided that the highly reliable construction of the hooks/pin connections intended to prevent the gates from falling have been incorporated in the hoisting arrangement.

5.6.4 Belci Dam

5.6.4.1 Incident:- The spillway of Belci earthfill dam (Fig. 5.86) consisted of four over flowing bay equipped with 2.5m x 11m flap gates. The two central openings are provided with bottom outlets equipped with 2.5m x 11m size radial gates (Fig. 5.87). The flap gates are operated by a vertically mounted hydraulic hoist, whereas the radial gates of the bottom outlets are Electro-mechanically operated. The electric motor & reduction gearing for the radial gate are housed in the operation chambers located in the concrete piers, accessed from the crest with the help of a shaft. During one night, the rain started heavily, although before the rain set in, the water in the reservoir was below normal level. At that time one of the radial gate was in partial opened position (about 50mm) for clearing the silt accumulated near the intake area. Also, the dam toe powerhouse was not in operation because of some fault. The operator observed a rapid rise in water level as a result of heavy inflow in the reservoir, and therefore initiated complete opening of partial opened radial gate. The electricity supply failed at the dam, when the gate was lifted only 40cm. In the meanwhile (over an hour), the electric supply from the standby power unit could be restored, the water level rose rapidly above the NWL, and entered in the operation chamber thus affected the electric motor of radial gate hoist. Therefore, it was not possible to lift the radial gate once the electric motors of hoisting arrangement were saturated. Operating personal tried to un-block and lower the flap gates manually in order to control the large inflow and rapid rise in water level. However, the over flowing water already flooded the flap gates, therefore only one flap gate could be lowered some how.

5.6.4.2 Analysis:-The earthdam was overtopped and subsequently failed due this exceptional high flood on that night of the accident and to the inadequate opening of gates caused by the accidental interruption to the electricity supply. Continuing operation of the gates with supply from the power unit was not possible as the mechanisms were located in isolated chambers, below the water level, and the electric motors were affected by the water entering the chambers. It is also mentioned here that because of increased silting of reservoir and therefore to safeguard the intake against silting, the sequence of gate operation was modified. The initial operating instructions provided for the opening in stages of the flap gates first and then of the radial gates. However, under the new instructions the gate operation was to start with the opening of the radial gates.

5.6.4.3 Recommendations:-The hoisting arrangement should be located such that it is accessible under all conditions. All the hoist equipment especially the electric motors & controls should be located such that these may not get submerged during high water levels. The operating personnel should be instructed to follow the best possible gate operation schedule for handling the flood (other than the defined one) if required in case of any emergency.

5.7 PLANNING

5.7.1 Messaure Dam:

5.7.1.1 Problem:- During the construction of the Messaure Dam on the Lule river in northern Sweden the water was bypassed by a diversion tunnel (Fig. 5.88). The tunnel intake consisted of the two vertical shafts, each provided with two opposite openings (Fig. 5.89). The reservoir was to build up by successively closing these openings with the help of a special type of vertical-lift gate designed for water head of 73m. When the reservoir filling had reached a level corresponding to 53m head on the these gates, a slide occurred in the right-hand bank of the former u/s diversion channel and the dam side openings of both the intake shafts were completely filled with stones and gravel. The gates were (Fig. 5.89) thereby blocked and could not be moved in any direction. The slide resulted in each intake shaft one free and one stone blocked opening of 0.4 x 19m.

5.7.1.2 Remedial measures:- For the closure of the free openings, rubber faced oak logs were lowered in front of it, which were swept into the opening by the flow of water and thus closing it partly. For the complete closing a reinforced strong plastic tarpaulin was dropped like a curtain in front of the u/s of opening, which was sucked by the water pressure and thereby a perfect sealing of the openings were achieved (Fig. 5.90).

5.7.1.3 Recommendations:- It is recommended that intake without adequate arrangement of coarse trashracks should not be operated at partial gate openings for any reasons. Also, the diversion intake opening should have larger dimensions in both directions i.e. width & height.

5.7.2 Kafue Gorge Dam

5.7.2.1 Problem:- Unexpected difficulties were encountered during the time of the final closure of the diversion tunnels. The bulkhead gate provided for the purpose could not be lowered to achieve complete closure of the opening and was stopped by some obstruction in a position leaving an unclosed opening of about 0.6 m high. Several unsuccessful attempts to close the opening were made by raising/lowering the gate a couple of time but a gap of 0.6m remained unclosed each time.

The two number diversion tunnels, each having a cross-sectional area of 120m^2, were designed for a total discharge capacity of 2 100m^3/s at a maximum head of 18.5m (Fig. 5.91). Each tunnel intake was bifurcated to limit the size of the gate. Out of these total four openings, three were having grooves for concrete stoplogs as well as also for the bulkhead gate. As only one bulkhead gate was planned to serve all the four openings, therefore, one of the openings of the tunnels was having a groove only for the bulkhead gate. The bulkhead gate remained suspended from a gantry crane, running on rails fixed on the top of the superstructure located well above the maximum water level retained during the construction.

On completion of the dam construction, concrete stoplogs were placed in three of the four intake openings under minimum inflow conditions with the help of bulkhead gate. After successively closing the three openings, the bulkhead gate was finally shifted to the remaining fourth opening of the diversion tunnels.

The bulkhead gate was having a height of 13.7m and a width of 4.2m. It was provided with eight pairs of wheels running on tracks located in the gate grooves. Sealing arrangements was planned on the d/s side of gate leaf (Fig. 5.92).

5.7.2.2 Analysis:- It was reported that because of some reasons, the start of the filling of the reservoir was delayed and the bulkhead remained in service with partial opened for regulation of flow over considerably longer period than expected. As the diversion was not provided with racks therefore, floating materials & debris were passing all around the partial opened gate. The debris some how got wedged at some narrow spaces between the gate leaf and the civil structure. Therefore, the complete closure of the opening could not be achieved.

5.7.2.3 Remedial measures:- Therefore, the help of divers was considered necessary to find out the reasons and also to affect the complete closure of the bulkhead. While carrying out the routine diving, it was found that in the wedge-like space at the top, between the d/s side of the gate and the adjacent concrete (i.e. near the location of the top seal), a firmly compacted conglomerate of twigs, weeds, silt, etc (Fig. 5.93) had accumulated. The divers could further ascertain that instead of a flat steel plate for clamping the top J- type rubber seal, an L-shaped section was used and this was creating an obstruction to the gate moment.

5.7.2.3 Recommendations:- The shape of the gate leaf, embedded parts and concrete surfaces (in the proximity of gate leaf) should be designed carefully. Especially, the design of protruding gate leaf parts and their clearances from the concrete structure & embedded parts faces should be such that may not obstruct gate movement. These factors are crucial for satisfactory operation of gated installations.

5.7.3 Sukkur Barrage Across River Indus (Pak.)

5.7.3.1 Incident:- After 50 years of service, one of the barrage gates failed because of damages suffered from severe corrosion. The failure of the gate prompted an appraisal of the condition and structural integrity of the other gates. The barrage gates 66 in number are of sizes 18.30m (span) x 6.0m(high). The gates are vertical lift types having lattice bow girder construction.

5.7.3.2 Analysis:- Originally, during the planning and construction of the barrage, provisions were not contemplated for isolating the barrage gates for carrying out their maintenance or permit their removal during normal barrage operation. Therefore, the damage to the gated structures was accelerated by corrosions. The failure of gate took place due to the structural weakness resulting from corrosion as also by aging effect.

5.7.3.3 Remedial measures:- Failure of gate necessitated a suitable mean for isolation of the bay for erection of a new gate as also for progressive replacement of dilapidated/ aged gates of the barrage in the remaining bays for assuring reliability and also preservation of water. For carrying out these operations, it was decided to provide a gate leaf across the bay at a working distance u/s of existing gate. At this stage, because gate groove could not be provided in, or fixed to the structure walls of the barrage due to the inadequate strength of civil structure. Therefore, a reverse acting, caisson type, radial gate configuration was adopted to ensure stability at any u/s and d/s water level and was designed to be semi-buoyant to assist in its lifting (Fig.5.94).

5.7.3.4 Recommendations:- The provisions for isolating the service gate by mean of an emergency gate /bulkhead or stoplog units must be invariably made in the original planning and design of the project. The regular maintenance and inspection is also one of the major factor in ensuring safety & reliability of gated installations.

5.7.4 Prakasam Barrage

5.7.4.1 Problem:- The barrage was equipped with 70 nos. of 12.192m x 3.66m size stoney type crest gates operated by chain hoists with counter weight. The gates were erected in sixties and remained largely un-attended as provision of regular stoplogs was not made in the original designs. However, provision of two number floating bulkheads was made at a later date. The gates are currently in a very precarious and dilapidated condition.

5.7.4.2 Remedial measures:- The existing gate leaves of bow type girders be replaced by new gates (with plate girders) with teflon cladded side seals. The provision of gun metal bushes in roller train assemblies be replaced by self-lubricating bushes to reduce the maintenance requirement of the rollers and to avoid frequent jamming. Number of floating bulkheads be increased to enable maintenance of more number of gates at a time.

5.7.5 Koka Dam

5.7.5.1 Problem:- The bottom outlets through the dam were not operated for some years and therefore entrance of the outlets had become blocked with silt.

5.7.3.2 Remedial measures & other modifications:- For the safety of the dam it was required that bottom outlet be returned to service. In addition, due to increased demand for water necessitated addition of a new irrigation draw-off works at the dam. Silt from the entrance area of the bottom outlet was removed so as to free the bulkhead gates. The existing u/s bulkhead gates and their hoist were removed from the structure, rehabilitated and retained for emergency. The existing vertical lifting gate was converted into a guard gate to close off the outlet in an emergency. The same bottom outlet was remodeled to incorporate a radial gate for the regulation of flow for irrigation requirements (Fig. 5.95).

5.7.3.3 Conclusion & recommendations:- The operation of the bottom outlets should be carried out regularly in order to ensure the reliability as also for removing the silt etc. accumulated in the vicinity of the gated structure. The sizes of opening should be adequately designed so as to eliminate/ reduce the possibility of gate jamming. Also, the larger size opening can effectively dispose of the debris and other floating materials with minimum damages to the civil structure as well to gate components

5.7.5 Kelinchi Dam

5.7.5.1 Problem:- The bottom outlets controlled by means of gates or valves are generally provided through the body of the dams in order to release water for different purposes as well as to lower the reservoir in an emergency. The type of arrangement that has been frequently adopted for a number of projects is shown in Fig. 5.96

The gated arrangement comprises a pair of wheel/ slide type vertical lift gates to close off or releases of water from the outlet. The regulating/ control gate comprises a slide type/fixed wheel gate operated by electrically actuated hydraulic hoist. To provide a second degree of protection, the control gate is provided with an emergency gate generally of fixed wheel type on its u/s side. The emergency gate generally remains suspended at the top of the intake towers by means of steel wire ropes, ready to be lowered under gravity in an emergency at a controlled rate of descent with the helps of drum type hoists.

For such outlets where the depth to maximum reservoir water level in restricted to about 30m, this type of gate designs is generally found to be more economic then a pair of hydraulically operated bonneted gates. The arrangement also offers considerable advantages for maintenance, since full access is afforded to the control gate with the emergency gate lowered and of course the emergency gate can be maintained at the top of the gate shaft / tower.

5.7.5.2 Conclusions & recommendations:- However, such an arrangement shall require a deep shaft for emergency gate. In such installations, the embedded parts, along with the hoisting ropes are likely to be damaged due to continuous submergence apart from the frequent maintenance requirement for the gate wheels. The erection of embedded parts over a considerable length and achieving perfect alignment for satisfactory operation of gate may be difficult. Moreover, in case of a gate suspended by means of long flexible link may result in vibrations whenever the gate is lowered in the flowing water. Therefore, it is preferable to adopt the arrangement shown in Fig.1.1, 1.5, 2.11 for higher head installations.

5.8 FABRICATION & ERECTION

5.8.1 Armed Zone Dam

5.8.1.1 Problem:- The dam was constructed in 1960, and the spillway gates installed at that time were removed during a subsequent military conflict. New gates were installed later but with only limited testing/commissioning due to further conflict.

The spillway radial gates were 15.64m high and 15m wide. The gateleaf had two guide wheels on each side, set 8.43m apart with the upper one at 5.40m from the top. As the gate tilt is limited by the clearance of opposite side's upper and lower guide wheels, therefore, it is desirable that the clearances between the embedded side plates and the side guide wheels fixed on gateleaf should be kept as small as possible (about 5-10mm) in order to avoid malfunctioning/ jamming of the gate during their operation. However, on these gated installation wider clearances as much as 24mm was observed at some places. Because of gross inaccuracy in alignment of embedded parts such high clearances were also required for ensuring the free moment of the gate. The excessive guide wheel clearances allowed top corner of the gate leaf to come in contact against the side plates thus leading to frequent (Fig.5.97) jamming of the radial gate during their operations. Moreover, once the gate gets tilted, the increased frictional forces retard the moment of that side and thereby tend to further tilt (Fig.5.98).

5.8.1.2 Analysis:- Providing suitable clearances was a challenge due to limited thickness the stainless steel side plates, poor alignment of embedded parts and to some extent the wide ranging thermal expansion/contraction of gate. The expansion of the 15m wide gates over the temperature ranges at site was also signification due to direct sun shines over the full width of the gates early in the afternoon, when the shade temperature is at its peaks. When the reservoir is full or nearly so, the temperature rise of the gates shall be limited.

5.8.1.3 Remedial measures & suggestions:- As the wider/ larger clearance between guide wheel & side plate were responsible for frequent jamming of the gates. Therefore, it was required to correct the alignment of the side plates to reduce the clearances apart from modifications in side seal assembly (Fig.5.99). The side seals assembly should be modified to allow greater flexibility of the seals and two additional guide wheels near the top corners should also be provided to counter the tendency of gate tilting. The hydraulic hoist controls should be modified to improve their quick response to any tilt of the gate. The side seal arrangement shown in Fig.3.5 is considered to be more flexible & suitable for taking care of reasonable amount of inaccuracies in the sealing surfaces. Therefore, should be adopted instead of that proposed in Fig. 5.99.

5.8.2 Mita Hills Dam

5.8.2.1 Problem:- In water resource system, gates in particular are exposed to water and air constantly and therefore, require protection and maintenance. Hydraulic gates which have surfaces exposed to water, air and sunlight need not only protective coating but also special treatment to avoid any unforeseen. When the spillway gates for the Mita Hills Dam situated in northeast Zambia were commissioned and tested at such a time when the reservoir water level was rising rapidly and therefore, the spillway radial gates were tested successfully under various operating heads without any problem. The moment of gate over the entire range of travel was also carried out successfully. After the commissioning, these spillway gates remained in the closed position for most of the time for years together except a few operations only in year of high inflows.

For ascertaining the safety of the dam as also the gated structure, it was decided to carry out a routine test on the spillway gates. At the time of routine test, the ambient air temperature was very high and water level in the reservoir happened to be quite low. During the tests, it was found that neither of the spillway gates could be moved from their closed position, when the raising operation was initiated.

5.8.2.2 Analysis:- The gates were in fact jammed in their closed position and there was no doubt that the gateleaf had responded to the high temperatures and expanded beyond the clearances available between the gateleaf ends and the embedded side guide plates. It was also observed that prior to the installations of gateleaf, black bituminous paint had been applied to the skinplate surfaces for protection.

5.8.2.3 Remedial measures:- In order to reduces the thermal expansion of gate leaf because of high atmospheric temperature during day time, it was decided to apply silver finish paint over the black paint on the skin plate of the gate leaf. After applying the silver paint on the gate leaf, the gates moved freely and are operating ever since. The heat absorption through the black paint had been sufficient to increase the temperature beyond all expectation, and the gates had simply expanded unprecedently. The reflecting qualities of the silver paint had been sufficient to bring the expansion to within the reasonable limits allowed for in the design.

5.8.3 Beas Project (Irrigation Tunnel Slide Gate)

5.8.1.1 Problem:- The Pong Dam of Beas Project is a 132.60 m high earth core gravel shell dam having powerhouse located at the toe of the dam. It has five diversion tunnels each of 9.14m diameter with inlet at riverbed level. Two of them now have been converted into irrigation outlet tunnels, while the remaining three into power tunnels. Each of the two irrigation tunnels is bifurcated at the gate control shaft into rectangular conduits for accommodating in each, an emergency & a service gate in tandem designed for a head of 105.5m (Fig. 5.100b). The conduits again merge into a circular tunnel in d/s of the gate shaft. The slide type gates located in embedded steel bonnets are having sizes of 2.13m x 3.20 m with u/s skinplate. The load bearing/sealing plates attached to the gates are of bronze and slide over stainless steel track plates fixed to the embedded frame. A double acting hydraulic hoist of 625t capacity is provided for operation of service gate i.e. for opening, holding it in partially opened for flow regulation as also for exerting positive downward push for closing. (Fig.5.100a & b).

The original gate slot (Fig. 5.100d) comprised of 8mm thick stainless steel, sliding track plate mounted on a 22mm thick steel plate. These two plates were together screwed to the 56mm thick base plate by mean of counter-sunk stainless steel screws. Lead packing (3mm thick) was introduced in between the 22mm thick plate and base plate. Similarly, lead packing was also provided behind the top seal plate.

During the test operation of the gate under a head of 66m, it was observed that the side and top track plates of the service gates had become loose and the lead packing at their back has squeezed out. Similar damages, although somewhat lesser were also observed in case of emergency gates. The heads of some of the loosened screws had come out beyond the face of track, while the heads of some were sheared off during the movement of the gate.

5.8.3.2 Analysis:- Use of thick lead packing behind the track plates and the inaccuracy in the alignment of embedded track plate/ base were found to be the major cause of these damages. The lead packing got squeezed by the large hydrostatic & hydrodynamic acting on the gate leaf and thereafter completely displaced by the hydraulic forces. The model test has indicated that the embedded parts/ gate leaf parts lying in the slot are subjected to considerable hydraulic forces. These forces tend to lift the embedded parts from their fixtures. The other reasons could be the inadequate tightening / length of the track screws and the inadequate rigidity of the 8mm and 22mm plates.

5.8.1.3 Remedial measures & suggestions:- The gate slot details were modified as shown in Fig. 5.100e. The base plate already embedded in concrete was not perfectly aligned. Therefore, it was grounded, in-situ, such that the track plate may bear more uniformly on it, however, the perfect matching of the surface of these two plates was not possible at this stage. Also, the new track plate was arranged having thickness equal to the total thickness of the previous track plates and the lead packing. New track plates were machined such that their back surface could match with the average profile of the base plate.

The inevitable gap ranging upto 2mm between the track plate and the base plates on account of their non-matching surfaces was to be grouted with plain epoxy. In order to guard against the possibility of the two plates not touching each other, it was advised to adequately tighten the track screws.

5.8.4 Singur Dam

5.8.4.1 Incident:- One of the 15.00m x 13.50m size spillway radial gates operated by rope drum hoists failed during operation at 60% of the design load when the reservoir was being built up for the first filling. The washing away of the gate took place due to detachment of left side trunnion girder because of failure of welded junction between the load carrying tie flats and trunnion girder. The failure of this joint raised doubt about the integrity and safety of similar welded connections between tie flats and embedded anchor girders.

5.8.4.2 Analysis:- On inspection of all gates, the following deficiencies of gate structures were observed:-

(1) Inadequate welding between trunnion girders and tie flats. In fact the flats were welded only at flanges of trunnion girders.

(2) Existence of substantial gaps of varying degree between tie flats and webs of trunnion girders.

(3) Eccentricity due to incorrect alignment of trunnion girders resulting in one of the four bolts of trunnion bracket fixing remaining outside the upstream flange of trunnion girders.

(4) Apprehensions about inadequacy of weld strength and procedure that was actually followed for welding the insulated tie flats with anchor girders.

5.8.4.3 Remedial measures:- (1) An improvised scheme was adopted to connect the webs of the trunnion girders and tie flats by way of welding additional plates all along the web of the trunnion girder on either side of each tie flat. The location and size of additional plates were selected for each specific gate depending upon the prevailing gaps. The other sides of these additional plates were then welded to the tie flats (Fig. 5.101).

(2) In order to tackle eccentric transfer of load from trunnion bracket to trunnion girder, additional plates of triangular shape were welded on the flange plate of trunnion girder and bolted with the existing hole in the bracket (Fig.5.100)

(3) In view of suspected deficiency of tie flat- anchor girder junction, one tie flat near upstream flange of anchor girder was exposed and it was revealed that the tie flats were welded only to flanges and not to the webs of the anchor girder. Series of tests such as pull out test and load test were conducted before deciding future course of action.

A large number of alternatives were studied for strengthening the tie flats-anchor girder junction and it was finally recommended to drive pins to connect the tie flats and anchor girders and weld the pins to lock (Fig. 5.101). The block-outs were then filled by epoxy mortar and epoxy grout.

5.8.5 Daulatpura Wier

5.8.5.1 Problem:- The project consisted of two number 16.00m x 7.80m size emergency gates of fixed wheel type operated by rope drum hoists During erection of emergency gates of a weir structure, the bottom horizontal girder flange was found to be obstructed by ogee crest thus preventing the seating of skin plate on the gate sill. A gap of 270mm between skin plate bottom and sill beam was left.

5.8.5.2 Remedial measures:-After site inspection, a number of alternatives were considered and following modifications were eventually carried out:-

(1) Extension of skin plate at bottom by 80mm-alongwith suitable stiffening of extended portion of gate bottom.

(2) Reduction in depth of horizontal girder, alongwith provisions of an additional web plate.

(3) Removal of bottom girder flanges from current location and re-welding modified and strengthened bottom girder with provision of additional flange plate thus making an 'L' shaped girder instead of 'I' shaped.

(4) A complete review of design of the gate was carried out to ascertain the adequacy of original design provisions.

5.8.6 Nagarjuna Sagar Dam

5.8.6.1 Problem:- The project is equipped with nine number of 3.050m x 4.575m vertical lift fixed wheel type service gates operated by rope drum hoists. One gate was not in operation since inception due to problems in raising and lowering and was getting stuck up. The remaining gates were also found to be not operating smoothly and were poorly maintained. It was also reported that the gates were not self-closing even at low reservoir levels. On inspection, it was observed that the stainless steel cladding of rubber seals had peeled off at certain locations and wheels were not rotating freely. Certain guide shoes had sheared off. It was also noticed that there was rust formation on the skin plate and other steel components, peeling off stainless steel cladding from seal seats and bulging of stainless steel plate of liner of breast wall.

5.8.6.2 Remedial measures:- (1) The seal seats and breast liner plates cladded with 1.25 to 5mm stainless steel plates be removed fully as it was damaging the seals and obstructions to movement of gate.

(2) Stainless steel cladded seals be replaced with Teflon cladded seals.

(3) Two oil seals provided in cover plates of wheel assembly and thicker cover plates used.

(4) The bottom shape of gate be modified by reducing the depth of girder, while maintaining a lip angle of not less than 32° atleast in one gate in the first instance and observe the performance.

CHAPTER-6

INNOVATIONS

6.1 SAFETY & RELIABILTY OF GATES

6.1.1 Safety of Radial Gates

6.1.1.1 General:-Radial gate arms are generally designed to withstand bending moments resulting from the nominal friction on the trunnion bearings, but from experiences, it could be concluded that the lack of lubrication and years of deterioration lead to increased friction and even seizure of the bearings (Fig.6.2& Fig.6.3). The excessive bending moments produced by the increased bearing friction could be beyond the capacity gate arms, thereby resulting in collapse of gate structure (Fig.6.1)

Generally, the earlier installations of Radial gates (i.e. before 1980) were designed with trunnion bearings using a carbon steel pin and bronze bearings. Some of the installations have chromium plated trunnion pins, and the bearings are usually lubricated manually with grease. The trunnion bearings of radial gate remain static with relatively a small movement only during operation. Therefore, lubricant, when applied externally, cannot be distributed on the high-pressure side of the bearing. Even when applied under pressure to the trunnion bearing, the lubricant often finds its way to the low-pressure side, leaving the high-pressure load transformation zone without lubricant.

The most common factors responsible for the deterioration of bearings are corrosion and contamination. The water if present, acts as an electrolyte with the carbon steel pin as an anode and thus leads to corrosion on the bearing surface of the pin. The increased roughness from pitting, corrosion products lying in the bearings and tight radial clearance of the bearing effect the friction of trunnion significantly.

Radial gate arms are generally slender steel structures, normally designed to withstand bending and buckling from water pressure only. Friction forces are often not taken into consideration, or nominal values of friction coefficient are used. Deterioration of the bearing surfaces lead to increased friction and thereby increased bending moment in the arms. This may cause failure of arms, either instantaneously or through fatigue. Cylindrical bearings with a manual lubrication system, combined with an automatic or remote operation of gate, can be most vulnerable for such disasters.

6.1.1.2 Arm design:- The critical areas of concern in the arms design are the transition zones especially in the vicinity of arms and hub connections. From the large cross-section & sturdy hub, the bending moments (due to trunnion bearing friction) are transferred to the slender gate arms. Moreover, in the transition zone between hub and arms, the stress concentration is especially high and the stress changes its nature (i.e. from positive to negative) whenever the gate movement changes its direction, thus exposing the transition zone to fatigue loadings.

6.1.1.3 Trunnion designs:- Trunnion designs may vary with respect to vulnerability of seizure of the trunnion bearing. In case of the cantilevered trunnion pin anchored to the abutment, symptoms of bearing seizure are difficult/ impossible to be detected by visual inspections. High friction moments can be transferred through the trunnion pin without visible indications of increased bearing friction /distress before the collapse occurs.

Also, the dismantling trunnion bearings of radial gate can not be executed routinely to access the condition of the bearing, except when the symptoms of bearing seizure are evident. However, on radial gates, total collapse may also occur without prior indications/ symptoms.

An increase in lifting force could be detected, however, the bearing friction constitutes only a small fraction (5-10 %) of the total lifting force on a typical radial gate especially with u/s lifting. Therefore, change in trunnion bearing friction can not be ascertained accurately by this method, because of the fact that other factors like seals, guides, etc may also affect the hoisting efforts significantly during the gate movements.

Therefore, instead of this, it will be of worth to measure the strain in the arms resulting from trunnion bearing friction during the gate movement. A technique has been developed to accomplish strain measurement even without dewatering the radial gates or dismantling the trunnion bearings. The method detects friction on the bearings during operation of the gate with the help of strain gauges attached to the gate arms. The mechanical stress variation is measured in the gate arm, near the trunnion bearing, using two strain gauges. One strain gauge is attached at the upper side of the gate arm, and another attached at the lower side of the gate arms. Each strain gauge measures the surface mechanical stress.

It has been revealed from actual measurements recorded on a radial gate, that the gate remaining stationary without maintenance or lubrication has a considerably higher coefficient of friction (Fig. 6.2) than expected values for the trunnion bearings. Also, inspections were carried out on the dismantled trunnion bearings of same radial gate, which revealed traces of seizure on the bronze bearing surfaces apart from seizure and corrosion on the surfaces of the cast carbon steel pin (Fig. 6.3). It was also evident that the manual lubrication system had not functioned as intended, partly due to clogged grease channels and partly due to the fact that the grease escapes from high-pressure side of the bearing.

6.1.2 Mrica Project:

6.1.2.1 General:-For seismic design purposes the gated structures can be classified based on their relative importance, and the consequence of a failure affecting the integrity of the dam. Measures should be taken to avoid permanent deformation in the most important structures. For quasi-static analysis, it is assumed that an increase in hydraulic pressure during the earthquake is influenced by the depth of the gate below the water surface relative to the depth of the reservoir.

6.1.2.2 Design considerations:-For ultimate state earthquake loading conditions, permissible stress for the design of structure can as high as yield strength of the material, although in the case of the radial gate arms, stresses should be limited to 1.35 times the normal permissible stress. For the normal load analysis, design stresses are multiplied by a coefficient to take into account the gate types, location, duty and maintenance access, as well as corrosion and other indeterminate forces. For the extreme load analysis, design stresses upto 0.80 of yield strength can be permitted, although the stresses should be limited to 1.25 times the normal permissible stresses for design of arms of radial gate. Similarly, for the safety of vertical lift gate installations, the wheel tracks can be designed & stiffened locally to sustain the combined wheel load of a closed gate being acted upon by the hydrostatic load plus earthquake loads.

In case of u/s sealing gates, ventilation of conduit d/s of gate can be affected naturally through the gate shaft, but at this project, the diversion intake gates had to remain operational with the intake structure fully submerged. Therefore, to meet the air demand, each gate shaft has a 1.5m wide and 18.5m high vent pipe mounted at deck level on a fabricated cover, which seals the gate shaft against reservoir water level.

The originally planned arrangement of attaching the piston rod of hydraulic hoist to the top of the gate was found to be unsafe under seismic conditions because of the larger unsupported length of the cylinder protruding above the deck level. Therefore, for safety of structure and the reliability of gate operation, the hoist cylinder was lowered to provide support at approximately its mid-height, thus reducing the unsupported upper length of cylinder. The lower portion of cylinder, which is being acted upon by the added forces induced at the maximum extended piston rod (i.e. closed position of gate), is also supported from the concrete structure to safe guard against the buckling (Fig.6.4& Fig.6.5). For accommodating the lower attachment point of the piston rod end, a lifting bracket was mounted on the d/s side of the gate. This eccentric lifting arrangement induces additional moments and the gated arrangement necessitates u/s guide wheels on the gate leaf for satisfactory performance (Fig. 6.4). The wheel rim as well track for intake vertical lift gates should be manufactured from corrosion resistance material in order to have reliable operation of such gate, which remains submerged continuously for a long time (Fig.6.5).

To ensure the continuos operation of both the diversion tunnels, the design of gated installations provides for supporting the gates on hydraulically operated spragging devices interlocked with the gate controls. This will relieve the hoist from loading during the most of the diversion period, because the gates will also remain fully open most of the times. This precaution will also ensures the tunnels to be remain operational in the event of an earthquake, even if the gate hoists are damaged.

6.1.2.3 Suggestions & recommendations:- It may also happens some times that a gated diversion arrangement or construction sluices provided for facilitating construction of dam/related hydraulic structure, have to used beyond their capabilities because of economic or the other reasons. To fulfill such requirement, it is possible that gate may have to be operated partially opened for a long period before the final closure of the diversion facilities takes place. In-depth evaluation of capability and likely problems resulting from such application must be considered before taking such actions.

A major consideration influencing the spillway radial gate design can be the possibility of a flood coinciding with a power failure, resulting in the gates to be overtopped by waterborne debris. To prevent such an occurrence, the d/s gantry crane beam can be designed to forms a breast wall u/s of each spillway radial gate having a nominal operating clearance (Fig. 6.8). The spillway radial gates can be guided between the piers wall plates by spring-loaded brackets located on the centerlines of the horizontal beams. The guide brackets are provided with low-friction slide contact pads, which bear against side, guide plates embedded into the pier walls. The spring washers are arranged in-groups to provide a light contact during normal operation, however capable of absorbing seismic-induced cross-stream shock loads. To accommodate the predicted pier settlement, the radial gates are to be mounted on plain self-aligning spherical bearings contained in sealed housings in the hub castings, this provisions shall ensure satisfactory operation of gate.

Also, it is desirable to have stoplog unit of higher height and fixed wheel type. This will help for lowering them in flowing water with a reasonable depth of water in case of emergency i.e. malfunctioning or failure of main gate. More over, the increased unit height will reduce their numbers, thus requiring the lesser storage facility (Fig. 6.5).

6.2 PLANNING, DESIGN & MANUFACTURING

6.2.1 Dashidaira Dam

6.4.0 General:-Sediment flushing from the reservoir deserves attention. However, many a times, bottom outlet/ river sluices provided for releases of water are being employed also for sediment flushing. The river flow, if containing considerable sediments can impair the functioning of such a combined arrangement of flow regulation & sediments flushing, and the gated arrangement is likely to be defeated to serve either of its purpose. Therefore, a full-fledged arrangement should be provided for the purposes of sediments flushing. Sediment flushing facilities at the Dashidaira Dam along the Kurobe River (Japan) is a noteworthy installation in this regard and is an example of full-scale gated sediment flushing facilities (Fig. 6.9). The design of sediment flushing facilities is based on hydraulic model result. The bottom surface and the sides are lined with steel plates to prevent abrasion.

6.2.1.2 Gated arrangement:-The gated arrangement consists of a slide gate in the u/s for maintenance and inspection, a fixed wheel gate in the middle for blocking water and sediment inflow, and a radial gate in the d/s for water cutoff and for any other emergency situations (Fig. 6.10). The gate slots of the slide gate are closed off by a protection frame to prevent from damages likely to be caused by sediment flow. A cover plate is also provided on the u/s face of the gate leaf to prevent sediment from flowing and accumulating into the main horizontal girders web sections.

Fixed wheel gate leaf is provided with legs which close off the gate groove while the gate is in fully open position. The legs are encased in a slot provided at the bottom of the housing when the gate is fully closed. The gate leaf is provided with a stainless steel skinplate on u/s side and the lower 2m portion of the skin plate is designed to be thicker. The bottom and rear sides of the gate leaf are also covered with steel plates. The rip section is made of replaceable stainless steel members. Rubber seal for water cutoff were not recommended because of expected damages likely to be resulted due to abrasions and impact of sediments during the flushing operations.

6.2.1.3 Seals & lining:- However, the radial gate is provided with u/s rubber seals on all the four sides. The rubber seal on the top and bottom are of flat bars and those on the sides are of J-type.

Supplementary 'antijet' rubber seal is also providing at the top to avoid emerging of water jets from the top, when the gate is being operated. The skin plate is made of stainless clad steel with the lower 2m portion having extra thickness as in case of the middle gate. The lower rip section of the skinplate is replaceable and is provided with thick stainless steel plate to minimize damages while blocking the water flow. Cover plates have been attached to the bottom surfaces of the gate leaf and radial arms for protection against the likely damages during the flushing operation.

Although, the entire flushing channel has been lined as per the requirement of locations (Fig. 6.11). However, a specially designed lining for the portion of conduit located u/s of the slide gate have been evolved because of its inaccessibility. The resistance of this portion against abrasion has been reinforced by using stainless clad steel on the upper part and high manganese steel on the lower portion of conduit. The traction apparatus is used to sweep sediments that enter into gate slots. The flushing channel gradient was designed to be steeper (1:30), in order to effectively discharge all those sediments that have entered in to the flushing channel.

6.2.2 Heavy Duty Spillway Gates in China

6.2.2.1 General:-Among gates made for overflow spillways in China, the largest cross-sectional area of a gate exceeds 400m^2, the highest design load exceeds 50,000 kN (5000t), and the heaviest weight of a gate exceeds 400t. For sluice gates the design head is 140m and the highest water thrust on a single gate is about 80,000kN (8000t). In Chinese practice, sluice radial gates are designed with its arm length to be 1.7 times the height of the gate; the trunnions are placed at a position 1.3 to 1.5 times the height of the gate, to avoid interference with the spilling water. For overflow spillways, radial gates often have shorter arm, equal to 1.2 times the gate height, and the gate hinges are generally arranged at 1/3 to 2/3 of the gate height, according to the flow profile.

An innovative layout of the gated arrangement for split-level gates is shown in Fig.6.12. The upper gate is vertical-lift type and the lower one is radial gate. This double-decker sluice gate was designed to take account of the high silt content of the river flow, the long service time (about 7 months a year), the need for under-flow energy dissipation, the frequent gate operation because of the small reservoir storage capacity, and the considerable seasonal variation in river flow. Pre-stressed anchorage has been used for the radial gate and these gates have operated about 4000-6000 times every year.

6.2.2.2 Eccentric trunnion radial gates:- For higher heads installations (exceeding 100m), it is difficult to find a suitable sealing material which can provide not only perfect water-tightness when the gate is closed, but also reduces the friction resistance during the operation of the gate so as to reduce the hoist capacity. The eccentric trunnions type radial gate can provide a satisfactory solution for such circumstances. With eccentric trunnions, different radii of rotation are provided. In the closed condition, the longer length of arms pushes the gate against its seal seat frame firmly and thus provides perfect water-tightness. During gate opening, the shorter length of arms separate the gate a little from the seal seat frame and thereby reduces the frictional resistance substantially during the gate movement.

A large radial gate, having a skinplate radius of 15m with eccentric trunnion arrangement was provided in the bottom outlet (Fig.6.13). The gate operates under a head of 119.5m and withstands a water thrust of 78,700kN (7870t). Eccentric trunnion was designed to produce a 60mm of eccentric displacement. For opening the gate, a rotary hydraulic hoist of 4,000 kN (400t) capacity first operates the eccentric mechanism and moves the gate backwards in its radial direction, thus forming a small gap between the gate and its seat frame; thereafter, a hydraulic hoist having a capacity of 3,000kN (300t) raises the gate.

6.2.2.3 Prestressed Anchorage:- With the development of heavy-duty radial gates, the design of the anchorage/ gate piers became an important consideration. The prestressed anchorages are adopted in order to withstand the heavy load. Earlier installations were designed with the full-prestressed anchorages. However, it was found that the full prestressing not only requires more steel cables and higher prestress values, but also causes harmful stress conditions in other directions of the piers under no load condition and therefore, to ensure safety of structures more reinforcements have to be provided. The shortcomings of full-prestressing method can be improved by the partial-prestressing method (Fig. 6.14). The design considerations for partial prestressing include the following:-

(i) Allowable tensile stress in the pier should be less than half the ultimate tensile strength of the concrete.

(ii) Cracks in concrete, if occur, should be limited to 0.1mm to 0.2mm in width.

(iii) The design should be checked for both the full load and no load conditions.

6.2.3 Reza Shah Dam

6.2.3.1 General:-The power intakes of Reza Shah Dam have unusual design (Fig.6.15& Fig.6.16). These deep intakes are equipped with radial gates (Fig.6.17) instead of the conventionally used vertical lift gates. Radial gate being simple has least machined parts i.e. only trunnion and moreover requires little maintenance. There is also no necessity of elaborate track plates, precisely machined and erected to the close tolerance for radial gate installations. However, a steel lined passageway. was required for providing direct access from one of the dam galleries to the gate and the hoist cylinder (Fig.6.17). The liner is designed to withstand the full external water pressure of the reservoir apart from a massive watertight steel door at the end of the passageway. The steel door swings out into the gate chamber such that it cannot be opened against the headwater pressure when the intake radial gate is open.

6.2.3.2 Design considerations:-The gate leaf was fabricated in four pieces and the radial arms were bolted together with the gate leaf in the gate chamber itself. No welding was used so that the gate can be dismantled and removed in the unlikely event of gate repairs or replacement. Also, being an unusual arrangement for the shaft intake, extensive model testing was required for predicting behavior of the prototype in respect of the following:-

(1) Effect of flow separation at the bottom edge of the gate during opening or closing. The separation could possibly lead to dynamic pulsation in the penstock.
(2) Effect of flow from the gate shaft during closure of the gate. The shaft empties through the gate arms, imposing an additional closing force on the gate.
(3) Flow pattern in the intake & around the gate, when the gate is in open position.
(4) Need for a flow guide in the form of screen attached to the bottom of the gate arms.
(5) Possibility of vortex formation at low reservoir level and its effects.
(6) Effect on the gate resulting from closure of the turbine wicket gates.

6.2.4 Alicura Project

6.2.4.1 General:-Bottom outlets (Fig. 6.18) of the project have a steel lined bellmouth for ensuring the smooth transition between the tunnel section and twin rectangular sluices. Each sluice has been provided with a guard gate and a regulating gate. The steel lined roof section of sluice is slightly converging between the two gates.

For limiting the hydrostatic load in case of higher head gate, sizes of the opening have to be limited. This has been accomplished by providing a tapered pier, which separates the sluices and gradually joins the two sluices to from a single conduit d/s of the regulating gates. Pier design, accuracy in construction, provision of lining and an air vent groove at the end of the steel lining are important factors/ considerations for ensuring satisfactory operation of such installations.

The sliding type vertical lift gates operated by hydraulic hoists are provided to with stand a maximum head of 118m. The u/s guard gates are normally open and are used mainly to facilitate maintenance of the regulating gates. However, in case the regulating gate is not operational, the guard gates are also capable of regulating the flow.

6.2.4.2 Steel linings:- Special attention must be given to erosion by cavitation for high head outlets, to avoid premature damages. Therefore, u/s of the guard gates (3m portion) the steel lining for the sluice is designed as the self-resisting type, as are the gate housing i.e. bonnet. d/s of the regulating gate, a length of 1.5m is lined with stainless steel plate to avoid cavitation damages. The steel lining ends at a ventilation groove. The function of the groove is to admit air around the conduit walls and floor to eliminate the possibility of concrete erosion near the junction.

Special care has been taken to eliminate all surface defects, especially, those perpendicular to the flow direction. Therefore, all the weld projections have to been carefully grounded to meet the stringent requirement of smooth surfaces. The maximum size of acceptable local defects (cavity or protuberance) is shown in Table 6.1.

Table- 6.1: Design specifications for tolerance of local defects

Section of Structure	Acceptable Defect Size (mm)
Bell-mouth	≤ 2
Conduits u/s of guard gates	≤1
From u/s of guard gates to pier end	≤ 0.5
From pier end to ventilation groove	≤ 1

6.2.4.3 Gate leaf:- Each gate-leaf is connected to its operating hydraulic cylinder rod by a two-part nut screwed to the rod end, because such design of connections allow clearance-free transfer of loads between cylinder rod and gate leaf. Also, each gate leaf slide into the slots with a very small lateral clearance (about 1mm) to avoid the gate leaf being inclined when its bottom touches the sill, and also to ensure the desired water tightness.

6.2.4.4 Embedded parts:- The straightness and flattening of the embedded track/seal plate must be such that when the gate leaf is placed against them, the maximum measured clearance does not exceeds 0.05mm, because, these parts also ensure water-tightness of gated installation apart from bearing the water thrust. It has been observed that clearances over 0.05mm, under a head of about 100m, may result in unacceptable leakages. Therefore, the track plates were machined on site with the same degree of accuracy as of gate leaf shop machining. The flatness and straightness of embedded parts help to reduce the hoist capacity considerably in addition, they guarantee a long service life of the installation.

6.2.4.5 Sealing:-Water-tightness for the regulating gates is ensured at the top (lintel) and on the vertical sides by a perfect contact between the sliding surfaces. For the guard gates, the contact between the sliding parts on vertical sides and an u/s rubber seal at the top ensure the desired water-tightness. Water tightness between the gate-lip and the sill is achieved by the compression of an adiprene rubber seal in both of the gates.

6.2.4.6 Auxiliary isolating gates:- In this project, an innovative scheme has been evolved for maintenance of guard gate i.e. an auxiliary gate made of stainless steel and operated by a manually controlled screw mechanisms. This auxiliary gate is located perpendicularly to sliding plane of the guard gate and is supported by bronze sliding flat bars. The balance head operation of this gate is achieved by crack opening and thereby filling the upper portion of bonnet. However, this gate can be dismantled for maintenance purposes by closing the u/s sealing guard gate.

6.3 ECONOMICS

6.3.1 Itaipu-Diversion Gate

6.3.1.1 General:-The arrangement of gated installations is simplified by adopting a few gate of large size for closing the waterway as compared to arrangement of small size gates in large numbers. In addition, selection of large size gate also reduces the possibilities of floating matters obstructing a sluice. Therefore, after a worldwide analysis of existing large size gates, the maximum practical (of course unusual) gate size of 6.7m wide and 22m high, vertical lift fixed wheel type gates were selected for the diversion arrangement (Fig.6.19) Each gate is designed to withstand a maximum static water head of 140m. However, the flow velocities have been limited to 15m/s to safe guard against the cavitation / abrasion damages. In order to restrict cavitation damage in the sluice, steel lining was recommended for the portion of 2.2m u/s & 2.4m d/s of the gate centerline apart from the gate slot area.

In the initial scheme, the diversion gates were to be used only for diversion, and have to be left in place after final closure and the placement of the permanent concrete plugs in the diversion tunnels. However, later on, it was realized that substantial savings could be made if the gates were recuperated and subsequently used in the power intakes. The hydraulic hoists needed to actuate the intake gates could also be used to raise and lower the diversion gates. Therefore, providing a far safer and more flexible system of operation than offered by the conventionally used rope drum hoist. Also, some of the gate design features and quality controls used in manufacture and testing of the gates possibly could not have been justified had they been designed only as disposable diversion gates, rather than eventual permanent intake gates. Because of this innovative scheme, the diversion gates were safer and more reliable without incurring any additional cost.

6.3.1.2 Gate leaf design:- The Model studies indicated a negative pressure region on the u/s sloping section of the initial design of gate bottom, because of separation of flow at low tail water levels. Therefore, the gate profile was modified to eliminate this flow separation, a potential source of gate vibration. Also, the skinplate of the lower section of the gate was relocated on the u/s face, thus reducing the hydraulic downpull. It was not practical for such a large gate, to design the wheel to withstand water load imposed under the head of 140m. Therefore, elastic pad supports were considered for the wheels (Fig. 6.22).

The flow in the conduit d/s of a partially opened gate was also observed to be highly unstable and agitated when the down-stream level was high enough to drown the jet issuing from the gate underside. Therefore, tests were conducted to investigate and thereby eliminate the possibilities of resonance in both the diversion and intake gate application. The adopted geometry of the sluices, eliminated the necessity for a separate airvent at the d/s of the gates, because sufficient air was naturally supplied to the d/s face of the gate at all gate openings. The improvised gate slot design eliminated the possibility of bed load materials accumulating in the gate slots.

6.3.1.3 Guides and rolling surface:- The gate was designed such that the turbulence forces around the gate slots could not affect/damage the gate when lying in the standby position for closures. Also, a separate guiding arrangement for the gate was evolved for the opening portion, so as to exclude any possibilities of gate jamming. The design of the gate rolling and sealing components required close tolerances for the respective embedded parts. The combined rolling & bearing plate had to be erected with a tolerance of ±2 over the entire height of the opening and +2mm across the span of the sluices. Surface tolerances of ±0.5mm and ±1 mm were required over the entire length of the lintel (top seal beam) and bottom seal respectively.

6.3.1.4 Gate leaf Structure:- A general arrangement of the diversion gate is shown in Fig.6.20c. The gate was designed as a flexible structure such that each element could adjust itself to the embedded parts during closure of gate, for the two modes of transfer of water load to the civil structure, i.e. i) purely through the wheels and ii) through a combination of wheel & bearing beam (after compression of the elastic pads of wheel).

By making the gate flexible in both directions (u/s & d/s), loading of the embedded parts could be made relatively uniform. This consideration resulted in a gate constructed of ten separate panels. The upper nine panels with d/s skinplate were each of 2050mm high & weighing 294kN (29.4t). For stability of gate structure, the lower panel was planned to be 4050mm high, weighing 657kN (65.7t). Further, in order to reduce the downpull forces, the skinplate was located on u/s side for the lower panel. Individual panels were joined by two sets of bolted flanged connections, consisting of pre-stressed high tensile strength bolts. The inter panel joints were sealed by J-type rubber seals. Stringent quality controls were observed during the manufacturing of high tensile strength bolts to avoid any possibility of failure by stress corrosion cracking, which is common phenomena for such flexible flanged joint-connections. Retaining bolts for the seals were made from cadmium-plated carbon steel because of temporary requirement and later on these bolts have to be replaced by stainless steel bolts for use in the intake gate.

Designing the diversion gate wheels and supports to withstand the maximum head of 140m was absolutely impossible due to practical limitations, as was designing the gate operating mechanism to raise the gate under this head. Therefore, an improvised arrangement was evolved in which the hydrostatic force to be shared by the wheels would be limited corresponding to a certain water head consistent with the requirement to operate the gates under an acceptable differential head. The arrangement is shown in Fig. 6.21 & Fig. 6.22, it was planned to mount the wheels on elastic pads which would start to compress at a differential head of 30m. At a differential head of 45m, the deformation of elastic pad would be enough to permit the gate bearing beam to come into contact with the embedded parts and thereby, further increase in hydrostatic loading will not allow the gates to be reopened. Each wheel was manufactured from forged steel (hardened and tempered) and were mounted on a forged stainless steel (AISI 410) 140mm-diameter pin, equipped with two roller bearings packed with grease and sealed for protection against the ingress of foreign materials. The wheels outer surfaces were given suitable crowning to avoid the stress concentrations.

6.3.4 Gate operating mechanisms:- The total height of the diversion gate was 23.91m, and that of the intake gate was only 16.0m. Therefore, to facilitate manufacture and to re-use as much equipment as possible for the intake, two hydraulic hoists with a stroke length of 16.07m and 7.84m were manufactured. Both of these two hoists connected in series were used for the operation of diversion gate (Fig.6.20a). Hydraulic hoist with a stroke length of 16.07m shall be used in the intake after recuperation.

6.3.1.6 Conclusions & recommendations:- Pre-tensioning of high strength bolts may result in failure caused by hydrogen embrittlement & stress corrosion cracking which began at a small defects in the root of the thread. The electrolytic effects and thereby corrosion can be aggravated by the galvanizing, therefore, the bolts were not galvanized, however were painted and the maximum hardness was limited to 330HV.

For successful closure of diversion, three independent systems were used to observe the true position of the diversion gate. One was cable system attached to the gate and connected to a rotary dial, giving a continuous indication of the gate position to an accuracy of 10mm. The second was piano wire attached to the gate which, using a pulley and weight, gave the gate position at final closure to an accuracy of 1mm. In addition to this, final closure could be confirmed by an observer lowered into the gate slot, using a mark on the highest gate panel, which corresponded to a mark on the concrete.

CHAPTER-7

CONCLUSIONS AND RECOMMENDATIONS

7.1 SIESMIC & FLOOD OVERLOADING

7.1.1 Seismic:- The gated structures designed without contemplating seismic effect are vulnerable to extreme earthquakes. In addition, the gated structure designed with consideration of only static effect of seismic forces may not be capable of resisting the most dangerous dynamic forces during the earthquake. The damages to the gated structure can take place as result of the arching action of the stiffened skinplate and by buckling of radial arms. The most vulnerable component of gated structure in respect of safety and reliability of operation are radial arms and the trunnion. The radial arms being slender may initiate failure, where as misalignment of trunnion can effect the operability of gate.

The trunnion of radial gate can be designed to have self-aligning bearings for reliability of operation. The design of arms and anchorage should be conservative. Also, during transverse moment (i.e. in cross-stream direction) and possible displacement of piers, the radial gate may become wedged or suffer local buckling due to close tolerances between gate leaf & piers. Therefore, it is recommended that in order to counter the effect of cross-stream horizontal forces, the side seal arrangement may be designed such that it will deflect or buckle under severe impact. Similarly for ensuring the safety of vertical lift gate against the seismic forces spring loaded guide wheel capable of absorbing shocks may be provided to counter the horizontal accelerations.

The bottom outlets, irrigation and power intake gates may not suffer damages, can sustain earthquake forces of much higher magnitudes than the spillway/surface gate. Moreover, the bottom outlets are generally provided with vertical lift gates, which are restrained in both directions comparably better than the radial gates. Also, sealing surfaces (especially rubber seals) of vertical lift gate are arranged such that these act as insulator and dampen the shocks to some extent during the earthquake. Moreover, because of their deep locations, the magnitude of static load is higher than the more dangerous dynamic loads.

From the analysis of this gated installation, it can be concluded that sturdy & conservative design of spillway gate in always preferable. Self-aligning bearings, quality and tested material/ components can withstand to certain extent, the unusual/ unpredictable hydrodynamic loading resulting from earthquake or other extreme loading.

7.1.2 Flood:- It is concluded that during the overtopping of gate, the forces exerted on radial arms shall be significant and therefore, should be considered for the design of radial gate arms and their connections along with the hydrostatic loading. It is suggested that such force / load due to the maximum possible overflow depth should be considered in design. However, such loads can be avoided if gate arms are suitably protected from overfalling jet by an arrangement of side shields/deflectors etc.

7.2 HYDRODYNAMIC FORCES & VIBRATIONS

The vibrations are induced as a result of negative hydrodynamic damping, unstable flow separation around the gate and the poor configuration of bottom lip of the gate.

The gate designs should be such, which can avoided the self-excited vibrations. The dominant excitation frequencies should be kept away from resonance. The magnitude of random vibration should also be evaluated for the important installations. The performance of high head and large sized gates should be observed with the help of the mathematical & physical models to ensure safety of structure as well satisfactory performance of gated installations.

Vibrations in the gated installations are generally induced due to leakage of gate seal, poor configuration of bottom lip to induce flow instability layer, complicated flow pattern u/s and d/s of the gate, and the turbulence beneath the boundary layer (small gate openings).

The following measures can be adopted to prevent or eliminate the gate vibrations:-

i) Optimize the gate leaf configuration and streamline the flow pattern nearby the gate thus providing an excellent boundary condition for satisfactory operation.

ii) Check the strength and stiffness of the gate structure thereby obtaining the natural frequency of the gate, which is preferable to be kept far away from the resonance frequency of the dynamic force of the flow thus eliminating flow-induced vibration.

iii) Improve the seal arrangement thereby leaving out one of the genesis causing gate vibration. The provision of two rows of top rubber seal on the gate leaf reduces the water leakage as well as damaging effect of issuing water jets. The said measure is very effective in smooth functioning of gates.

iv) Provide a sound and reasonable planning, design, fabrication, installation and maintenance, thus guaranteeing the quality of the gate.

v) Adopt hydraulic hoist for high head gate, thereby providing dampening effect against the vibration during gate operation especially at partial opening.

vi) Arrange an excellent mode and sequence of operation, thus yielding smooth and promising functioning of gate.

vi) Slide gates should not be used for prolonged operation at gate openings less than 75mm or 50% of thickness of gate bottoms whichever is more. In the case of regulating gates, it must be ensured that the sealing surfaces are effective in maintaining the water tightness throughout gate travel in order to avoid vertical water jets which is likely to induce vibrations and cavitation damages. When there is a finite seal width across the bottom of the gate leaf, there will be a gate opening below which cavitation will occur between the gate seal and the floor of the waterway due to the short tube phenomenon. This opening will be about one-half the seal width for free discharge, however, when the flow is submerged, the critical opening may be somewhat larger.

vii) If u/s seal gates are to be used for crack opening for filling the conduit for balance head operation of the gate, care should be taken to provide wider clearance between the d/s side of gate and the gate shaft. Also, a slow rate of penstock/ conduit filling is recommended so that adequate time is available for water pressures to balance on top and bottom of gate, so as to avoid the uplift exceeding the net downward forces (i.e. gate weight, frictional forces etc.). However, it is preferable to provide bypass-filling systems to avoid the catapultation of gate.

It has been observed by hydraulic/ mathematical model, that significant hydrodynamic forces act on the gate leaf when the flow is suddenly interrupted by it. The magnitude of hydrodynamic force depends upon the height from which the gate fall (i.e. velocity of falling gate). These forces are several time of the static loading, therefore these can result in severe damages to gated structure as also to the surrounding civil structures.

Some of the gates are handled by means of gantry cranes & lifting beam/blocks, with the help of the hooks attached to the gates or lifting tackle. In case of malfunction of the system of automatic devices and signaling system, unsafe positioning of the hook on the pin or latches may occur, with the result that the gate may slip past the support and fall swiftly on its sill. Such accidents may induce substantial hydrodynamic forces on the gated structure and surrounding civil structure. The hydrodynamic impact loading, which may several times not only the normal load, but also the ultimate strength of the civil structure and gate structure.

Therefore, handling of the gates by such means at the important hydraulic structures, whose failure can leads to disaster, may be allowed, provided that the highly reliable construction of the hooks/pin connections intended to prevent the gates from falling have been incorporated in the hoisting arrangement.

For vertical lip gate leaf, it is preferable to have u/s skin plate and the d/s flange of the bottom horizontal beam of the gate leaf should be kept about 0.6 times the beam depth above the gate leaf bottom. This provision will prevent the water jet hitting the bottom horizontal beam during partial opening of the gate. Provision should be made for openings in the web of the bottom horizontal beam of the gate leaf to allow air to be admitted to the space under the beam. A lip angle of about 20-25^0 can be adopted for long-span gates. For narrow spans end vertical girder and gate slots should be designed to eliminate the cross-flow and other undesirable flow patterns induced by slots.

Radial gates should not be considered for such installations where the conduit d/s of gate could ever flow full. Whenever the conduit d/s of gate flows full, excessive vibrations will be experienced due to water circulation in the gate chamber, around the raised gate, arms, etc. Moreover, compared to other types of gates, radial gates will also require much care and greater amount of air supply for satisfactory performance. Reservoir water pressure can be used to affect the sealing during the fully closed position of gate, in case pressure seals are provided. This type of seal arrangement can be adopted provided that water is not silty.. Another arrangement for radial gate for achieving satisfactory sealing for extreme high head applications consists of a hydraulic cylinder and a cam/eccentric system to force tight sealing of the closed gate. In the above sealing arrangement the seal are retracted before the gate is moved in order to reduce the hoisting effort as well damages to the seals during the gate movement

Radial gates are more suitable for such installations, where the gate leaf will not be drowned usually. Channels and culverts especially where tail water is high should be provided with vertical lift gates for regulation of discharges. Overshot gates such as weirs and tilting gates are normally provided to maintain a predetermined water level. Bonneted type vertical lift gates are used to close-off tunnels on high head installations. Where gates are counterweighted means should be provide for trimming ballast to attain the correct weight. Rigging screws should be provided at the connections of gate to lifting ropes to allow independent adjustment. To assist in the prevention of radial gates vibration, the angle between the sill and the gate skinplate should be designed as large as possible. Sufficient aeration to prevent gate vibration should be provided at tunnel closure gates and overshot weirs.

7.3 AERATION & CAVITATION

The following measures shall helpful in eliminating/ reducing the problems relating to cavitation: -

i) Streamline the gate slots for vertical lift type slide and wheeled gates. The width of conduit at the d/s corner of the gate slot is wider than at the u/s corner. A transition usually of 1:12 slope is provided from the d/s corner of the gate slot to the conduit normal width for water heads up to about 30m and for higher head a slope of 1:24 or flatter may prove to provide better protection against the cavitation damages.

ii) A flat bottom gate leaf is prone to cavitation and must be avoided. A 45^0 slopping bottom is recommended for slide and fixed-wheel gates with d/s skin plate. Wherever practical sharp vertical bottom with a rectangular bottom seal strip at the d/s side of the gate leaf should be preferred.

iv) Provide mild steel or stainless steel lining in the gate slots including the d/s corner. This is advisable under high-velocity flows to avoid erosion and cavitation damage within the gate slots and d/s of the slots. The conduit d/s of the gate leaf should be smooth without offsets and protrusions. Any offsets and protrusions should be ground smooth to a suitable slope depending on the velocity of flow.

v) Adequate aeration should be provided in the vicinity of the gate leaf /slots, embedded frame, and in the conduit d/s of the gate leaf. The size of air vent and extent of aeration should be in accordance with accepted practices or model study results. Ensure that the inlets of air vents remain free at all times without submergence or obstructions by water jets issuing from the gate.

The air vents should be preferably separate and independent of gate shafts. Hydraulic model studies may be essentially in some cases for high head gates installations to predict the behaviors of prototype under specific conditions.

Low pressures just d/s of the slots with parallel inline u/s and d/s walls make this design susceptible to cavitation. The pressures are much below the reference pressure at the d/s face of the leaf, and further decrease as the W/D increases. This type of design serves satisfactorily for head less than about 10-12m. A critically designed small deflector at the u/s of slots may give satisfactory pressure conditions. The slots with offset d/s corners and converging walls (having variable rate of convergence & rounded intersection) will be free from cavitation, therefore, such configuration may be adopted for the existing parallel inline slots operating under relatively high heads installations.

It was established that the vertical flow while turning through a right-angled bend at the tunnel result in low pressures at the conduit roof and thereby cavitation damages. The irregularities and projections on the concrete surfaces also promote cavitation erosion of the concrete. Location of trunnion should be at relatively higher position.

The size and location of the air vents / ducts must be determined so as to provide the maximum possible aeration of the flow in the bottom outlets. Sufficient aeration of the flow reduces the cavitation effects of high velocity flows considerably. The ventilation galleries must be situated such that water does not enter them. Provide well-designed air vent and air entertainment device, thus preventing or eliminating the cavitation and noise as well as vibrations.

7.4 PLANNING & DESIGN

Radial gate arms are generally designed to withstand bending moments resulting from the nominal friction on the trunnion bearings, but from experiences, it could be concluded that the lack of lubrication and years of deterioration lead to increased friction and even seizure of the bearings. The excessive bending moments produced by the increased bearing friction could be beyond the capacity gate arms, thereby resulting in collapse of gate structure. Moreover, the trunnion bearings of radial gate remain static with relatively a small movement only during operation. Therefore, lubricant, when applied externally, cannot be distributed on the high-pressure side of the bearing. Even when applied under pressure to the trunnion bearing, the lubricant often finds its way to the low-pressure side, leaving the high-pressure load transformation zone without lubricant. The self-lubricating type bearing & stainless steal should be adopted for safety against such eventuality.

A major consideration influencing the spillway radial gate design can be the possibility of a flood coinciding with a power failure, resulting in the gates to be overtopped by waterborne debris. To prevent such an occurrence, the d/s gantry crane beam can be designed to forms a breast wall u/s of each spillway radial gate having a nominal operating clearance. The spillway radial gates can be guided between the piers wall plates by spring-loaded brackets located on the centerlines of the horizontal beams. The guide brackets provided with low-friction slide contact pads are also capable of absorbing seismic-induced cross-stream shock loads. To accommodate the predicted pier settlement, the radial gates are to be mounted on self-aligning bearings contained in sealed housings in the hub castings, this provisions shall ensure satisfactory operation of gate.

Also, it is desirable to have stoplog unit of higher height and fixed wheel type. This will help in saving a reasonable depth of water in case of emergency i.e. malfunctioning or failure of main gate. More over, the increased unit height will reduce their numbers, thus requiring the lesser storage facility.

Sediment flushing from the reservoir deserves attention. However, many a times, bottom outlet/ river sluices provided for releases of water are being employed also for sediment flushing. The river flow, if containing considerable sediments can impair the functioning of such a combined arrangement of flow regulation & sediments flushing, and the gated arrangement is likely to be defeated to serve either of its purpose. Therefore, a full-fledged arrangement should be provided for the purposes of sediments flushing. The design of sediment flushing facilities is based on hydraulic model result. The bottom surface and the sides are lined with steel plates to prevent abrasion.

For heavy-duty radial gates, the requirement of the prestressed anchorage/ gate piers is desirable/necessary. The partial prestressing instead of the full-prestressed anchorages should be adopted to reduce the harmful stresses under no load condition as also to reduce the reinforcement requirement.

An auxiliary gate (located perpendicularly to sliding plane of the u/s sealing guard gate) made of stainless steel and operated by a manually controlled screw mechanisms may provided for maintenance of guard gate in case of high head installations.

Pre-tensioning of high strength bolts may result in failure caused by hydrogen embrittlement & stress corrosion cracking which began at a small defects in the root of the thread. The electrolytic effects and thereby corrosion can be aggravated by the galvanizing, therefore, such bolts should not be galvanized and for safety their hardness can be limited.

Stainless steel can suffer from stress corrosion and pitting corrosion in case its surfaces not maintained properly. Therefore, it is recommended for safety of the system that the stainless surface should be kept clean to avoid pitting corrosions. Also, the geometrical shapes should eliminate/ reduce the possibility of stress concentration. The critical components of the gates should be tested ultrasonically to detect any hair cracks/discontinuity of material. Permanent approaches to the critical location should also be provided for carrying out regular inspection to avert eventuality/malfunctioning.

While carrying out modifications, it should be ensured that it should not contribute to the increase in the stresses of the components. The increased play /clearances in the bearings resulting from normal wear & tear can cause abnormal rise in stresses in the components.

Adequate factor of safety stress concentration resulting due to geometric shape in the critical region have to be adopted for safety The improved geometrical shape which eliminate or reduce the stress concentration should be adopted. By adopting such measures, it is also possible to reduce the induced stresses in the critical region of the existing components. Inter-crystalline corrosion can be eliminated by machining the existing components for ensuring the safety against the progressive failure initiating from the cracks is therefore can be a remedial measures.

The large cross-section, wooden and other poor quality rubber seals should not be used for gates as these result in the leakage apart from gate vibrations. The highs grade rubber or Neoprene seals and specially moulded corner seals should be adopted for safety as also satisfactory performance. Only machined & stainless steel seats should be fixed on the embedded gate frame, while ensuring a requisite pre-compression of all seals when the gate is closed. Seals between the top and bottom tier of multi tier gate should also be provided. Provisions of guide rollers with proper clearances to minimize lateral movement of the gates are other features desired for satisfactory performance of gated structure.

It was recommended that the sharp bottom lip design should be used for avoiding hydraulic vibration problems. Also ensures a positive clamping force on the rubber seal to avoid vibrations. Adopted shape of the side/top seal should provide greater flexibility to take care of probable gap resulting from construction inaccuracies, gate skewness, temperature shrinkage and expansion of gate, and normal structural deformation. Consideration should also be given to provide bottom rubber seal in the embedded sill bearing plate, however such seals will be more difficult to maintain than gate-mounted seals. Gates lip aeration helps in dampening the pressure fluctuation under the gate therefore can be considered as measures to eliminate / reduce gate vibrations.

By using a similar type of sill shape performing satisfactorily at one installation can not guarantee satisfactory functioning at another installations if the operating conditions and equipment details differs. The sill shape should avoid reattachment of the issuing jet with the gate bottom. The extremely small openings are liable to vibration, therefore gate operation in such ranges should be avoided for safety. The sill shape should be capable of gradually changing the direction of flow to avoid possibility of occurrence of negative pressures near the gate sill was reduced. By adopting such measures satisfactory performance of gates can be achieved.

The arrangement of bottom sills, which are likely to be seriously affected due to their strategic location and should be carefully designed. Water jet issuing below the gate bottom will result in low pressure and thereby ripping / squeezing out of flexible rubber seal from its fixture apart from damages to the surrounding concrete.

The over flexible /small bulb or hollow bulb seal assembly, when subjected high head, had a tendency to get laterally displaced under the water pressure. Therefore sealing arrangement should have adequate thickness of clamp plates & size of holding screws, so as to clamping the rubber seals with sufficient force. Such arrangement shall prevent lateral displacement by virtue of increased friction between the rubber seal and seal base. The sharp edges of clamp plate & embedded seal seats should be grounded to avoid damages to rubber seal during gate movement.

In addition, the corner seals are gneiss of a number of problem, therefore, should be designed with due care. Planning of sealing surfaces and design of seal fixtures should be such that these shall avoid the undue stressing of flexible rubber seals.

The cause of the concrete failure in the gate slot can be its inadequate strength to bear the imposed loads as also the poor design of embedments of gate frame. The loading capacity of the concrete can be achieved by providing higher-grade strength concrete. Sufficient edge distances of bearing tracks should be kept to avoid concrete failure.

The inadequate free board over the gates may result in exposure of top main horizontal girder and other d/s members to continued wetness and development of undesirable lateral forces besides rusting and pitting of gate members.

It has been observed that the antifriction bearing are effected by deposition of silt and clay inside the bearing The seals of wheel assembly should be correctly oriented to avoid entry of foreign materials so as to have satisfactory performance.

For safety of the gated installations, it is desired to have the gate bottom a little above the top of conduit when the gate is in fully open position in order to avoid reattachment of flow to the bottom of the gate during fully open condition of gate. The slope in the top (i.e. roof) of conduit should be provided u/s of gate slot. The excessive slack in gate components such as guide wheel hoist links etc should be avoided for safety against vibrations. Where clearance between gate leaf & embedded parts are unavoidable, it is desired that the component be preloaded. The pre-loading arrangement for guide wheel of a gate leaf can be provided if clearances or slackness is unavoidable.

Length of the radial arms also should be adequate so as to avoid water splashes on the trunnion assembly. Adequate factor of safety in designs, protection & use of corrosion resistance material should be recommended for all the machined components of the hoisting arrangement because these are subjected to constant water splashes apart from the dynamic loads due to vibration etc.

For more reliable operation and reduction of leakage it is desirable that the rubber seals of the gates be pressed against their seating mechanically rather than relaying on the water pressure. In the trunnions, it is expedient to use anti-friction bearings instead of the sliding bearings.

The structural design of gate leaf & radial arms should be conservative. The rigidity & stiffness of the gateleaf shall prevent the formation of an eccentricity between the skinplate center of rotation and the trunnion pin center and therefore will reduce the occurrence of coupled mode of vibrations apart from withstanding overloading. Therefore, the conservative design will ensure safety and reliability of gated installations. The trunnion bearing should also be designed with adequate care. Self- aligning & self-lubricating bearing alongwith provision of corrosion resistance stainless steel pin can be made for ascertaining the safety & reliability.

The provisions for isolating the service gate by mean of an emergency gate /bulkhead or stoplog units must be invariably made in the original planning and design of the project. The regular maintenance and inspection is also one of the major factor in ensuring safety & reliability of gated installations.

By increasing the submergence of intake inlet as much as practicable can prevent the air entrapment problems. Increased submergence also decreases the strength of air entraining vortices apart from reducing the movement of debris towards trashracks. Air traps and vent shaft should be constructed at appropriate location to let out the trapped air so as to ensure satisfactory performance and the safety of gated structure.

7.5 FABRICATION & ERECTION

While planning the fabrication activities of the gate, the vertical joints should not be located at the centre of gate, instead these should be planned at the least possible bending moment location. Also splice joints should be suitably staggered.

A well-established quality control and assurance programme for carrying out inspection during fabrication, erection and testing should be formulated. There is an urgent need for third party inspection during these stages.

The provision of suitably designed dowel bars between different stages of concrete is essential for safety and performance of the structure. Adequate grouting measures should be provided for concreting behind the steel liners in order to grout any hollows that might be created during concreting operation or subsequent shrinkage.

The shape of the gate leaf, embedded parts and concrete surfaces (in the proximity of gate leaf) should be designed carefully. Especially, the design of protruding gate leaf parts and their clearances from the concrete structure & embedded parts faces should be such that may not obstruct gate movement. These factors are crucial for satisfactory operation of gated installations.

The existing gate leaves of bow type girders should be replaced by gates with plate girders in order to reduce corrosion & maintenance problems. The provision of gunmetal bushes in roller train assemblies should be replaced by self-lubricating bushes to reduce the maintenance requirement of the rollers and to avoid frequent jamming.

The arrangement having gates installed in a deep shaft require the erection of embedded parts over a considerable length and achieving perfect alignment for satisfactory operation of gate may be difficult. Moreover, in case of a gate suspended by means of long flexible link may result in vibrations whenever the gate is lowered in the flowing water. Therefore, it is preferable to adopt the bonneted arrangement for higher head installations.

The wider/ larger clearance between the gateleaf & embedded parts (guide wheel & side plate) may be responsible for frequent jamming of the gates. Therefore, it is required that the embedded parts be correctly aligned to reduce the clearances. Adequate number of guide wheels should also be provided to counter the tendency of gate tilting. The hoist controls should be modified to improve their quick response to any tilt of the gate.

In order to reduces the thermal expansion of gate leaf because of high atmospheric temperature during daytime, it is desired to apply silver finish paint over the black paint on the exposed surfaces of the gate leaf.

The model test has indicated that the embedded parts/ gate leaf parts lying in the slot are subjected to considerable hydraulic forces. These forces tend to lift the embedded parts from their fixtures. Therefore, the track should be hold properly with the embedded frame.

7.6 SILTING

Slides and fixed-wheel gates with d/s seals are susceptible to silting or sediment accumulation in the gate slots, especially if the gates remain closed for prolonged periods. Therefore, the arrangement of slide and fixed-wheel gates with d/s seal should not be recommended in any circumstances for bottom outlets having silt laden flow and especially when these gates not to be operated frequently.

Details of seal assembly should be carefully designed and provided on the u/s side of gate leaf and to prevent clogging by silt. Also, the provisions to force the compressed air or water jets into the gate slots at various elevations and locations should be made to help for removing the accumulated silts in the gate slots. Another silt-proof design feature with u/s sealing gates is to taper the d/s face of the gate slot at an angle of 45^0 or flatter, for a height of about 300mm from the gate sill to prevent silt, stones, and debris from accumulating within the gate slots. Hydraulic hoists of adequate capacity can be recommended to exert positive thrusts and pulls to overcome clogging due to silt and consequent increased frictional forces. For silt-proofing of gated installations, provision of silt seals along the vertical face of the gate slots to prevent silt entry can be made apart from providing cover plates on gates leaf to prevent silt accumulation on the girders/ beams, and silt seals on wheel assemblies. Forced lowering of gates having hard and sharp bottom has also been used to combat the problem of accumulation of silt and debris in the slot/ on the sill. Use of gates on the u/s face of the dam for bottom outlets should be avoided, unless the gates are intended as guard gates only. These gates should be normally kept in their fully open positions, provided that no possibility exists of bed load sediment accumulation on the gate sill. Maintenance must be ensured and the gates should be exercised regularly. The provisions of slot covers, which can be lowered in the gate slot whenever the gate is opened, may also prove to be useful for some installations.

Also, whenever an emergency gate is to be installed on the u/s face of an intake, airvent at highest point of the roof of the entrance immediately d/s of the gate should be provided to release the entrapped air. Otherwise, during the filling operation (to achieve balanced head condition for operation of the emergency gate), the air accumulated near the top of the entrance get compressed. Thereafter, the entrapped air may expand suddenly, thus hitting the gate with a heavy impact, which can result in damages to the gate and the neighboring structures.

7.7 CONCRETE DETERIORATION

The modifications/rehabilitation of spillway radial gates should be carried out in such manner that should be a long-term solution, apart from taking care of vibrations, overloading hoist component became of jamming misalignment etc.

7.8 OPERATION & MAIMTEANCE

Corrosion of structural members of all components of hydromechanical structures should be protected with suitable paintings and must be maintained in good condition. Lubrication of machinery components should be attended regularly. Lubrication of trunnion bearings is a very critical item. Lack of tightness of bolts can pose serious vibrations and malfunctioning of gates.

Overtopping of gates should be suitably protected. It can lead to vibrations and corrosion in the gate structure. Bonnet covers can adopted if overtopping is unavoidable.

Provision of stoplogs & walkways/platforms to inspection and maintenance requirement gates should be made. The sealing arrangement for spherical roller bearing of wheel assemblies should be designed and maintained with extreme care. Any slip up can result in jamming of wheels and hence non-operation of gate.

Reasons for non-closure of the gates can be insufficient gate buoyant weight; excessive wheel / slide and seal frictions; misalignment of gate guides and frames; tilting and jamming of the gates; and physical obstruction in the gate slots or on sill. Non-closure of gates can sometimes be due to hydraulic uplift forces that can occur at some particular gate openings. Problems of non-closure are usually encountered with rope drum hoists operated fixed-wheel gates having u/s sealing. Such arrangement is provided generally at inlet to penstock and power tunnels. For gate leaf closing under gravity, care should be taken to ensure that the frictional forces are computed conservatively and the net downward force always exceed frictional forces by at least 20 to 30%.

Frequent maintenance & inspection of the gated structures be carried out, also all the clearances critical for gate operation be checked & rectified in order to ascertain safety as well reliability. In case of gate operated by chain/ rope hoist, the position indicator capable of monitoring the actual position of gate leaf during operation should be installed on the installations.

The operation of the bottom outlets should be carried out regularly in order to ensure the reliability as also for removing the silt etc. accumulated in the vicinity of the gated structure. The sizes of opening should be adequately designed so as to eliminate/ reduce the possibility of gate jamming. Also, the larger size opening can effectively dispose of the debris and other floating materials with minimum damages to the civil structure as well to gate components. It is recommended that temporary diversion intake should not be operated at partial gate openings for any reasons. Also, the diversion intake opening should have larger dimensions in both directions i.e. width & height. It may also happens some times that a gated diversion arrangement or construction sluices provided for facilitating construction of dam/related hydraulic structure, have to used beyond their capabilities because of economic or the other reasons. To fulfill such requirement, it is possible that gate may have to be operated partially opened for a long period before the final closure of the diversion facilities takes place. In-depth evaluation of capability and likely problems resulting from such application must be considered before taking such actions.

The hoisting arrangement should be located such that it is accessible under all conditions. All the hoist equipment especially the electric motors & controls should be located such that these may not get submerged during high water levels.

Length of the radial arms also should be adequate so as to avoid water splashes on the trunnion assembly. Adequate factor of safety in designs, protection & use of corrosion resistance material should be recommended for all the machined components of the hoisting arrangement because these are subjected to constant water splashes apart from the dynamic loads due to vibration etc.

For extreme high head gate (above 75-100m) use of rubber seal is not recommended even for the sill/ bottom sealing. Instead, metal-to-metal contact between the gate leaf and the embedded gate frame seats should be used for affecting the sealing/ water-tightness of the gated installations. The gate not having the seal effective for entire travel should be designed to have the top seal effective for about 300mm travel of gate so as to maintain sealing atleast during small (critical) gate openings.

Multiple position indicator system should be adopted for successful operations of high head gates / remote operated gated installations

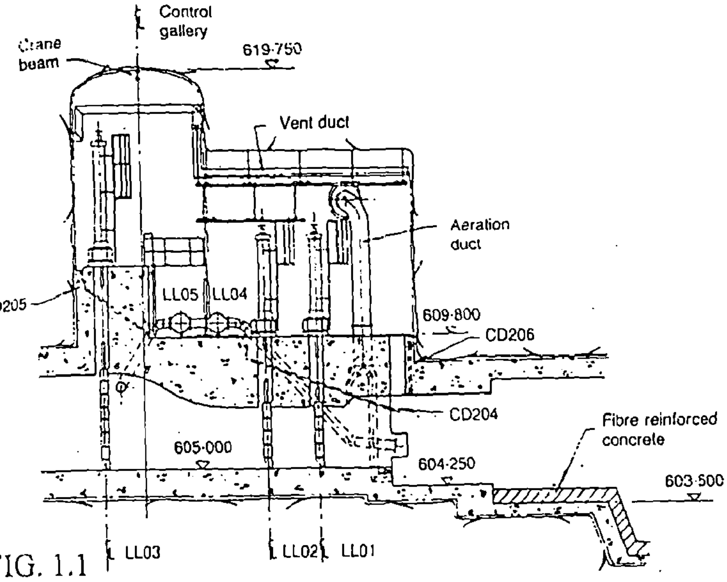


FIG. 1.1

Section through low-level outlet

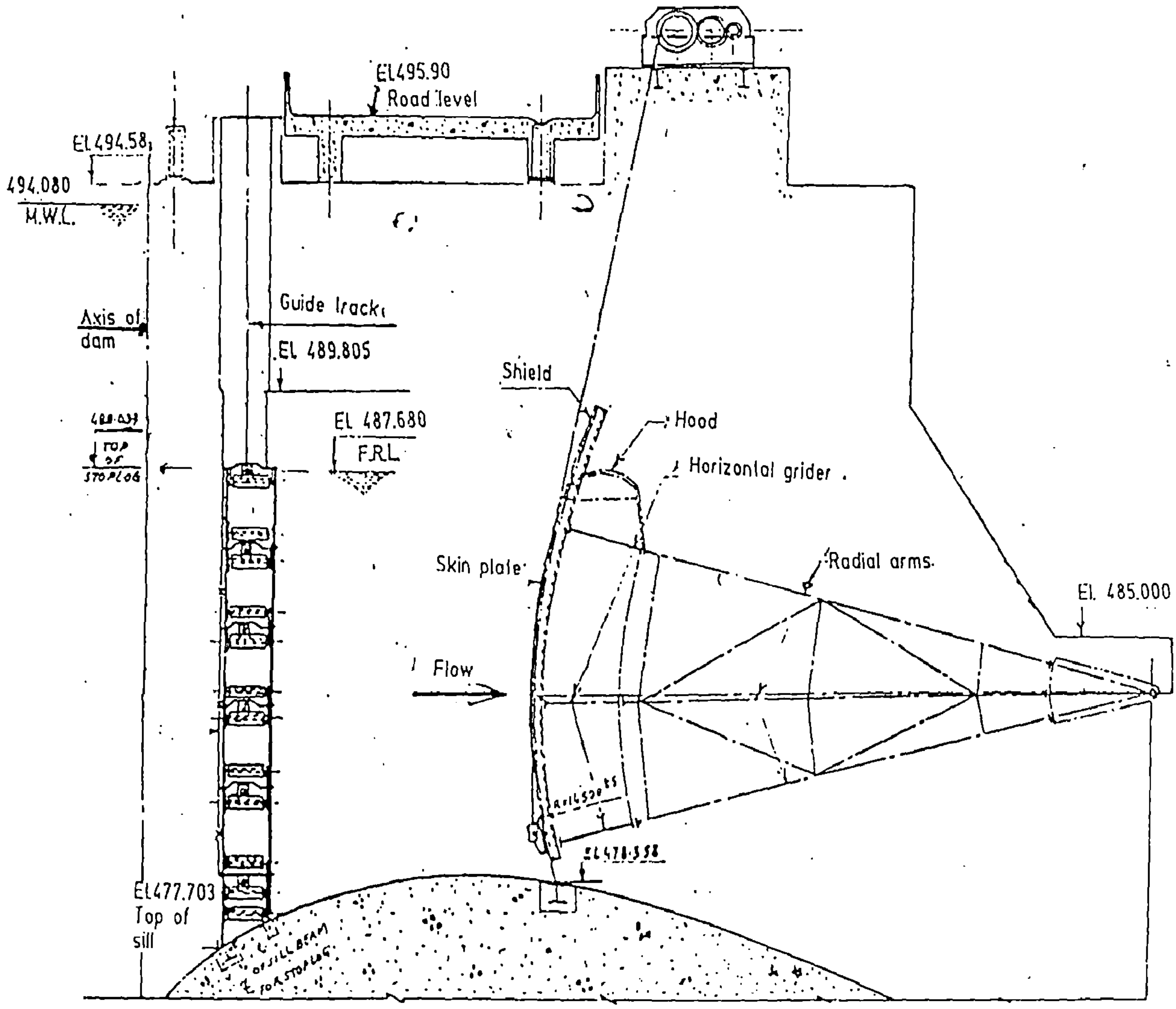
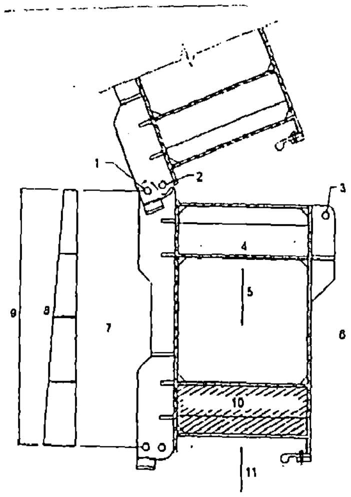
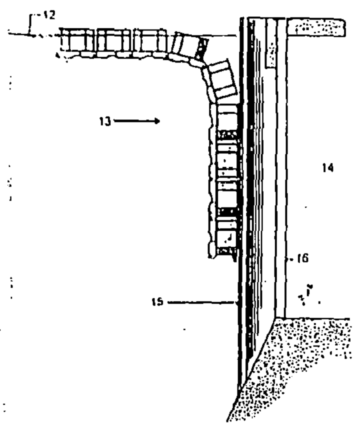


FIG. 1.2

Spillway Radial gate & their Stoplogs



Section through bulkhead (Caisson)



Bulkhead installation

(1) Pin connection
(2) Bearing pin
(3) J-Seal
(4) W-Beam (typ.)
(5) Unit weight
(6) Intake side
(7) Reservoir side
(8) Hydrostatic force
(9) One unit
(10) Water filled compartment
(11) Buyoant force
(12) Water surface
(13) Flow
(14) Intake
(15) Pier nose guide
(16) Stoplog slot

FIG. 1.3
Articulated floating bulkhead (Caisson)

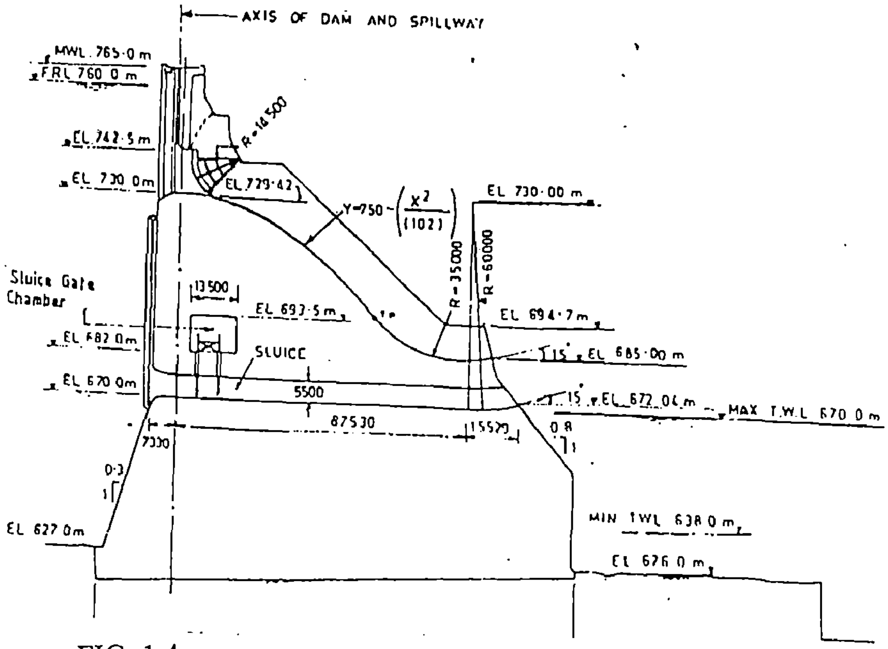


FIG. 1.4 Section Through Sluice and Spillway

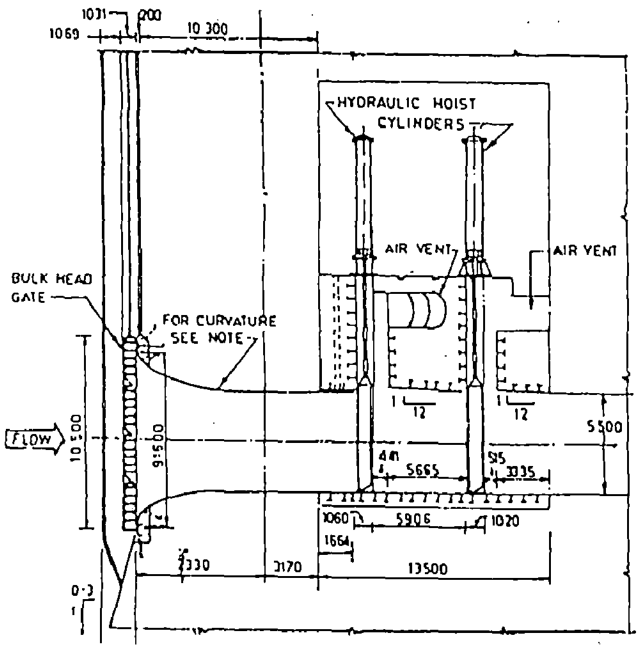
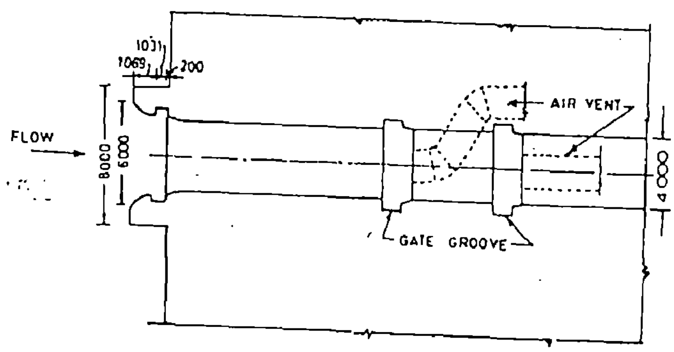
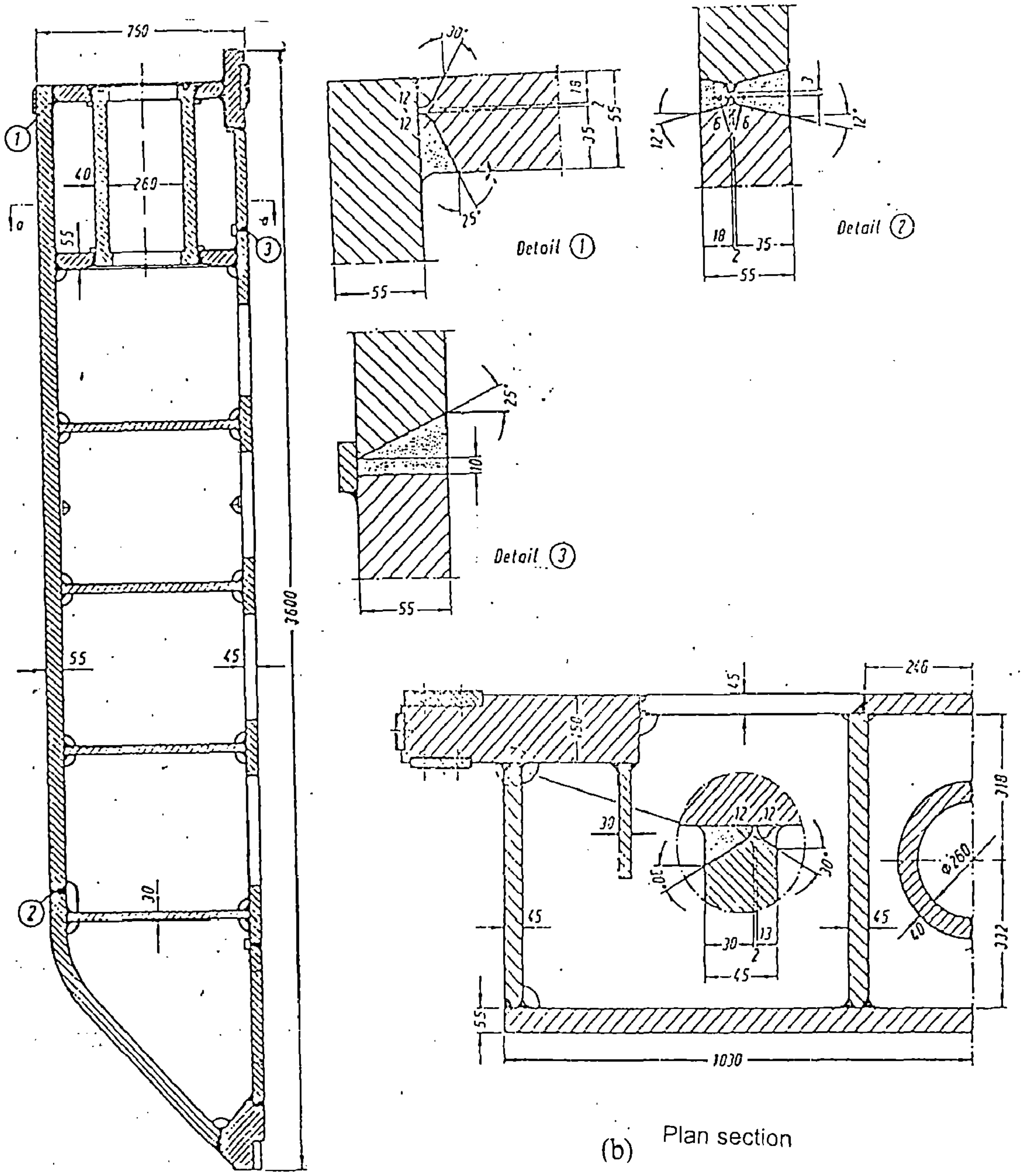


FIG. 1.5 Low Level Sluice Details at Entrance and Gate Slots

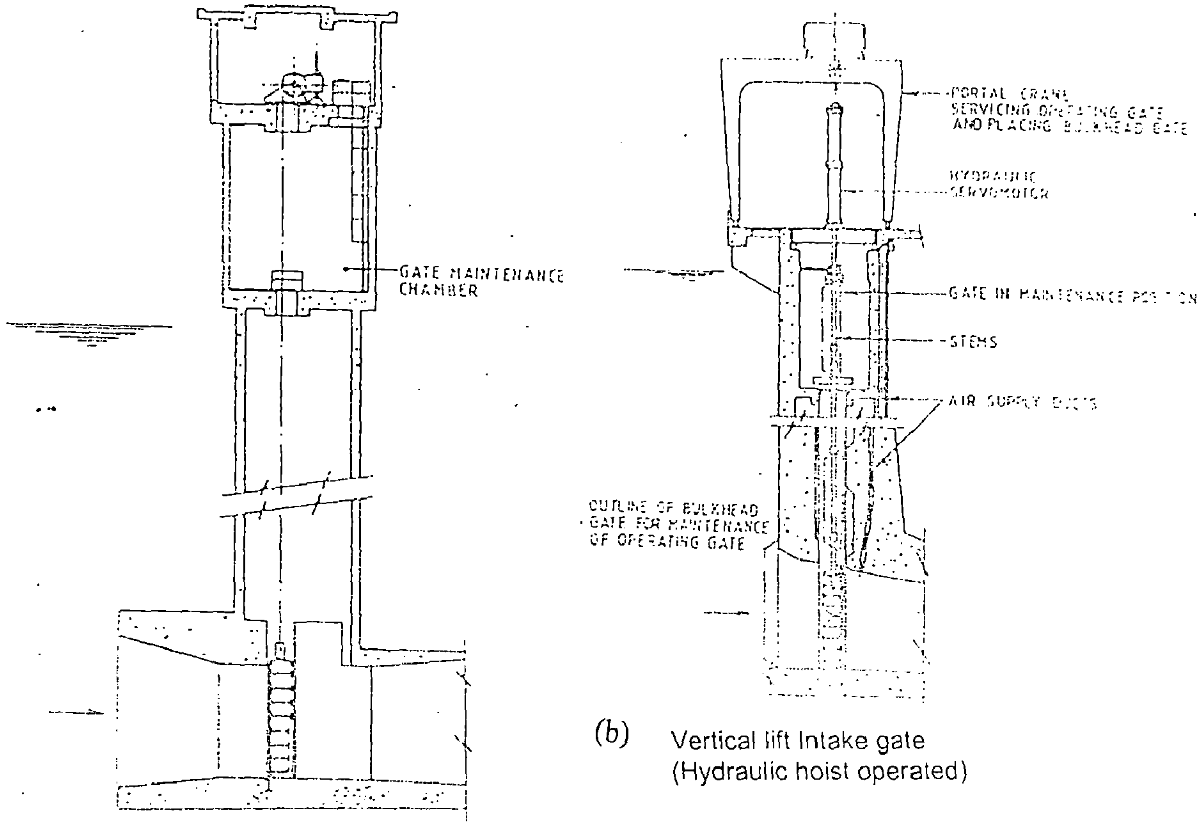




(b) Plan section

(a) Longitudinal section

FIG. 1.6 High head gate construction details



(a) Vertical lift Intake gate (Rope drum hoist operated)

(b) Vertical lift Intake gate (Hydraulic hoist operated)

FIG. 1.7

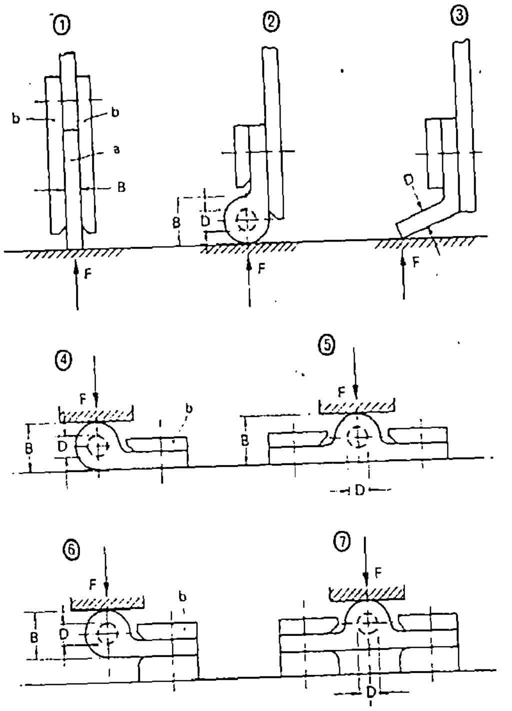
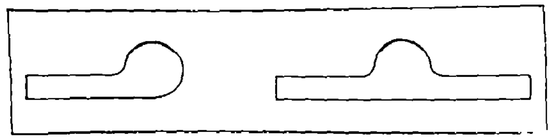


FIG. 1.9 *The most commonly used seal designs (a=sealing element, clamp, F=sealing force, B=bulb diameter and D=core meter).*

The typical applications for the various seal types .)

Type of gate	Water pressure	Bottom seal	Side seal	Head seal	
				Fixed	Sliding
Roller	low	1.2	2, 3, 4	4	6
	high	1	6.	4	7
Radial	low	1	3	(4)	(6)
	high	1	6	(4)	(7)
Flap	n/a	n/a	3, 4, 6	n/a	n/a
Mitre	n/a	1-7 (sill)	1-7	n/a	n/a

n/a = not applicable, (x) = occasional use.



Sites for PTFE claddings on J and double-stem seals.

FIG. 1.10

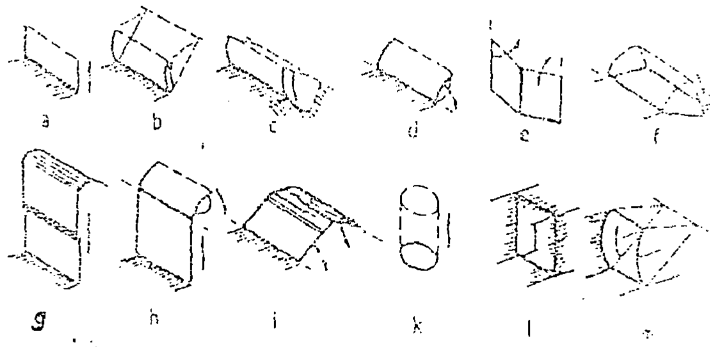


FIG. 1.8 *Gate boundaries requiring sealing*

a) Vertical-lift gate
b) Radial gate
c) Submergible radial gate
d) Bottom-hinged flap gate
e) Mitre gate
f) Drum gate
g) Two-leaf vertical-lift gate
h) Vertical-lift gate with flap
i) Bear-trap gate
k) Cylinder gate
l) Vertical-lift tunnel gate
m) Culvert valve (reverse Tainter gate)

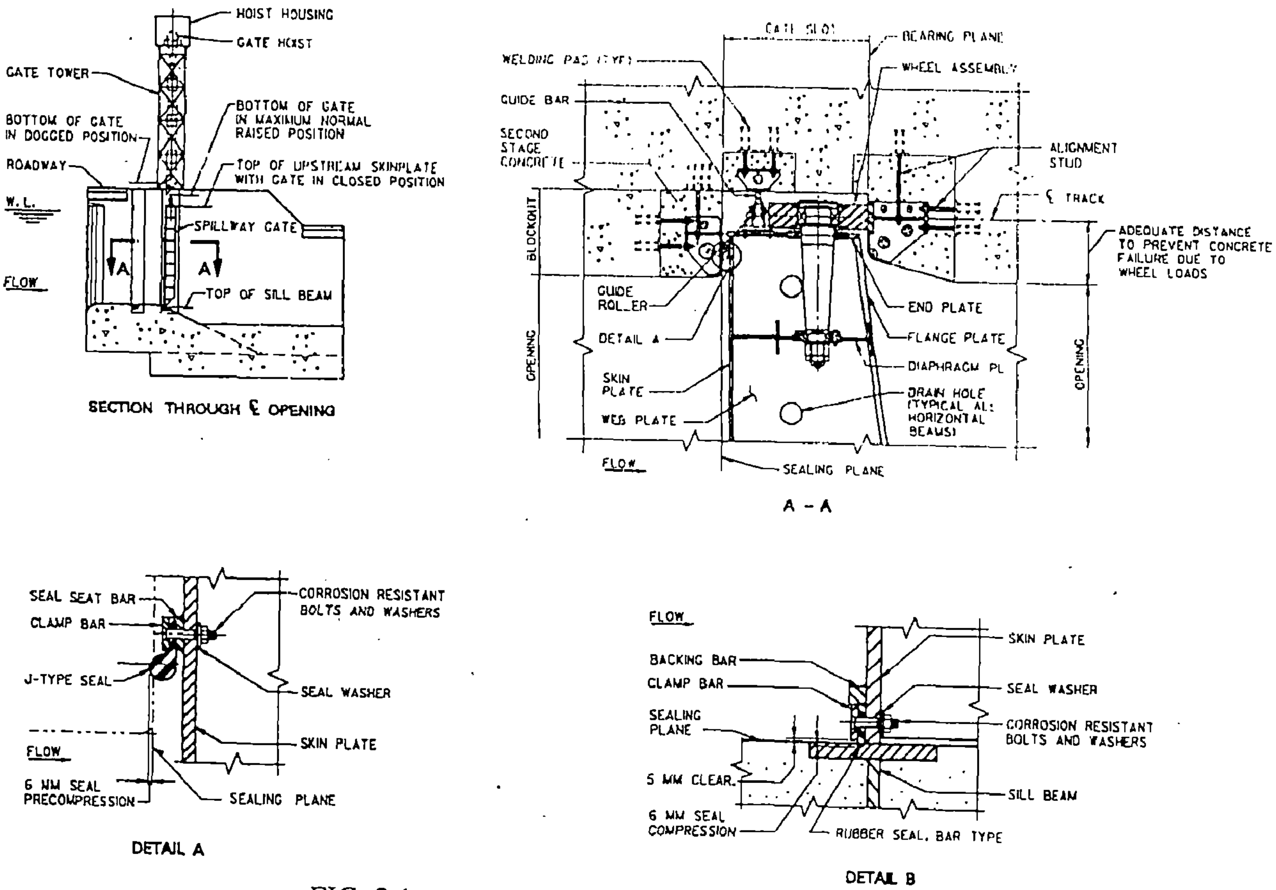
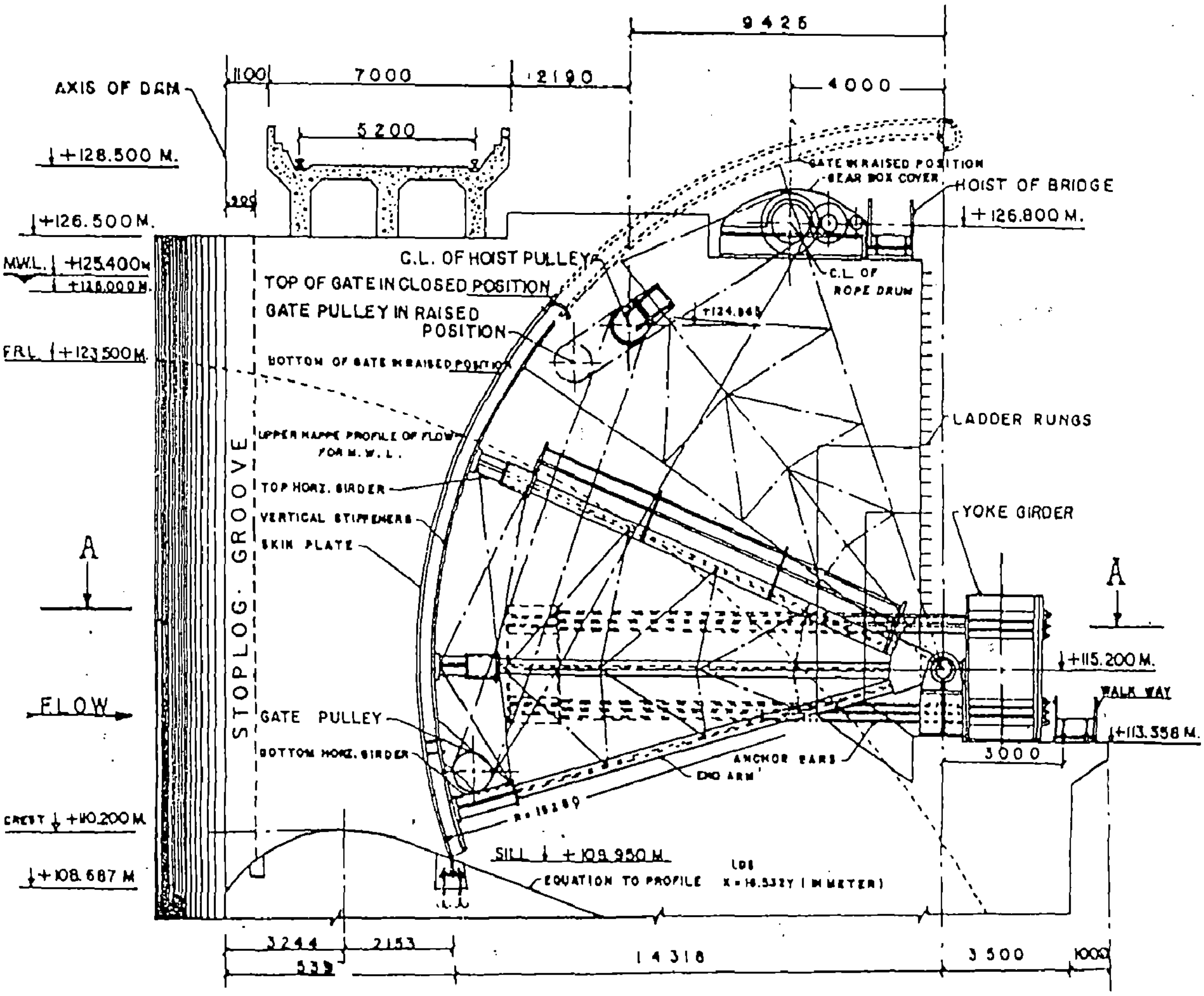


FIG. 2.1 Typical Arrangement of Vertical Lift Spillway Gate



SIDE ELEVATION

FIG. 2.2 General Arrangement of Radial Gate

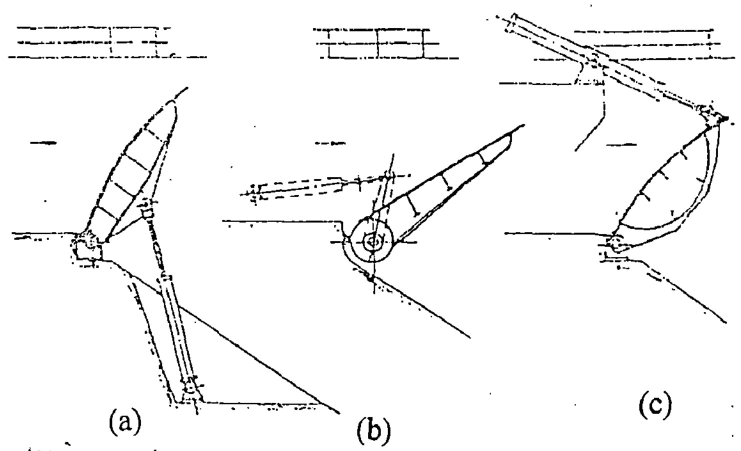


FIG. 2.3 *Different versions of bottom-hinged flap gates*

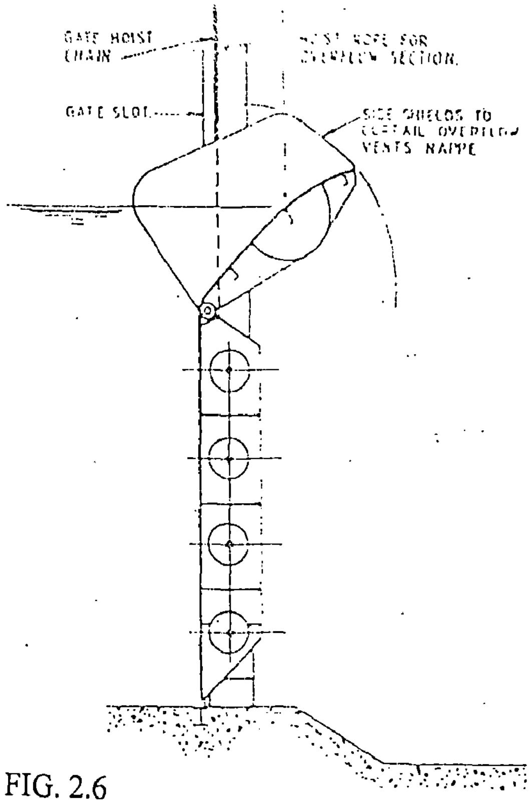


FIG. 2.6
Vertical lift gate with overflow section

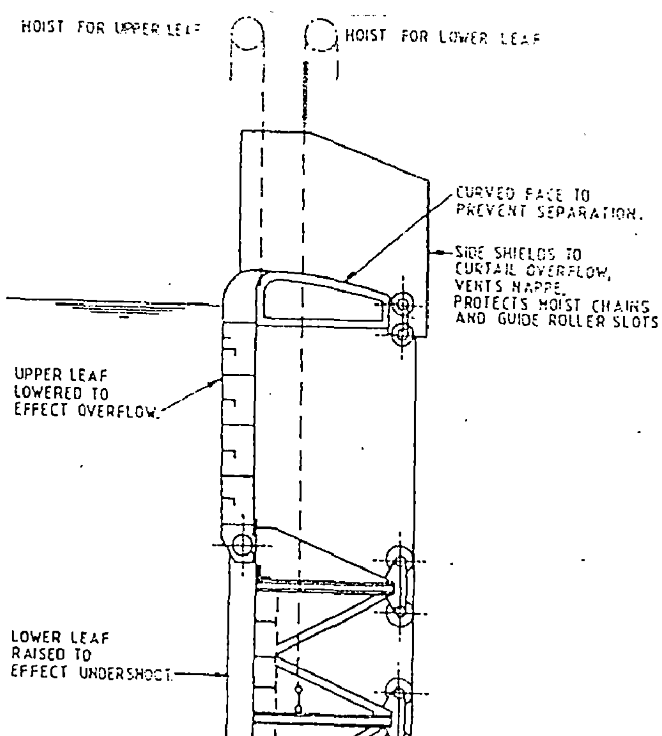


FIG. 2.5 SEGMENT GATE

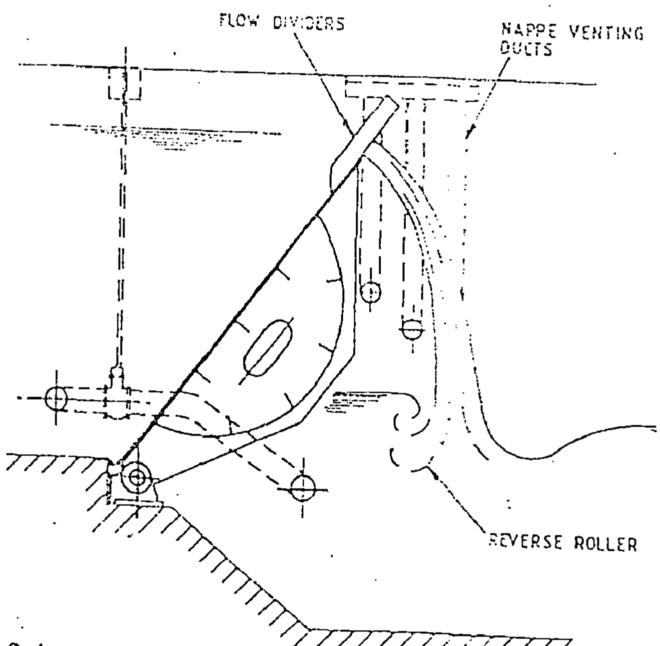
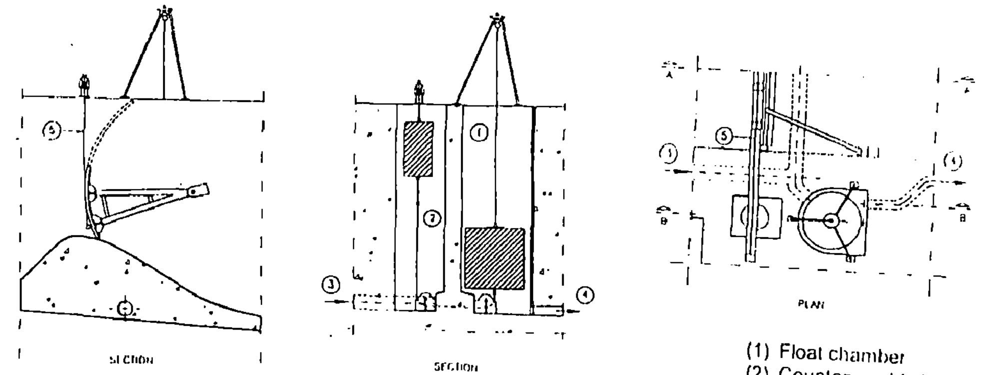
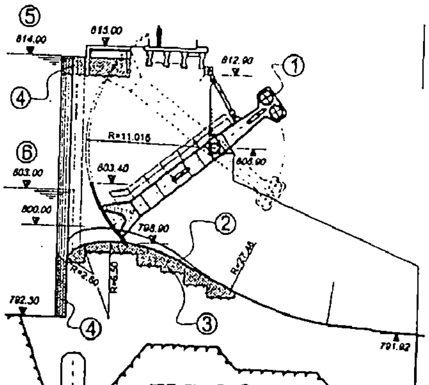


FIG. 2.4 *Bypass system for flushing debris accumulated downstream of a flap gate*



(1) Float chamber
(2) Counterweight chamber
(3) Pipe from reservoir to float chamber
(4) Pipe from float chamber to outlet
(5) Rope

FIG. 2.7
Float and counterweight system for automatic operation of a radial gate



1. Concrete counterweights
2. Modified overflow crest
3. Concreting works
4. Pier prolongation
5. Maximum water level
6 Normal water level

FIG. 2.8

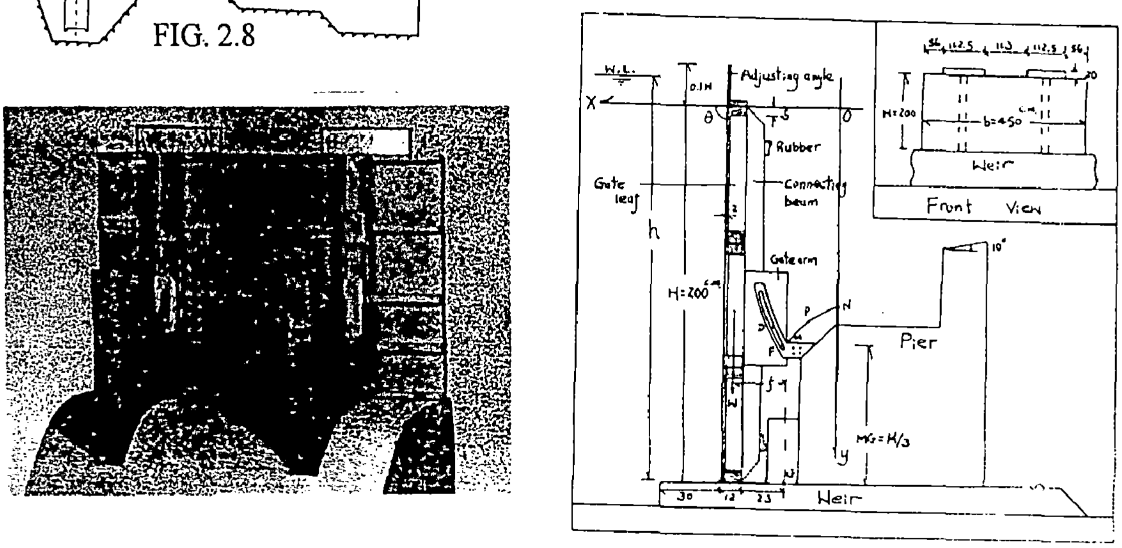
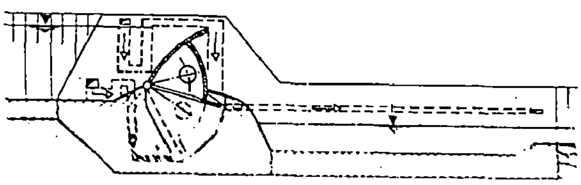


FIG. 2.9 **Q-Type Gate**



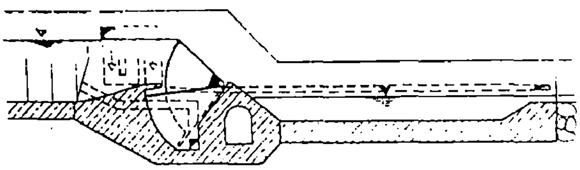


FIG. 2.10 *automatic drum gates.*

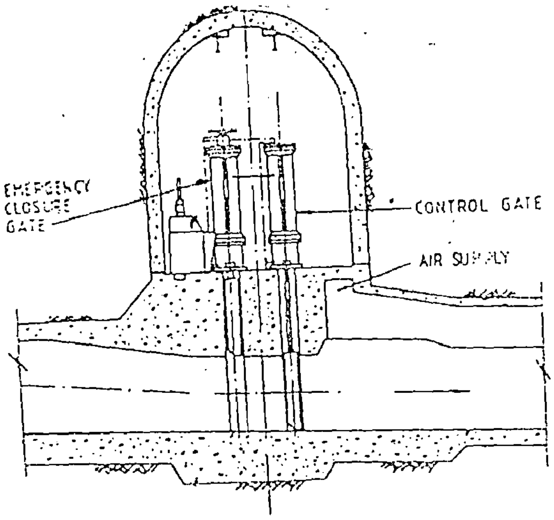


FIG. 2.11 *Control and emergency closure gates of the slide type*

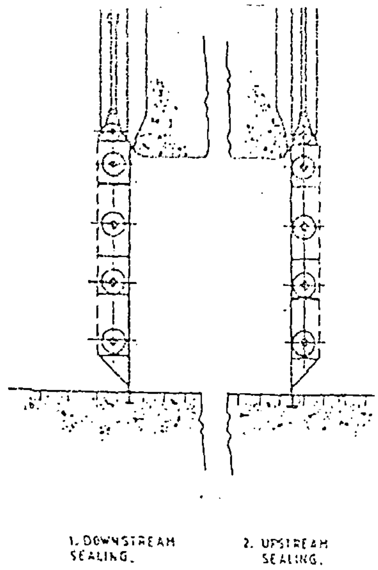


FIG. 2.12 FIXED ROLLER GATE *vertical lift gate*

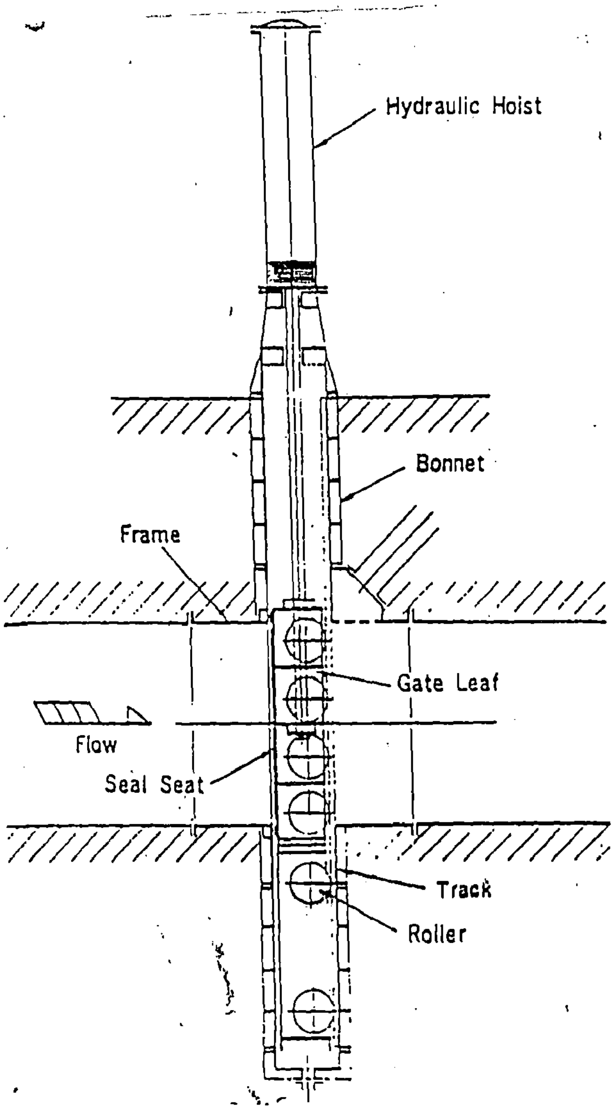


FIG. 2.15 Ring-Seal Gate

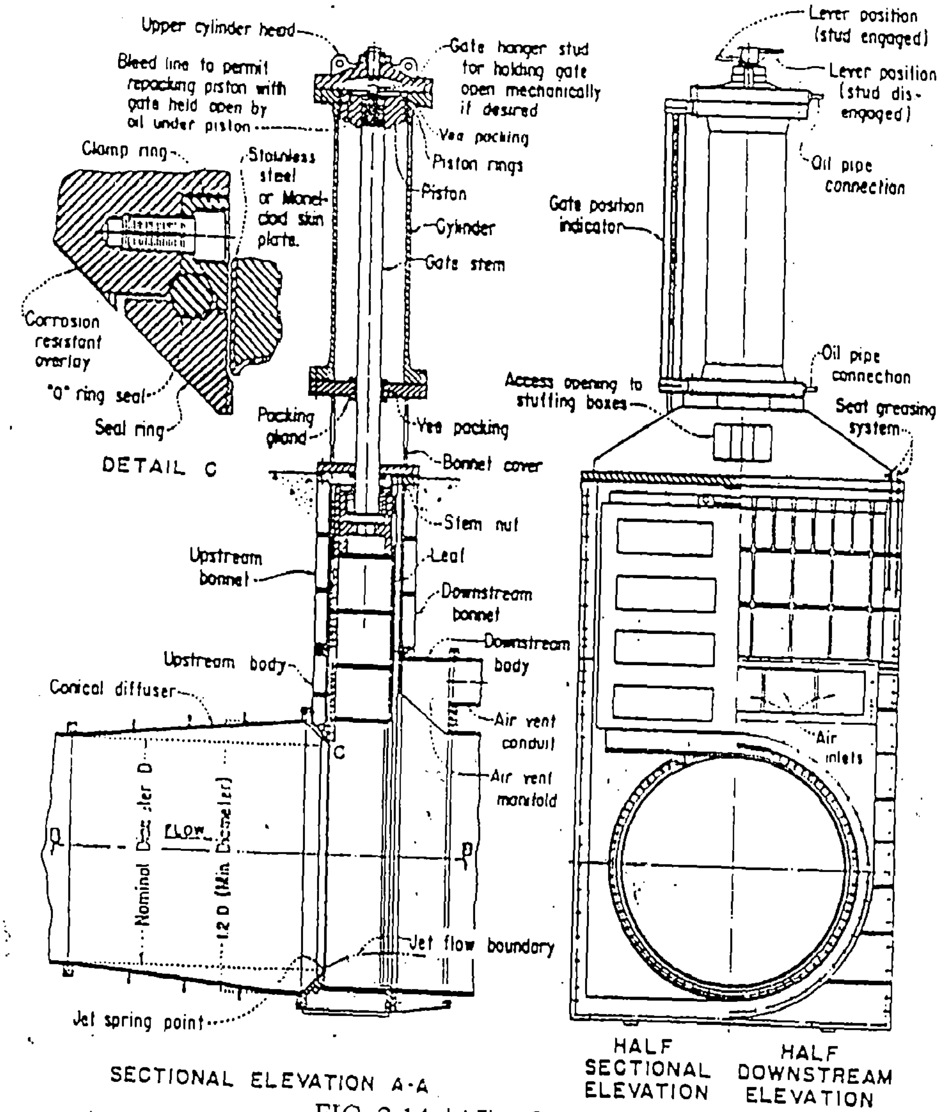


FIG. 2.14 Jet-Flow Gate

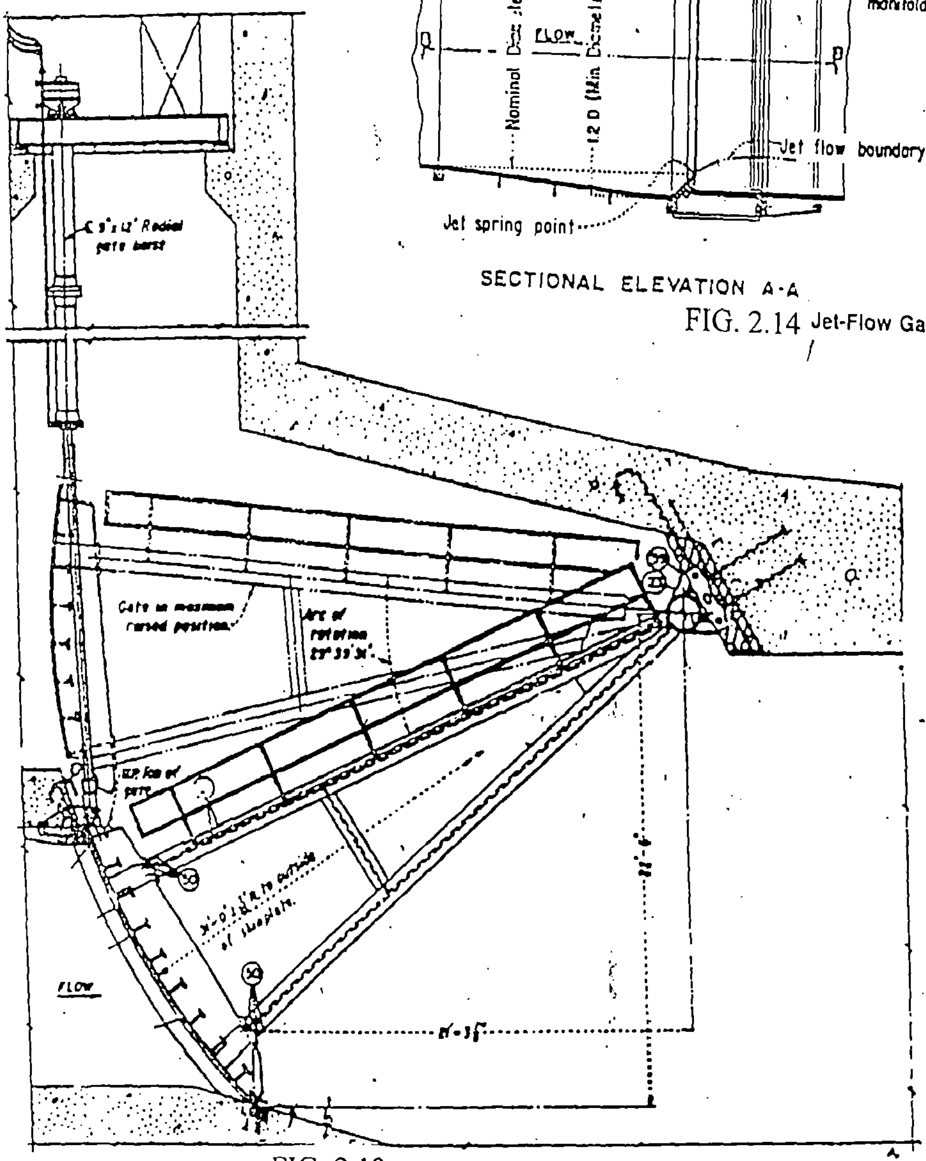
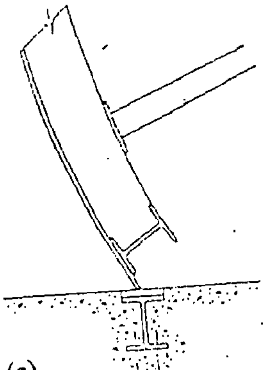
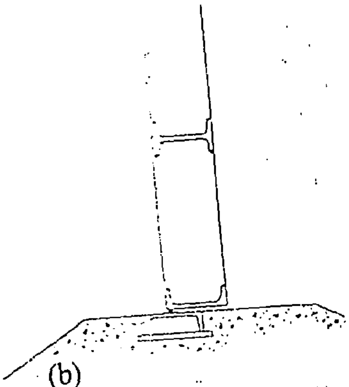


FIG. 2.13 Top-Seal Radial Gate



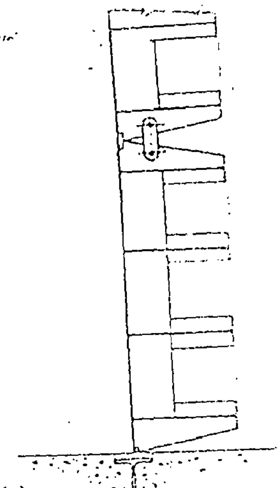
(a)

BOTTOM SECTION OF A RADIAL AUTOMATIC GATE WHICH SUFFERED SEVERE VIBRATION PROBLEMS



(b)

BOTTOM SECTION OF PERSHORE MILL GATES WHICH WERE SUBJECT TO FLOW ATTACHMENT AND VIBRATION (AFTER BRUCE ET AL.)

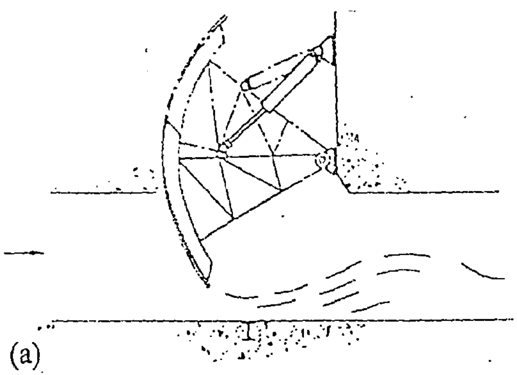


(c)

UNSUITABLE DESIGN OF THE BOTTOM SECTION OF A DIVERSION TUNNEL GATE. THE GATE IS REQUIRED TO CLOSE AGAINST A FLOW OF 150 m³/s

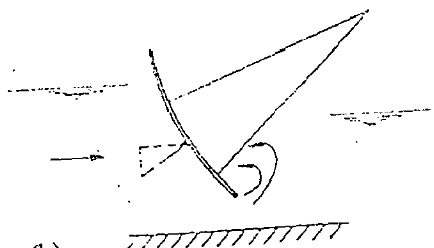
FIG. 3.1

Arrangement of unsuitable structural stiffening members at the bottom section of gates



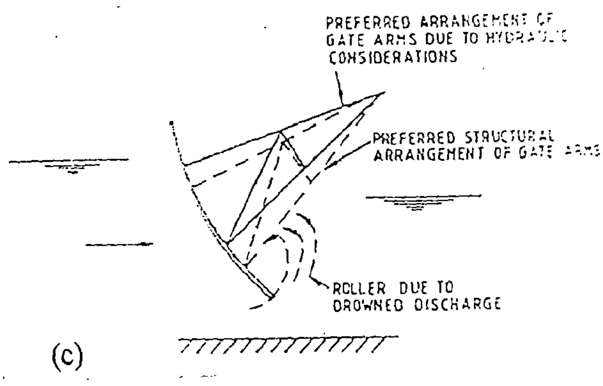
(a)

Radial gate used in culvert



(b)

Positioning of radial gate's arms



(c)

Effect of reverse roller on lowest arm of radial gate with drowned downstream side

FIG. 3.2

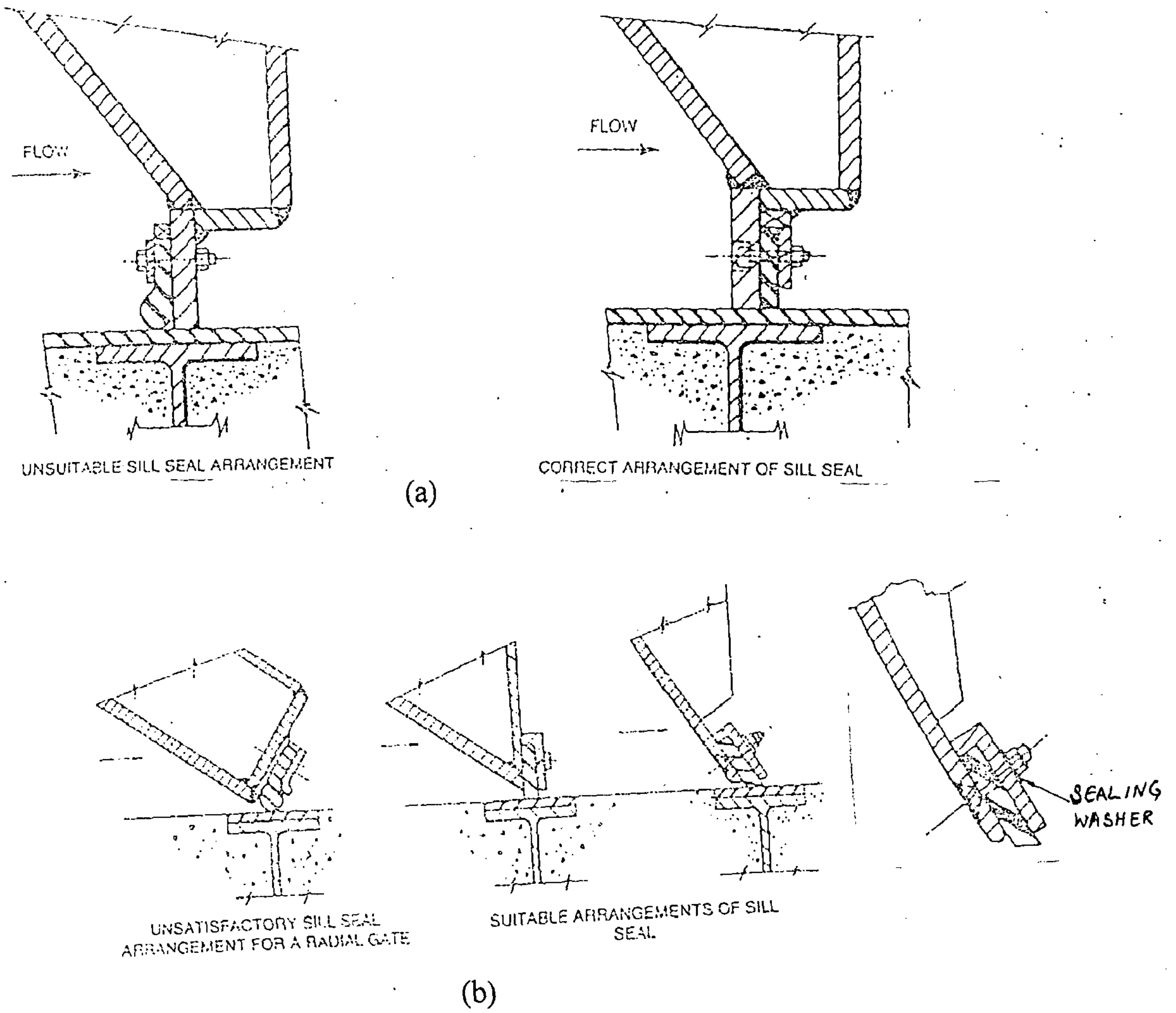


FIG. 3.3 *Arrangement of suitable and unsuitable seals*

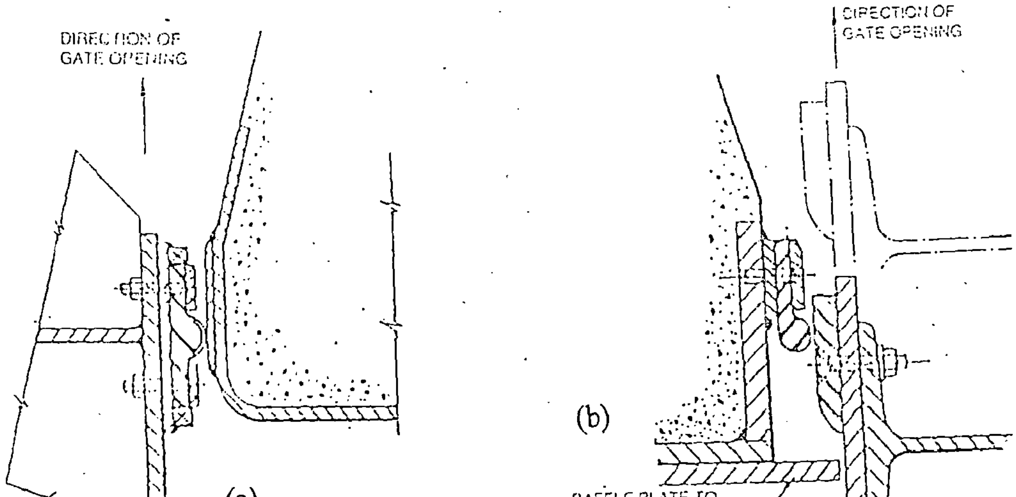
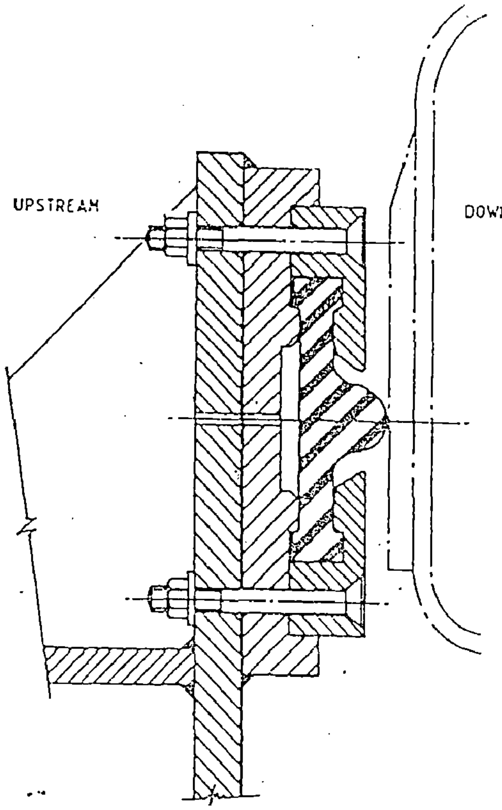
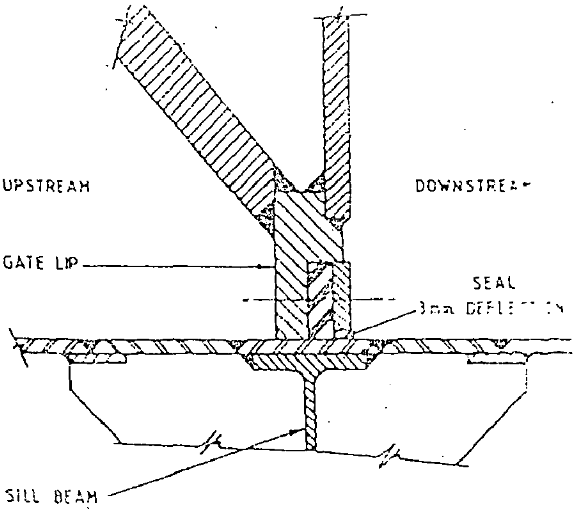


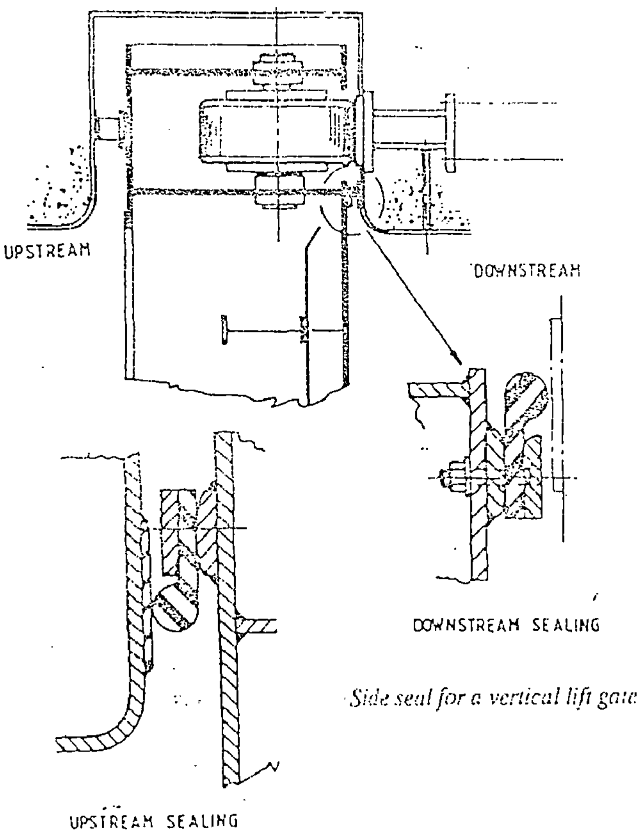
FIG. 3.4 *(a) A lintel seal arrangement which caused vibration before baffle plate was fitted[24]. (b) Preferred arrangement of lintel seal*



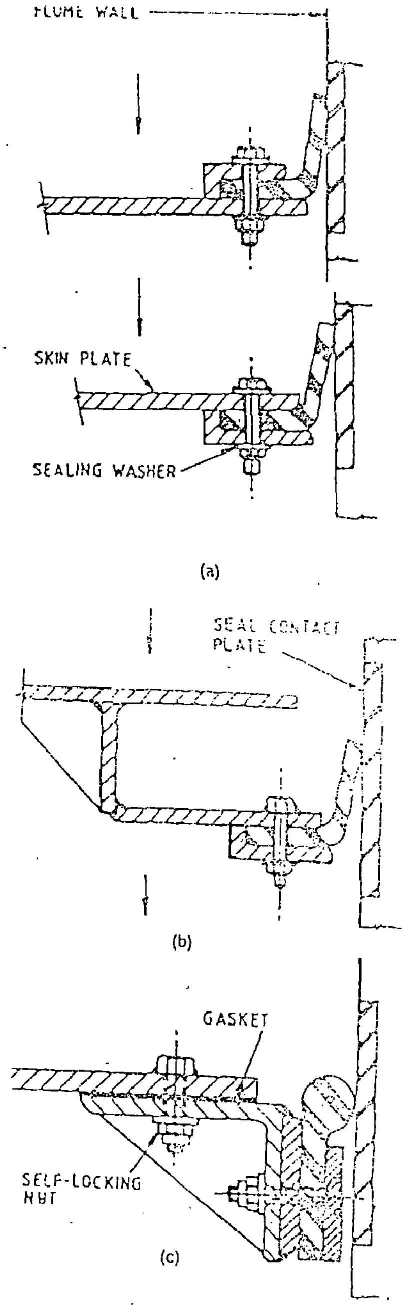
Lintel seal for a high head vertical lift gate



Sill seal for a high head for a vertical lift gate



Side seal for a vertical lift gate



Arrangement of side seals

FIG. 3.5
Side seal arrangement

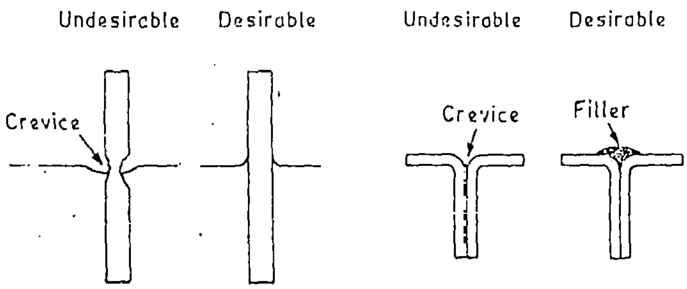


FIG. 3.7 Corrosion prevention by Avoiding crevices.

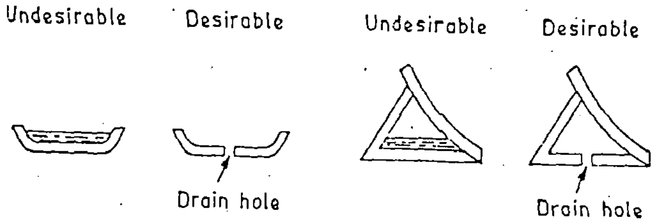


FIG. 3.6 Corrosion prevention by Providing drain holes.

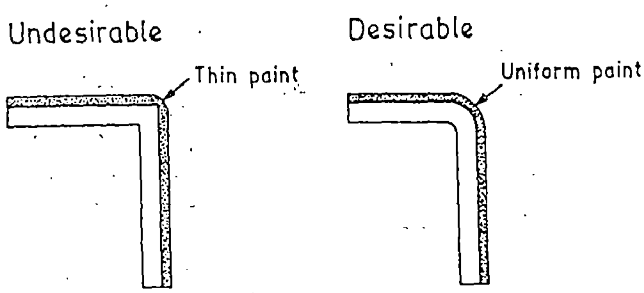


FIG. 3.8 Corrosion prevention by avoiding sharp corners.

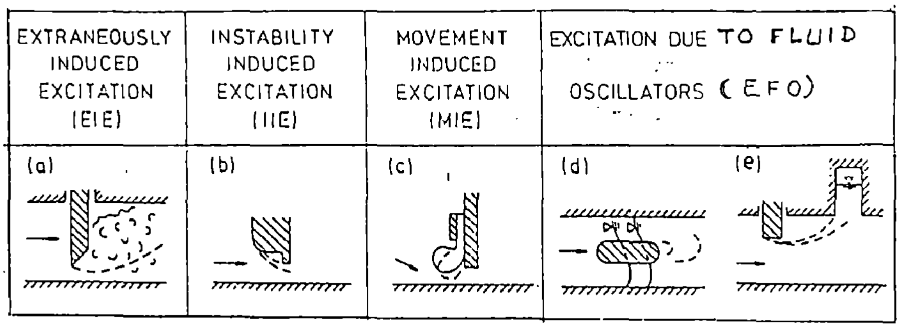


FIG. 4.1 Basic elements leading to fluctuating hydrodynamic forces.

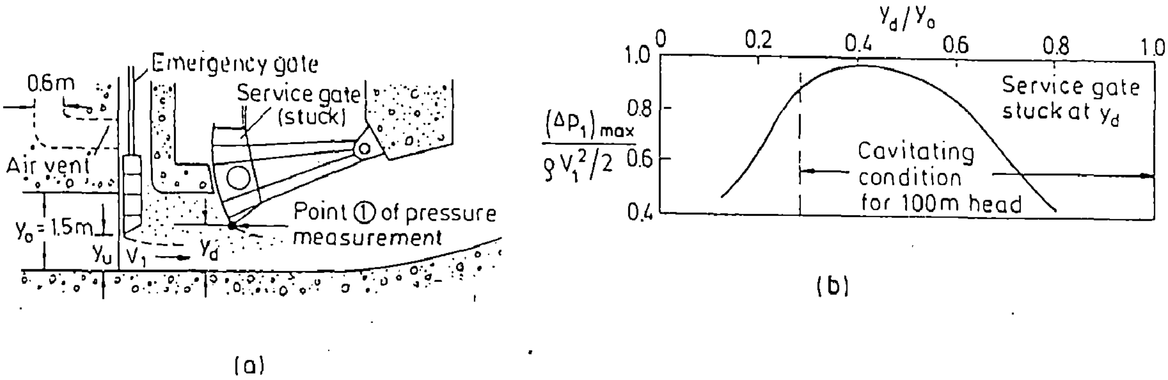


FIG. 4.2 Pressure fluctuations in lower part of service gate, which became stuck in mid position $[y_d]$, during closure of emergency gate, and maximum peak-to-peak pressure amplitudes recorded $[(\Delta p_1)_{max}]$.

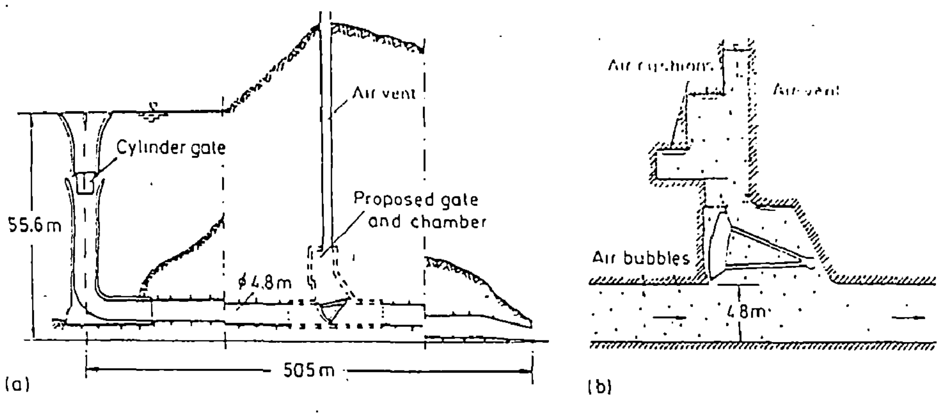


FIG. 4.3 (a) Flood-release tunnel with cylinder and Tainter gates; (b) Bubbly flow at large gate openings (after Rouvé & Traut, 1980).

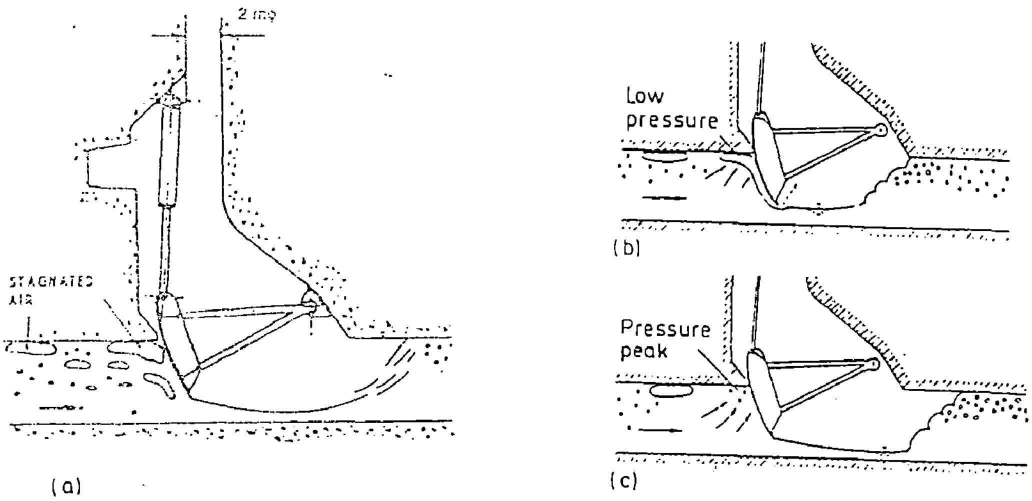


FIG. 4.4 (a, b, c) Sketch of blow-out process at 20% to 40% gate openings

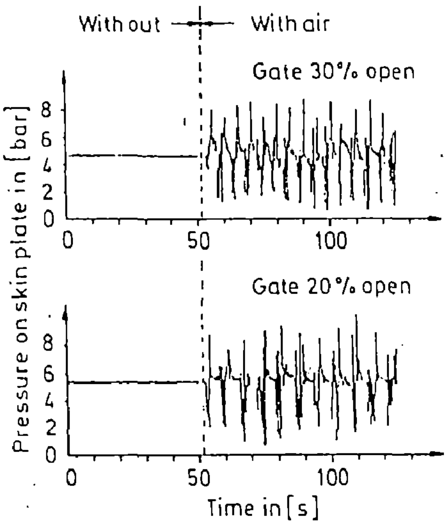


FIG. 4.5 Typical histograms of pressure fluctuation on upstream skin-plate (after Rouvé & Traut, 1980).

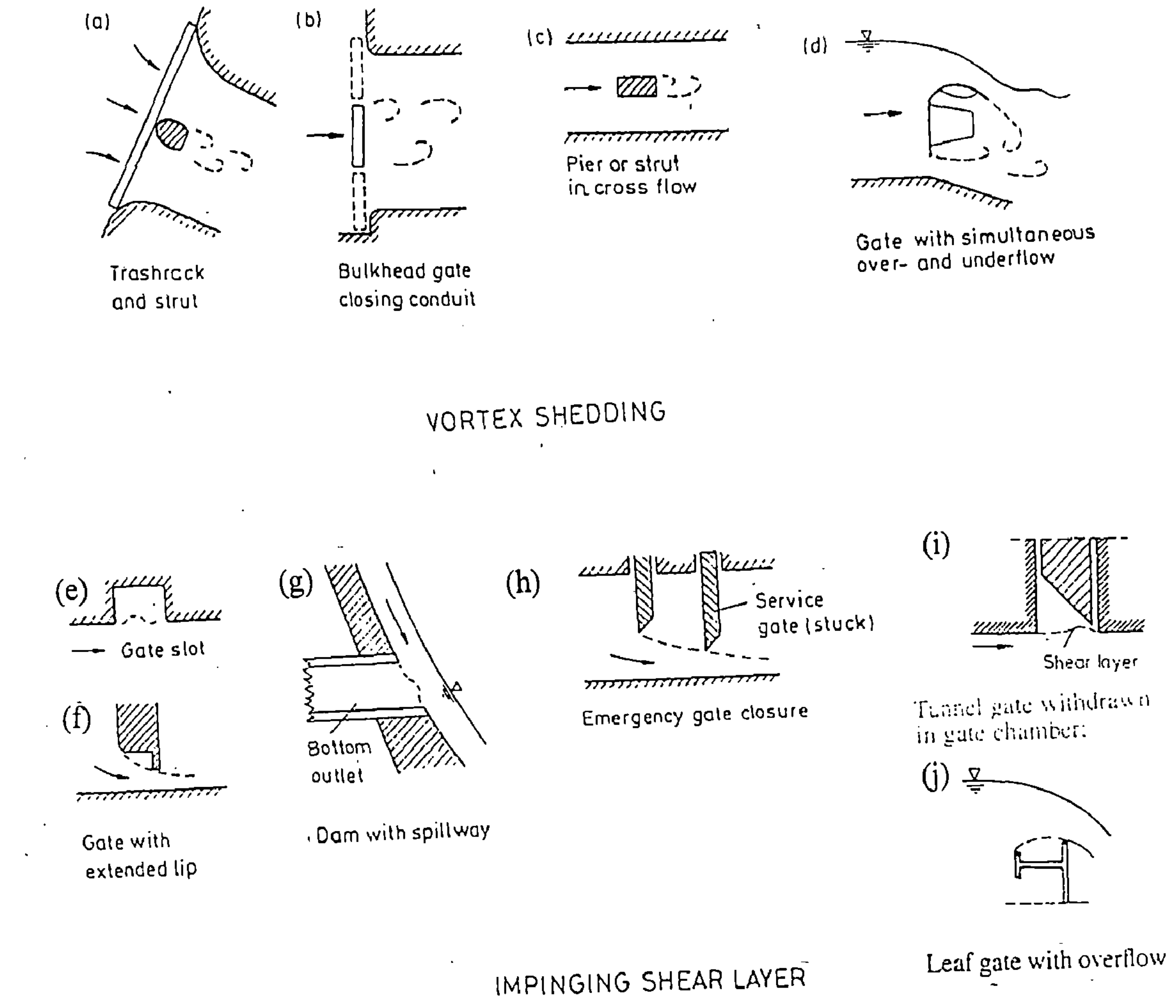


FIG. 4.6 modules leading to instability-induced fluctuat-

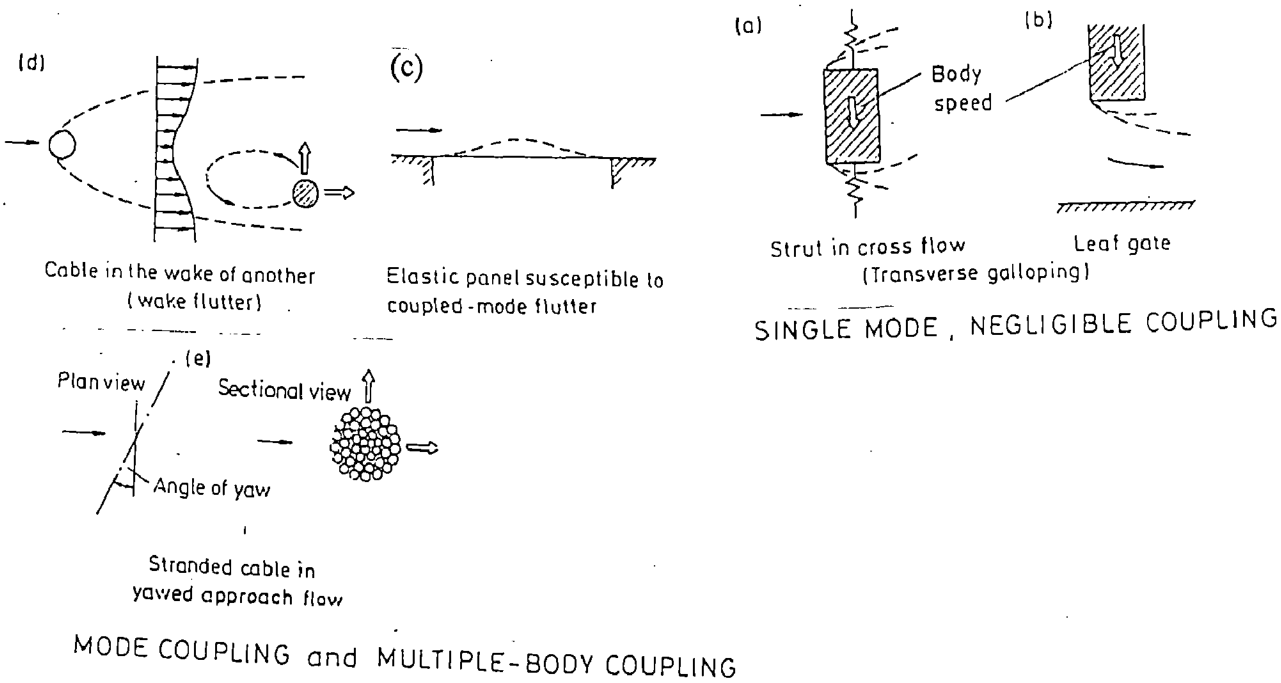


FIG. 4.9 Basic MIE modules leading to movement-induced fluctuating forces

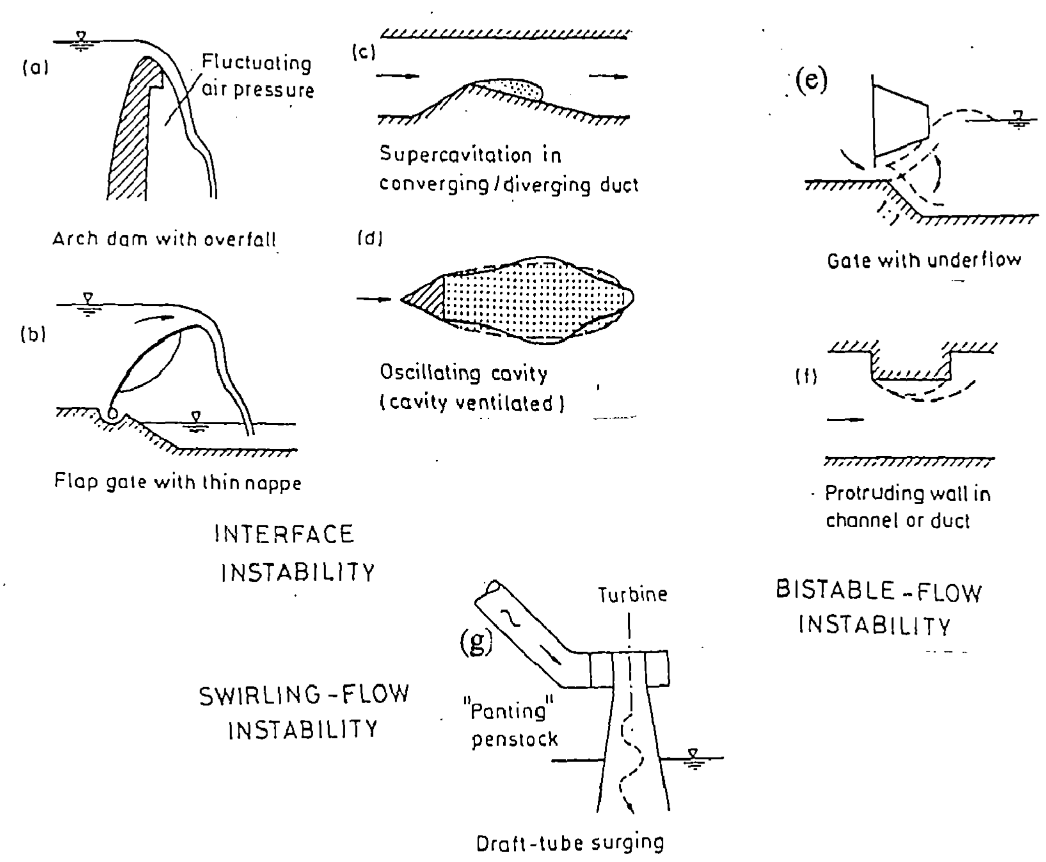


FIG. 4.7 basic IIE modules leading to instability-induced fluctuating forces

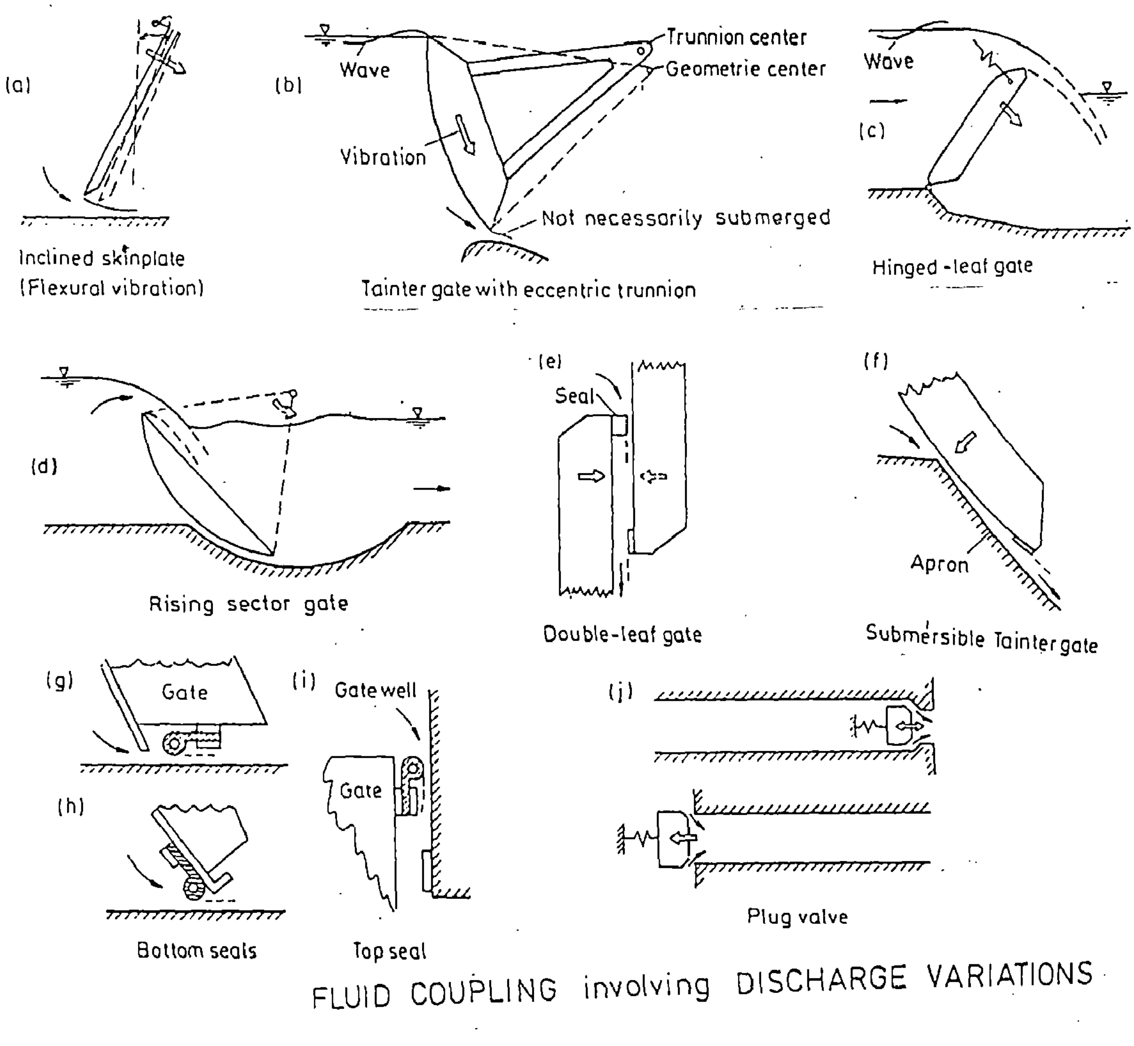


FIG. 4.8 basic MIE modules leading to movement-induced fluctuating forces

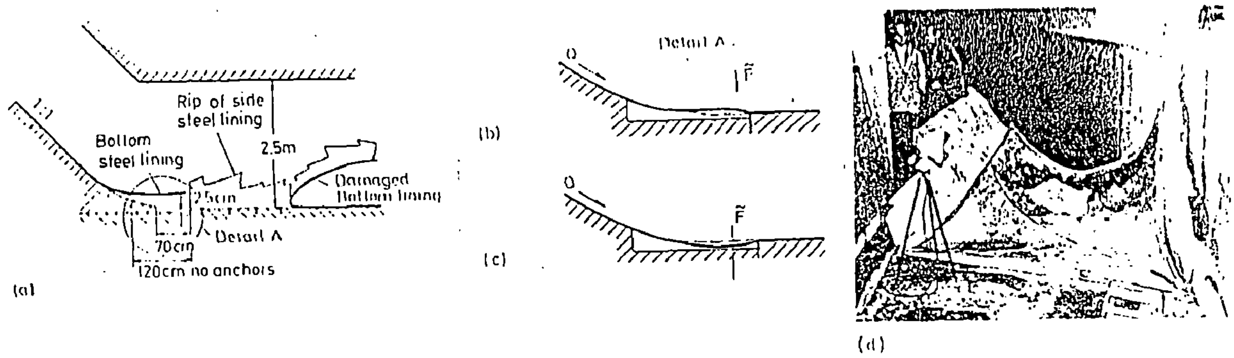


FIG. 4.10 (a, b, c) Steel lining of spillway, damaged during the release of a flood of $Q = 3.6$ m^3/s ($V = q/y \cong 15$ m/s); (d) Damaged bottom steel lining seen from upstream (B = 2.5 m).

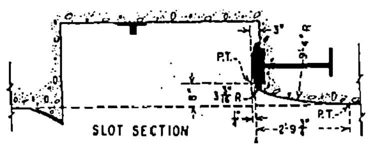


FIG. 4.12

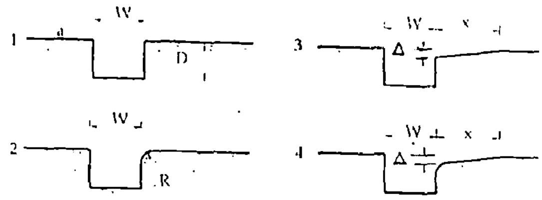


FIG. 4.11
Shapes of slot

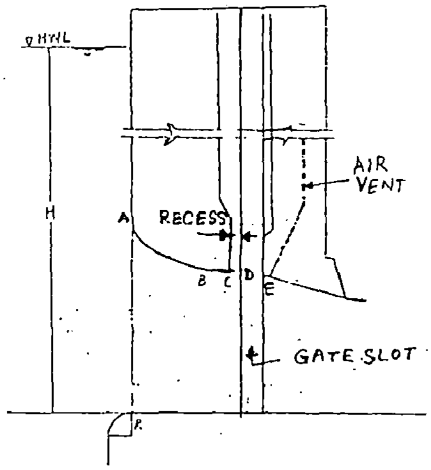


FIG. 4.13

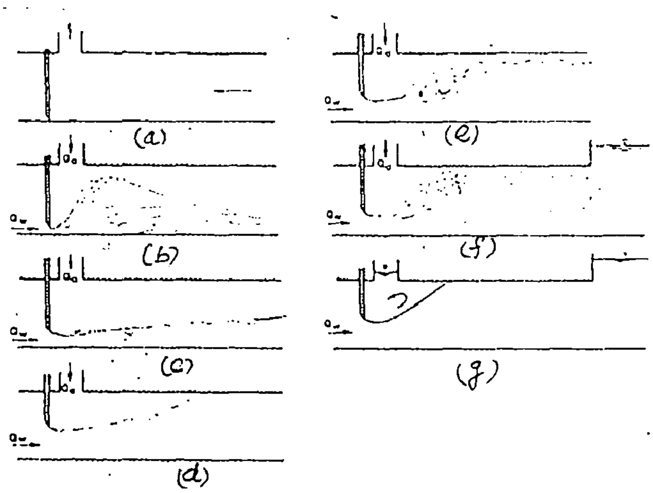


FIG. 4.14 Typical flow pattern in gated conduits (a) Flow of air alone; (b) Spray flow; (c) Free flow; (d) Foamy flow; (e) Hydraulic jump followed by free surface flow; (f) Hydraulic jump followed by pipe flow; (g) Flow of water (submerged or drowned hydraulic jump)

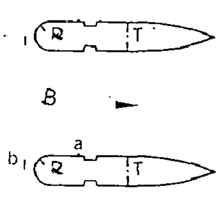


FIG. 4.15
Pier form and its spacing

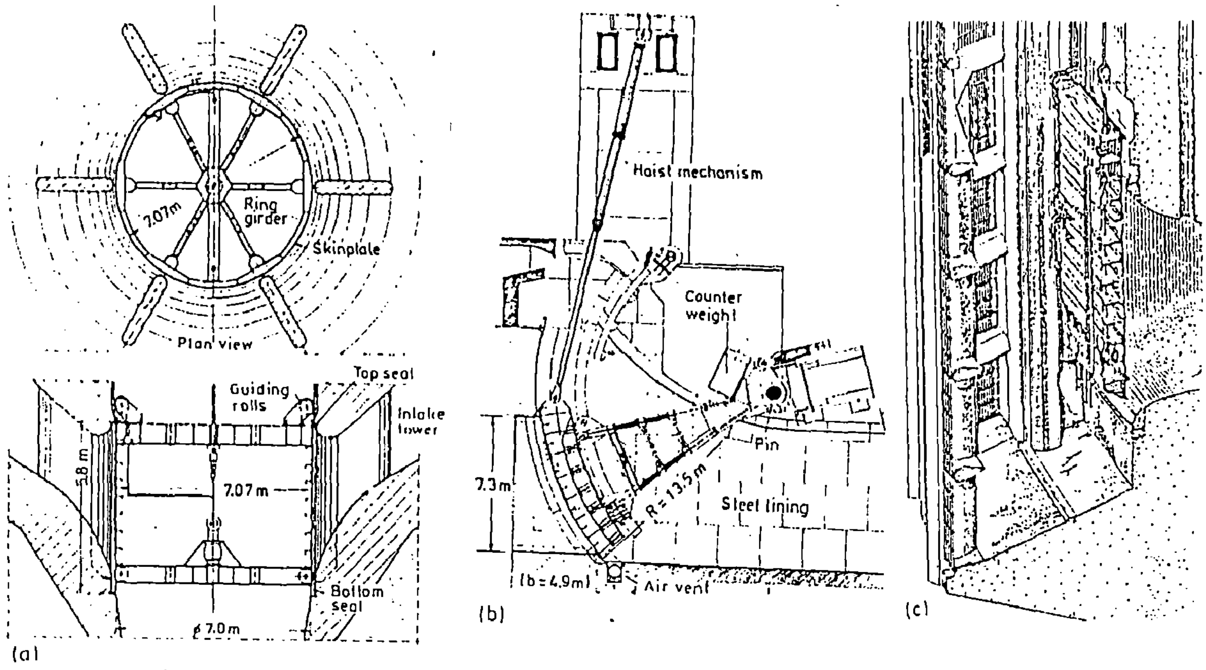


FIG. 4.16 Typical high-head gates. (a) Cylinder gate for 50 m head and (b) Tainter gate for 136 m head according to Schmausser & Wickert (1987); (c) Face-type leaf gate for 87 m head (Grand Coulee dam project) according to US Bureau of Reclamation.

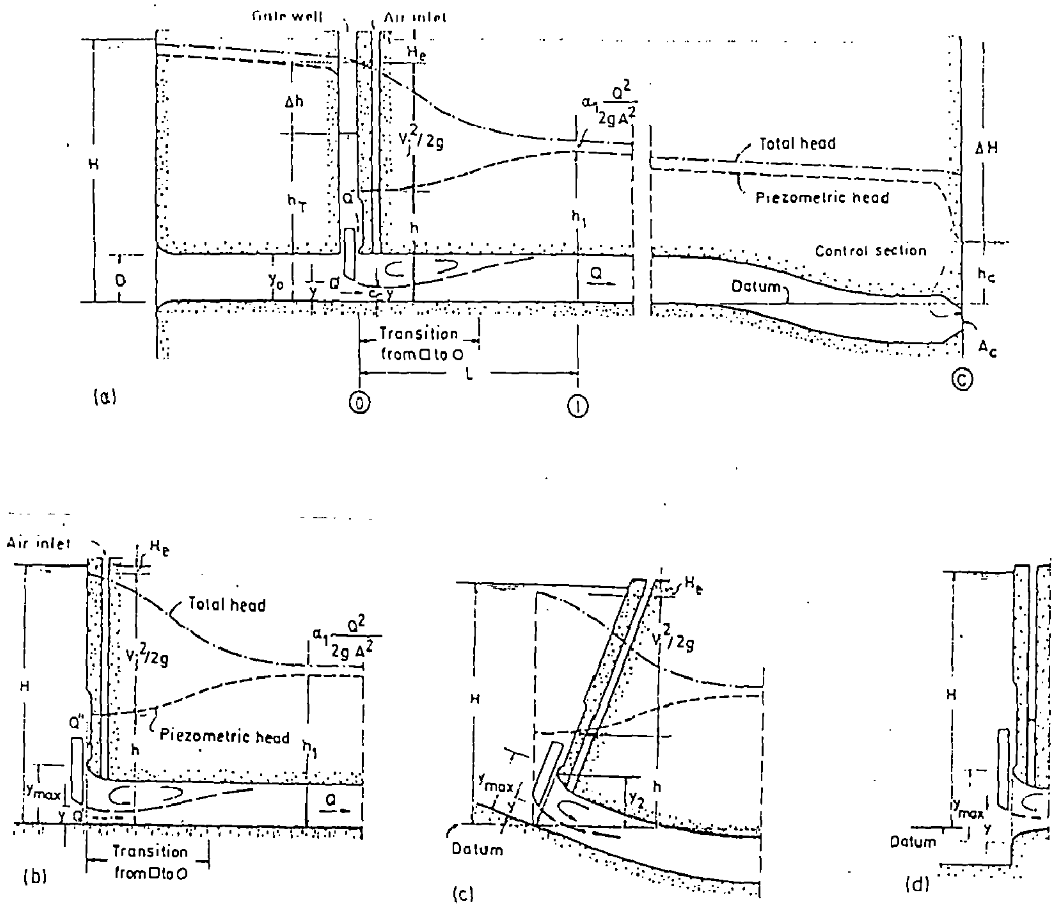


FIG. 4.17 Schematic representation of typical leaf-gate arrangements under submerged flow conditions. (a) Tunnel-type gate; (b, c, d) Face-type gate.

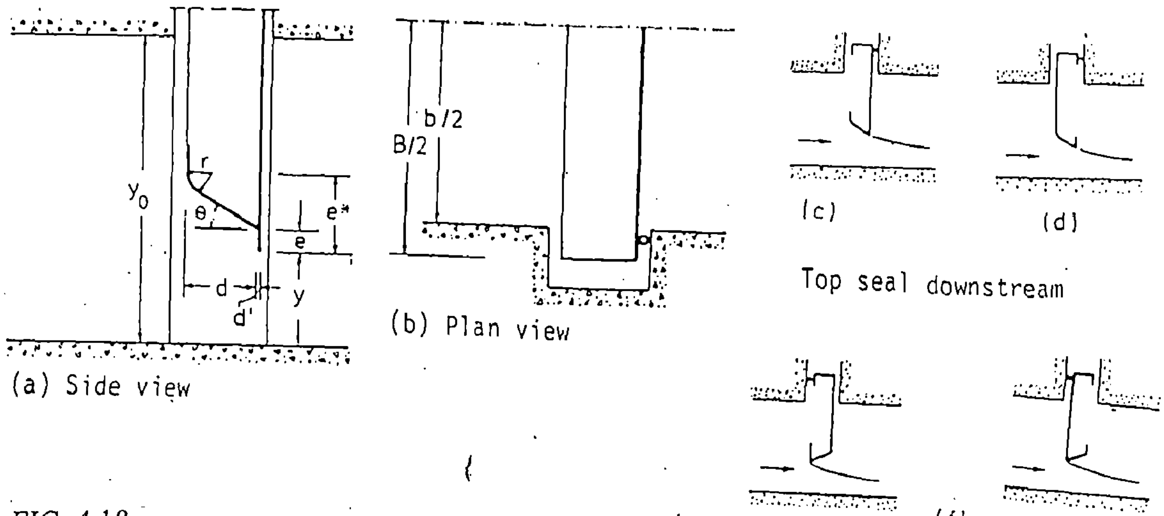


FIG. 4.18 Definition sketch of common geometry and possible top-seal and skin-plate arrangements for tunnel-type high-head leaf gates.

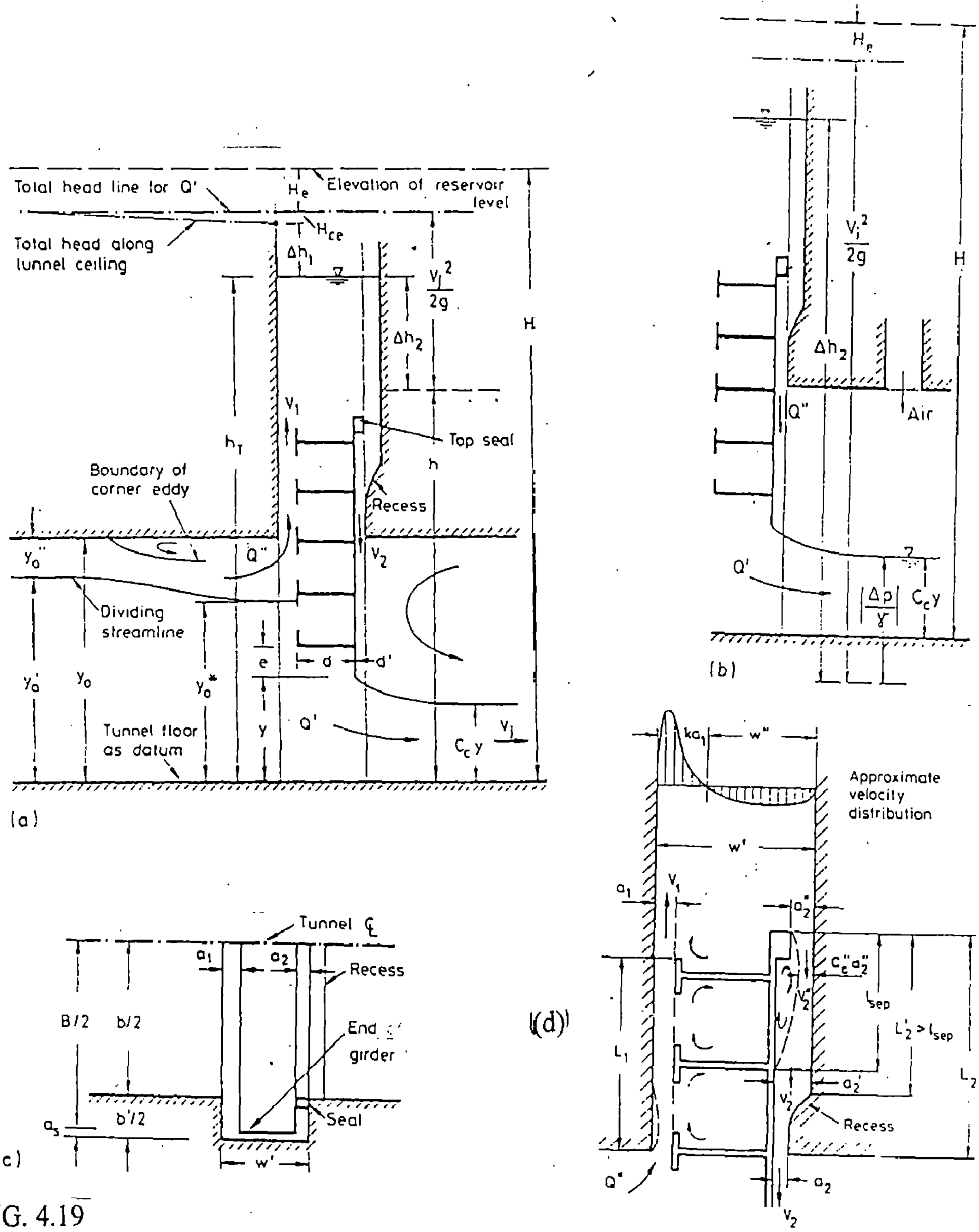


FIG. 4.19 a tunnel-type gate with flow over the gate. (a) Submerged flow; (b) Free-surface flow ($\Delta p/\gamma \le 0$); (c) Half-plan view

(d) overflow condition for typical arrangement of gate and gate chamber.

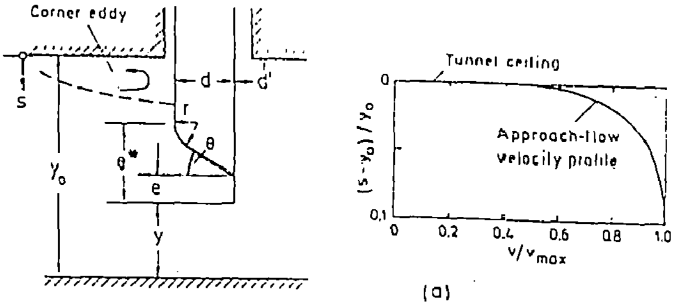


FIG. 4.20 Variation of C_c with relative gate opening for submerged flow as a function of geometric parameters θ, e/d, r/d, and y_o/d.

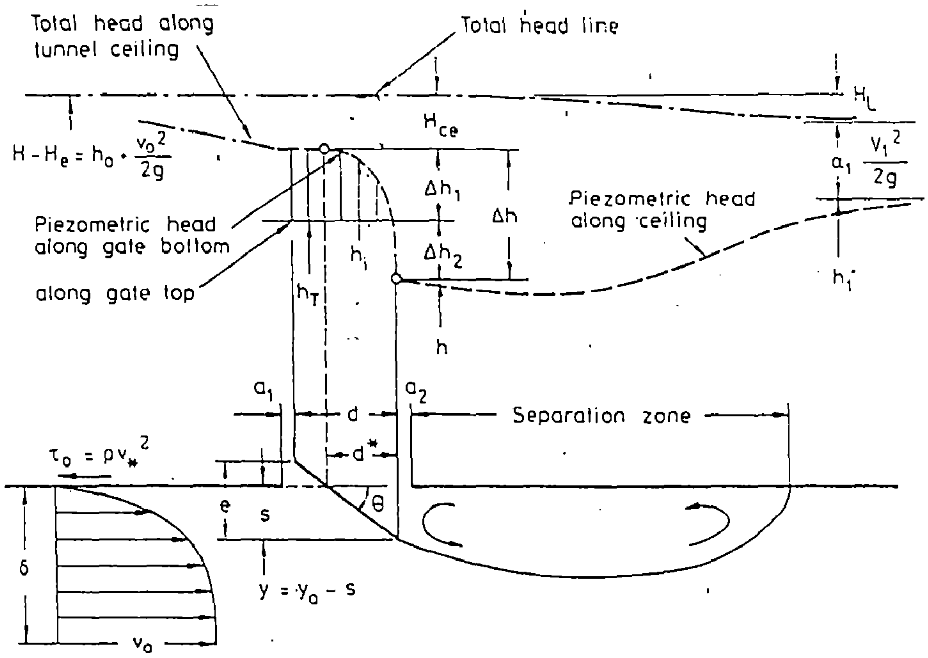
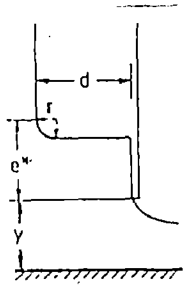


FIG. 4.21 flow conditions for extremely large gate openings ($y/y_o \rightarrow 1.0$).



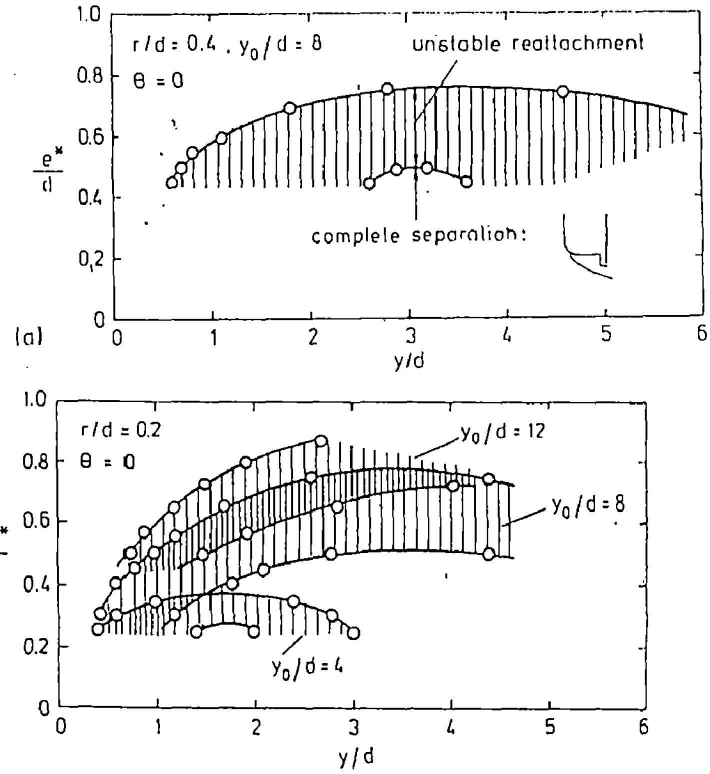


FIG. 4.22 Conditions of unstable reattachment of flow on the gate lip as a function of e^*/d and y/d.

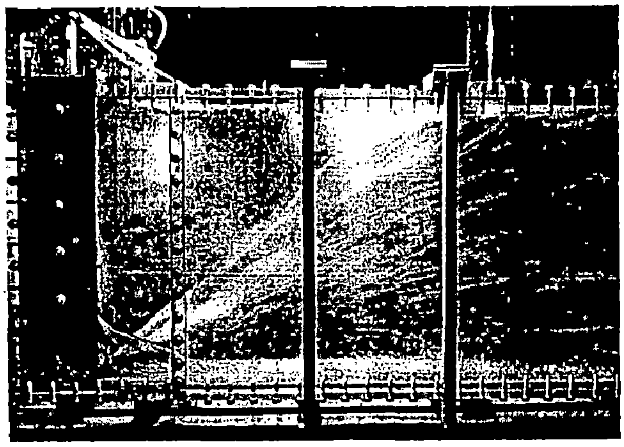


FIG. 4.23 Typical picture of spray jets emerging from gate slots at small gate openings with free-surface flow.

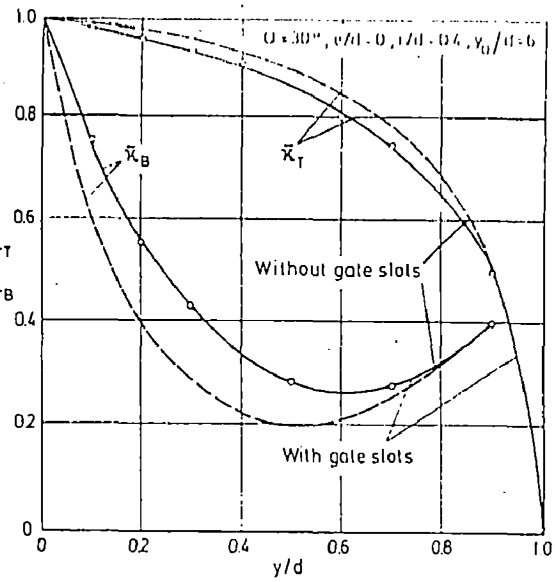


FIG. 4.24 Effect of gate slots on downpull coefficients for a typical tunnel-type gate without overflow

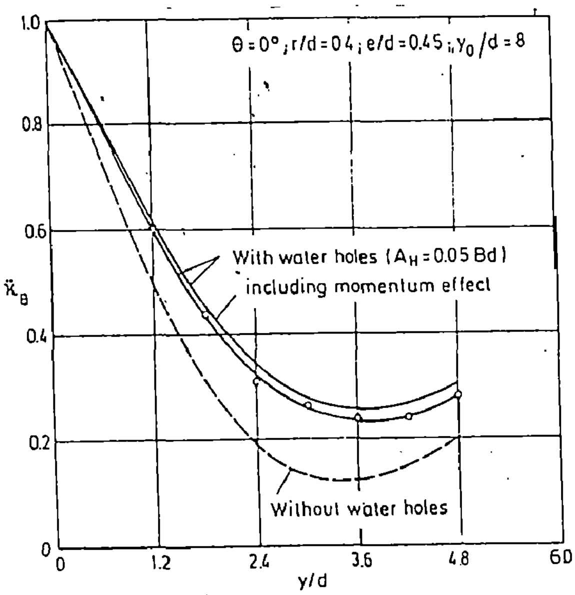


FIG. 4.25. Effect of water holes on $\bar{K}_B$ for a typical tunnel-type gate without gate slots and with no overflow.

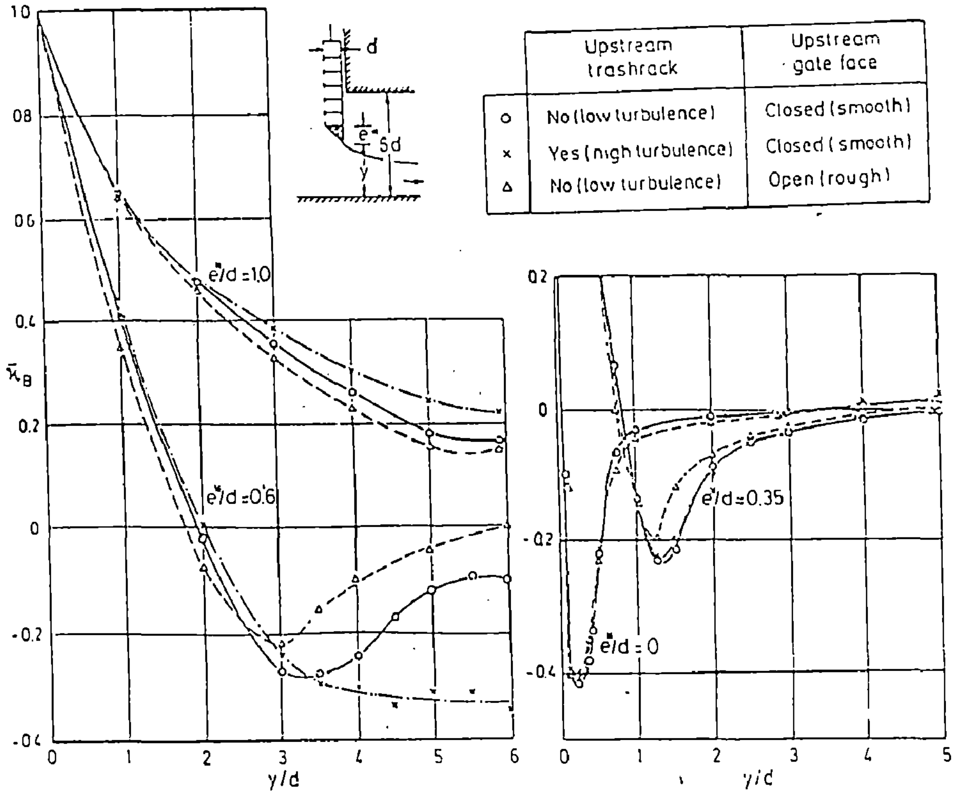


FIG. 4.26 Effect of approach-flow conditions on $\bar{K}_B$ for face-type gates (y_o/d = 20) with inclined bottom (r/d = 0) and no gate slots.

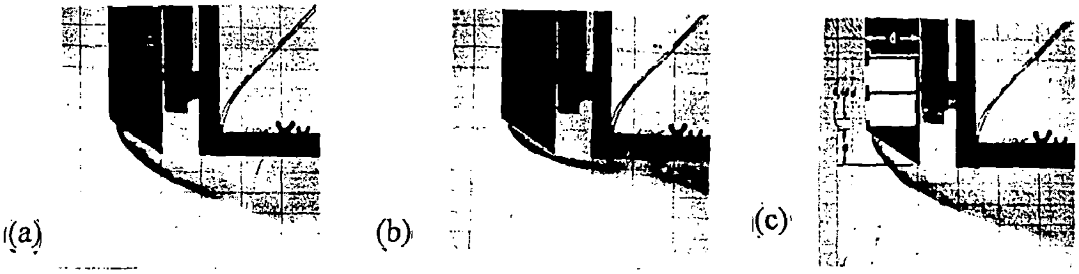
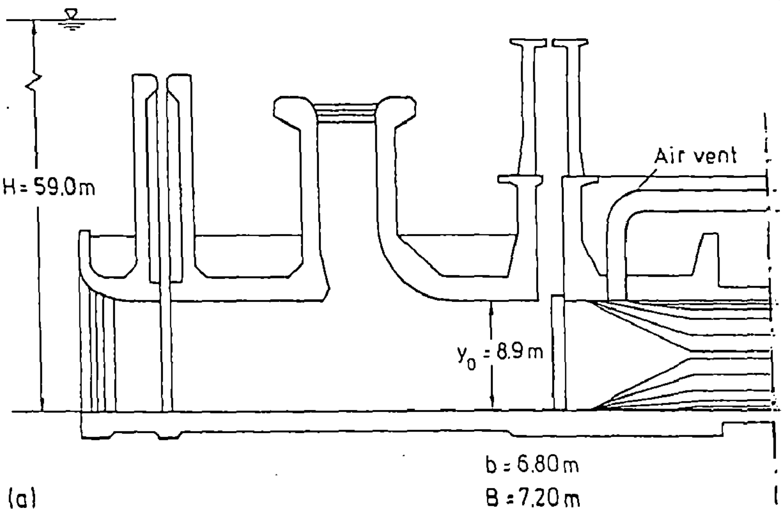


FIG. 4.27 Effect of approach-flow conditions on position of free shear layer face-type gate with $e/d = 0.6$ at $y/d = 6$. (a, b) Smooth upstream face; (c) Open girders.



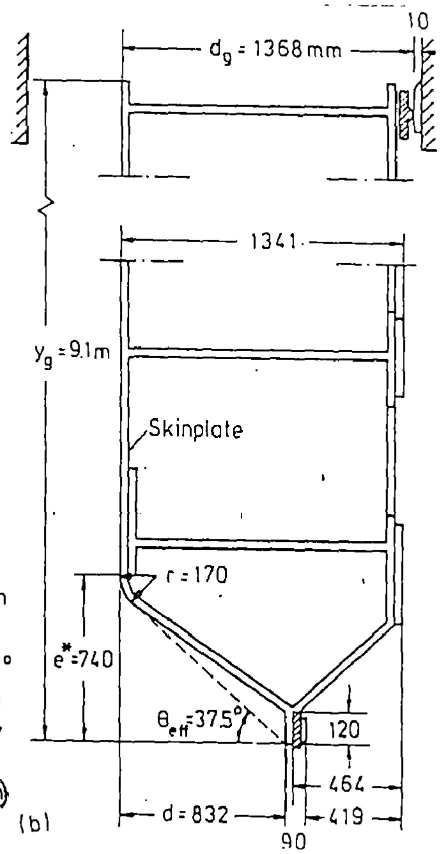


FIG. 4.28 (a) Bottom outlet with vertical leaf gate; (b) Cross-section of leaf gate.

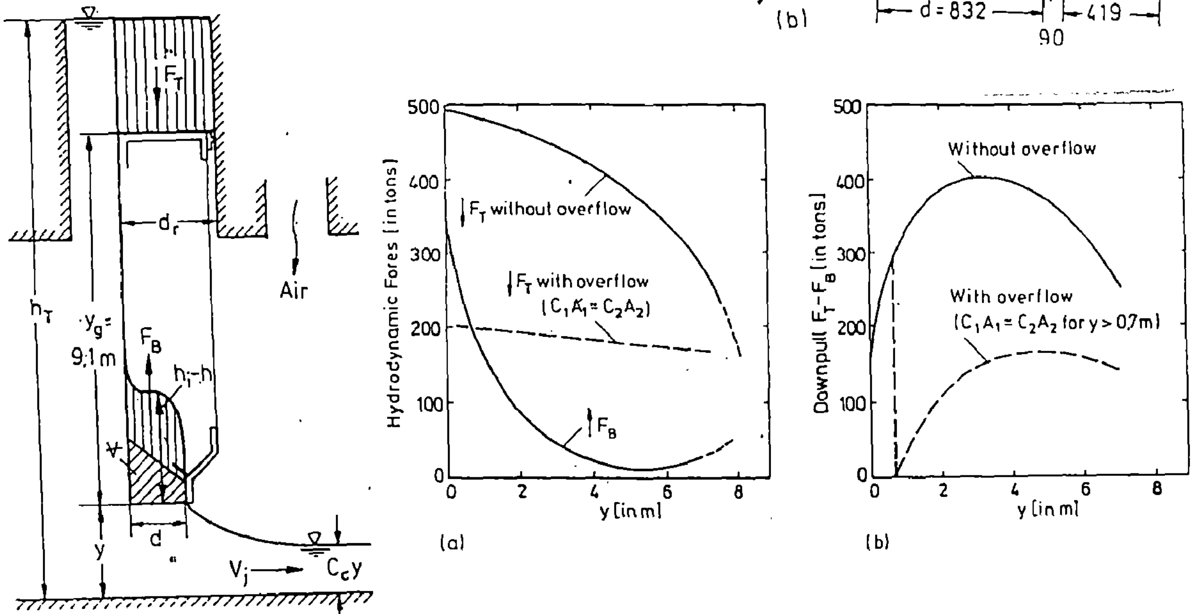
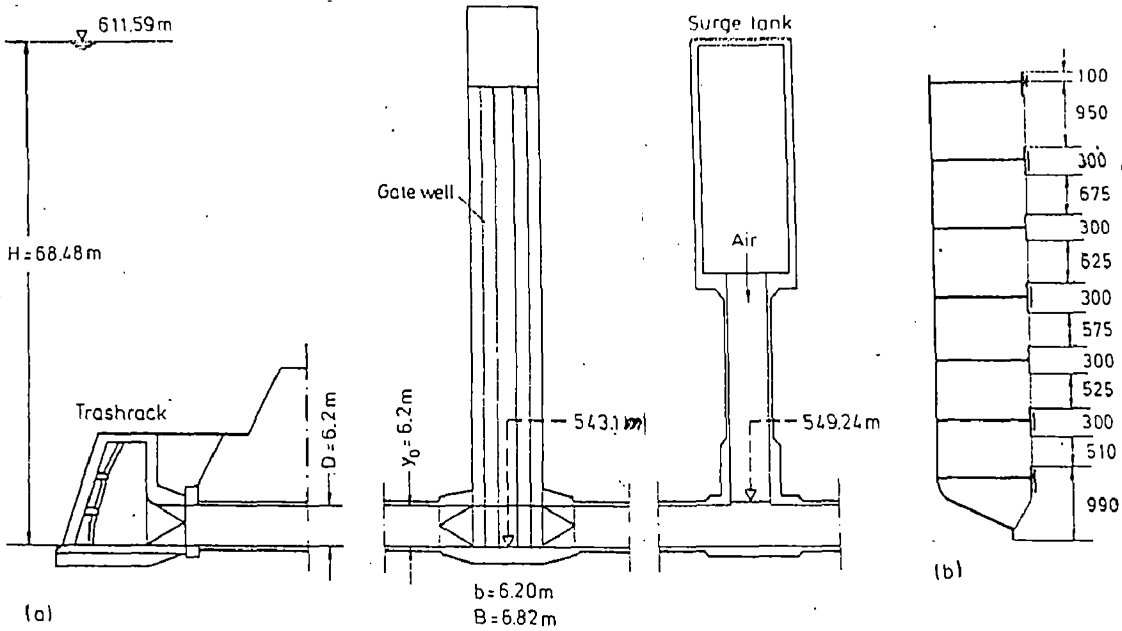


FIG. 4.29 Hydrodynamic forces on gate during operation (free-surface flow).



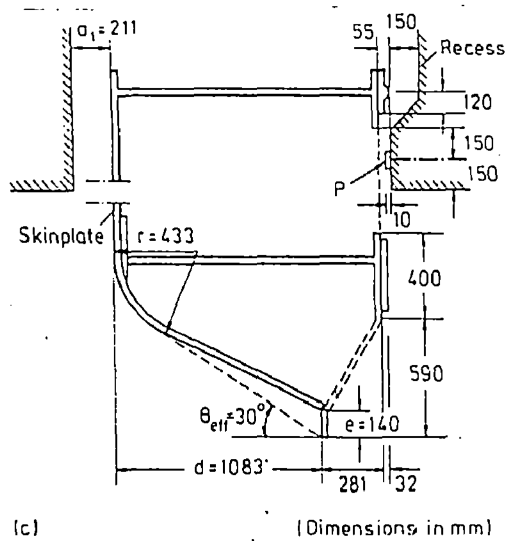


FIG. 4.30 (a) Turbine inlet with vertical leaf gates and surge tank; (b) Cross-section of leaf gate. (c) Detailed cross-section of gate.

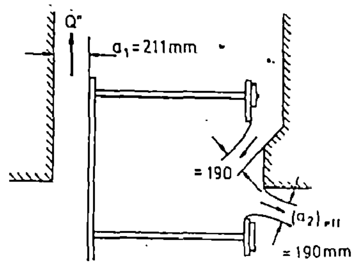


FIG. 4.31 Estimated flow configuration in gate chamber for gate opening $y \approx 570$ mm.

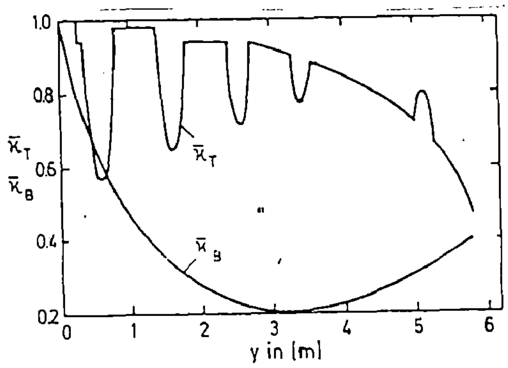


FIG. 4.32 Downpull coefficients

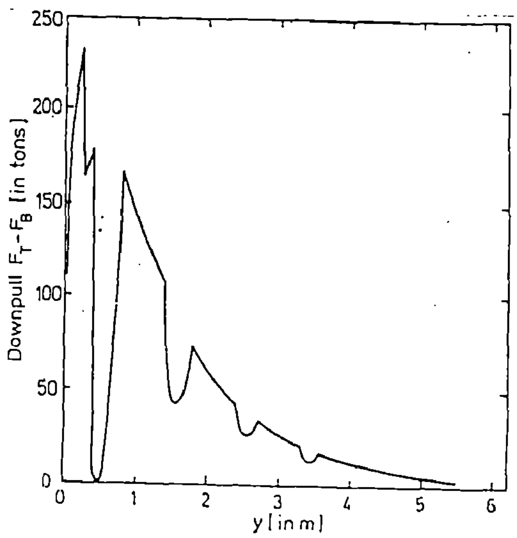


FIG. 4.33 Downpull on gate

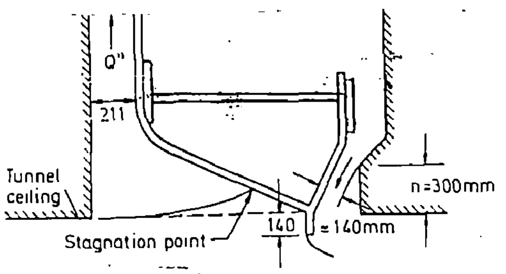
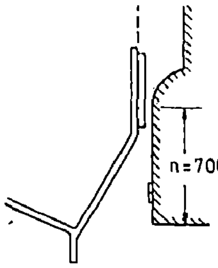


FIG. 4.34 Flow condition in the gate chamber for $y = y_o - e$ = 6.06 m.



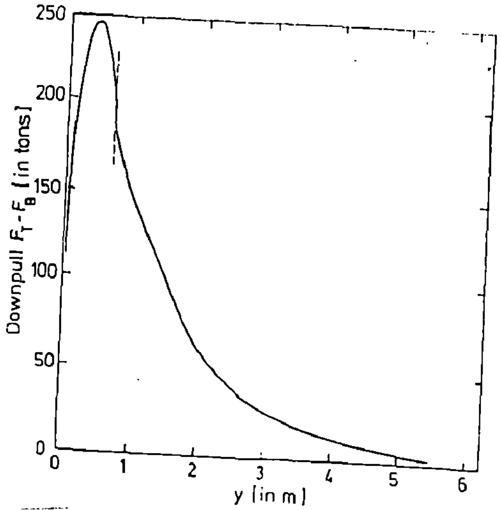


FIG. 4.35 . Downpull on gate with *n* changed from 300 to 700 mm

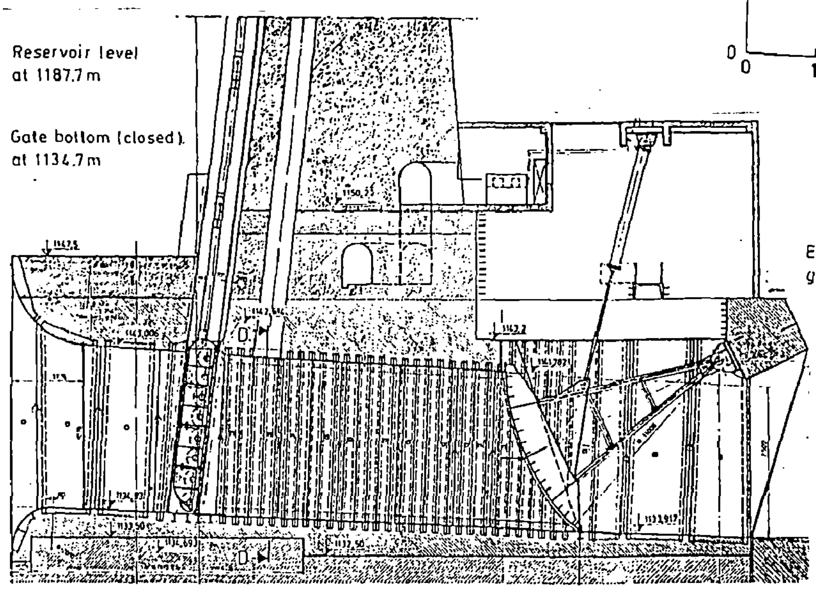


FIG. 4.36 Bottom outlet with emergency leaf gate and service' Radial type gate

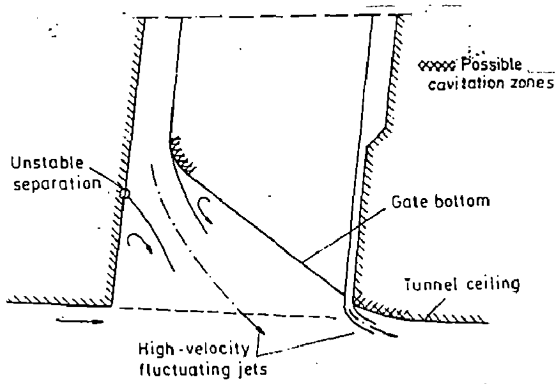


FIG. 4.37 Leaf gate in upper-most position (cavitation-danger spots shown by cross-hatching).

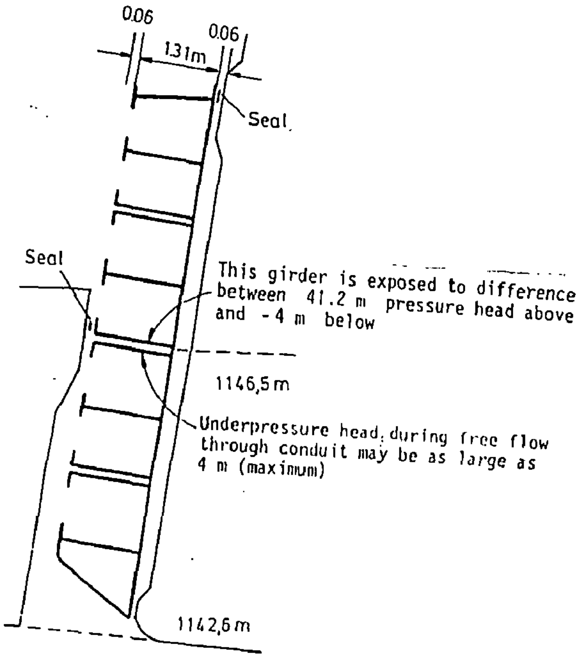


FIG. 4.38 Leaf gate with seals stopping the jet flows shown in Figure 3.53.

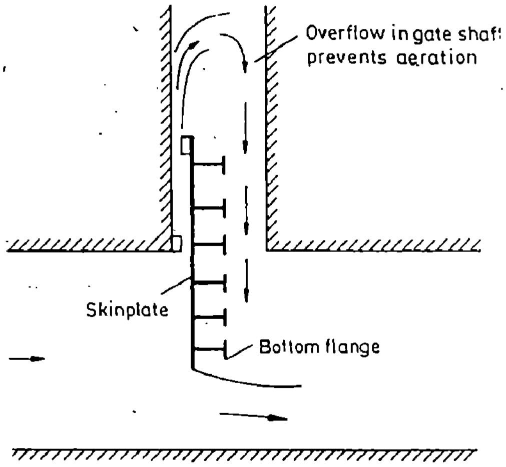


FIG. 4.39 Sketch of bottom outlet with free-surface flow past a leaf gate with upstream seals and skinplate.

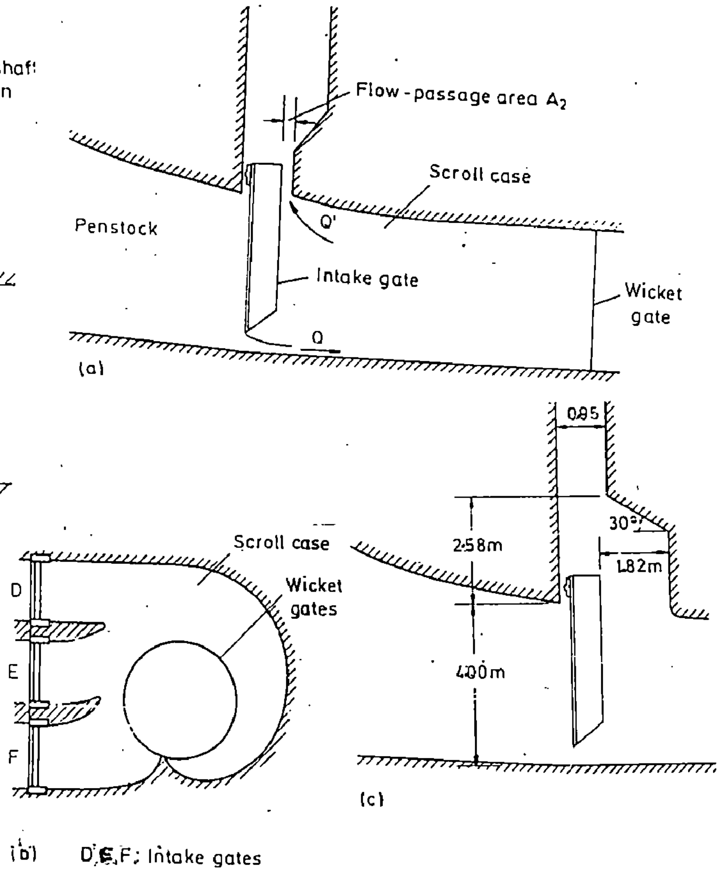


FIG. 4.40 Sketch of intake gates in a power house. (a) Watering-up operation with original design; (b) Plan view of scroll case with gates; (c) Improved design for safe watering-up operation.

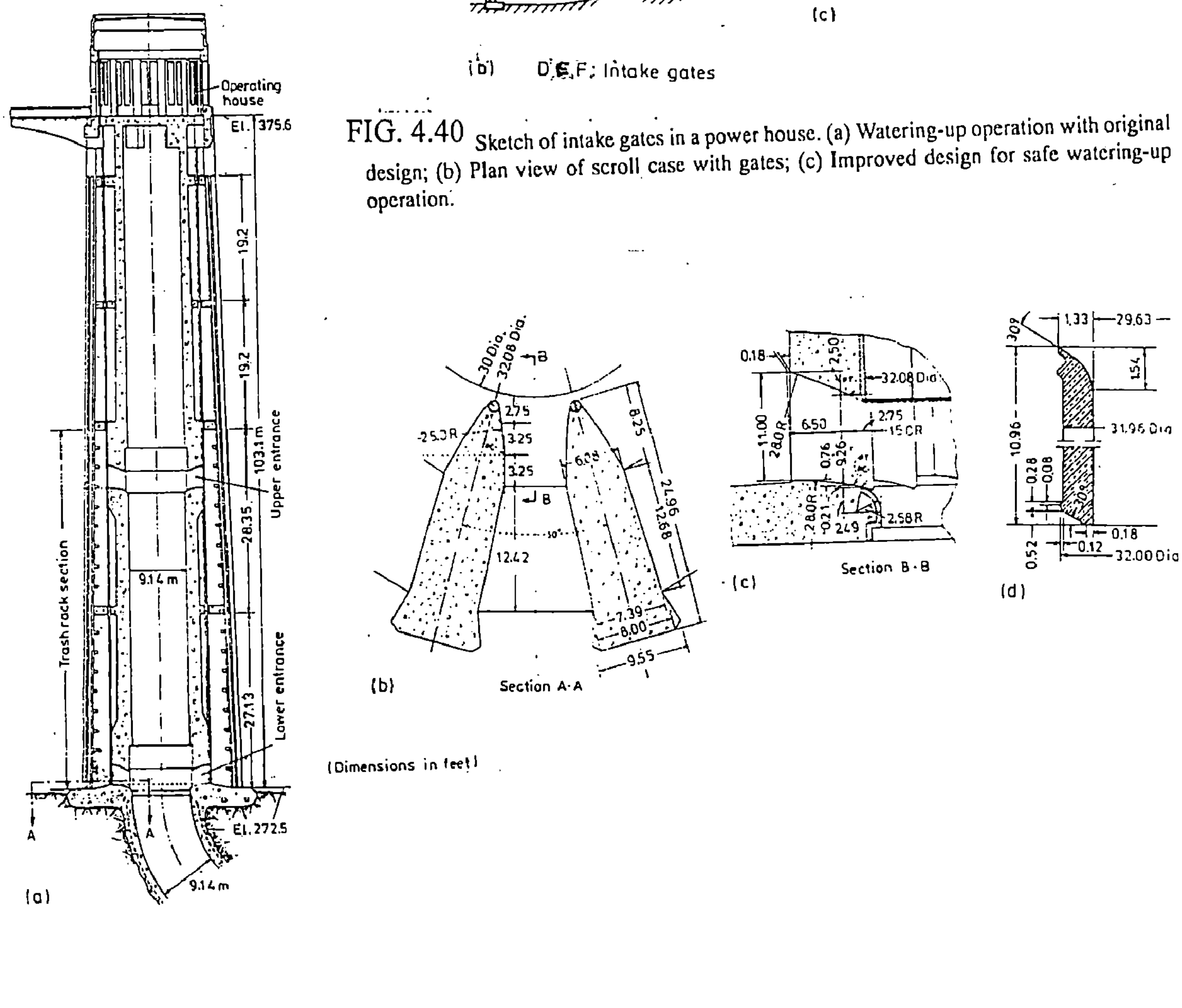


FIG. 4.41 (a) Vertical section of typical intake tower (Hoover-dam project); (b, c) Details of lower entrance; (d) Section of lower cylinder gate (after Martin & Ball, 1955, Colgate, 1959).

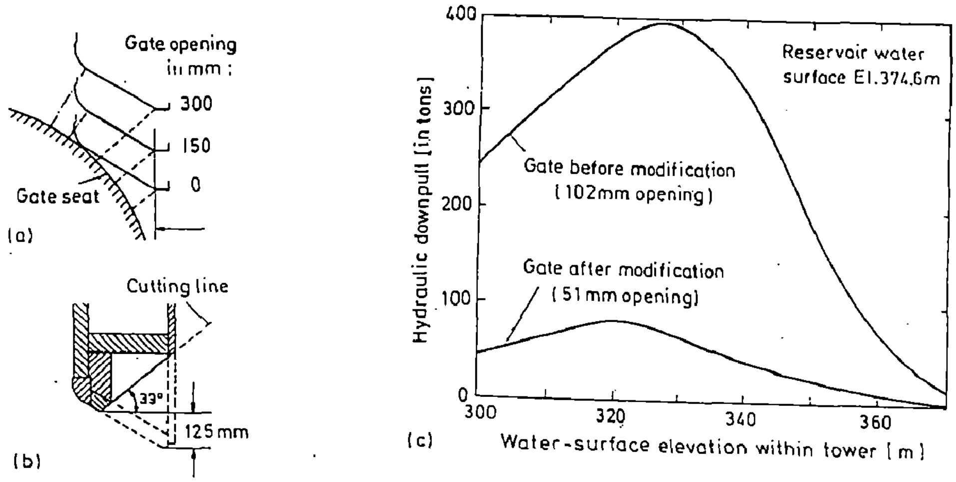


FIG. 4.42 (a, b) Gate bottom of lower cylinder gate shown in Figure 3.57d, (a) before and (b) after modification; (c) Hydraulic downpull as a function of water-surface elevation inside the tower for gate openings producing maximum downpull (after Martin & Ball, 1955).

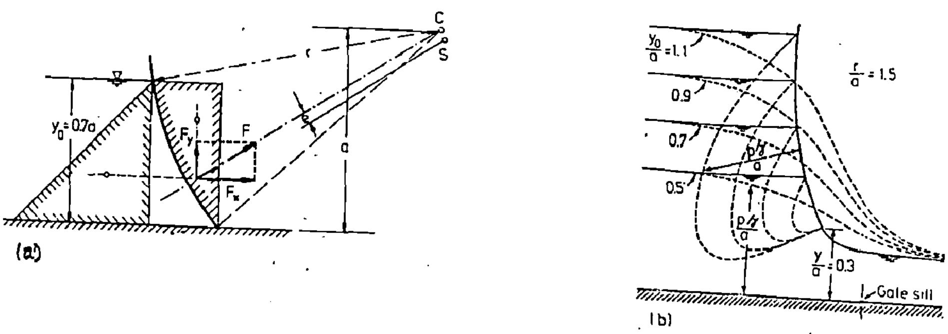


FIG. 4.43 (a) Hydrostatic load of gate with center of skinplate curvature at C and supporting pins at S; (b) Hydrodynamic pressure distribution of same gate for free-surface flow at gate opening $y = 0.3a$ (after Metzler, 1948).

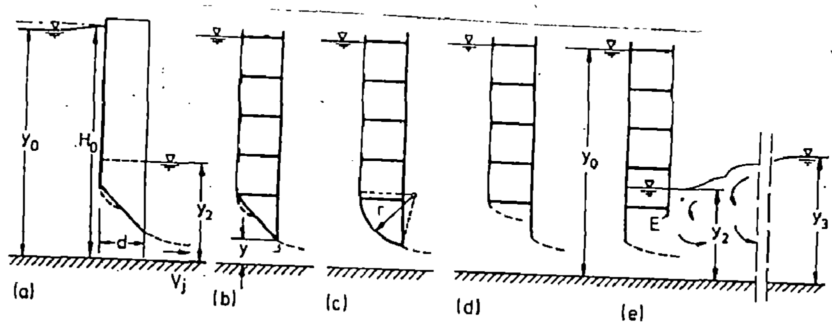


FIG. 4.44 Geometric configurations near the emerging jet common for vertical-lift gates with underflow.

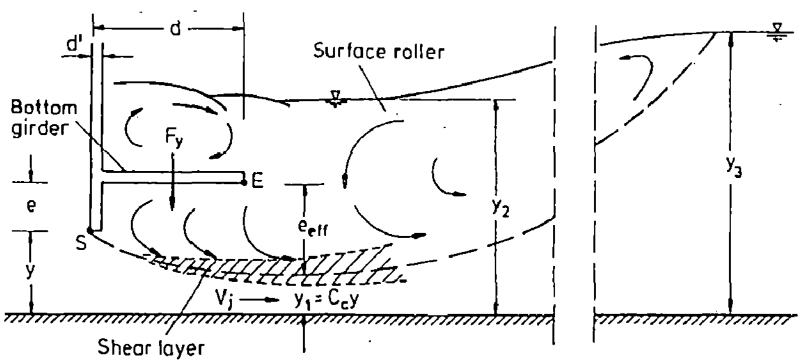


FIG. 4.45 Sketch of flow condition under a gate

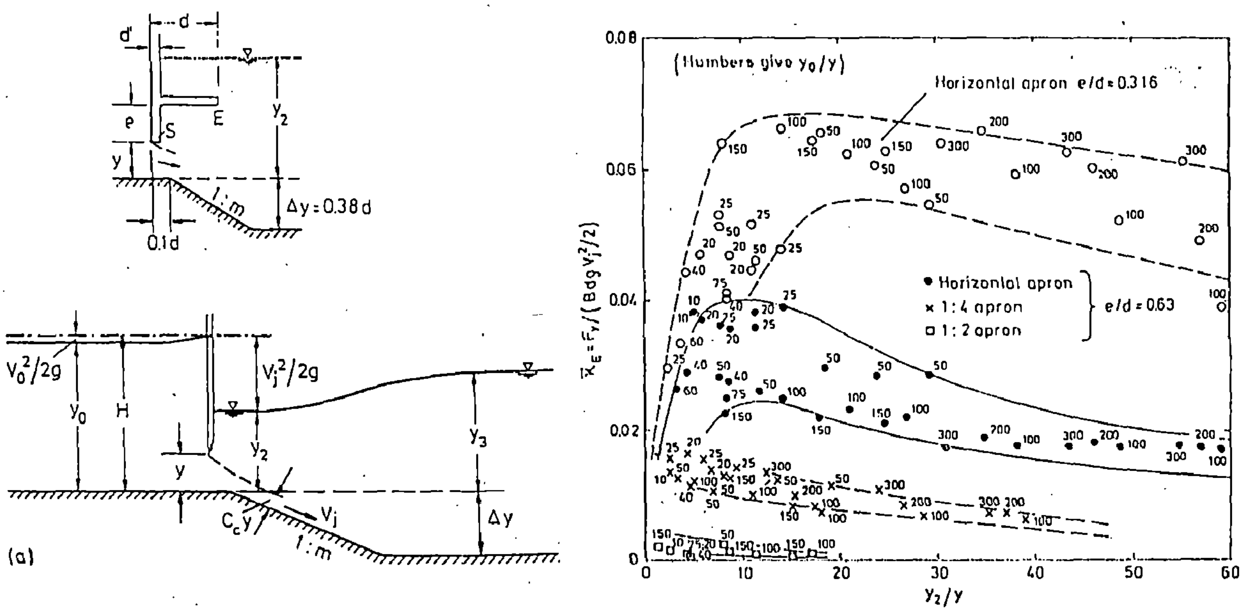


FIG. 4.46 Variation of $\bar{\kappa}_E$ with relative submergence for a gate according to Figure 4.18e (after Böss, 1954, and Naudascher, 1988).

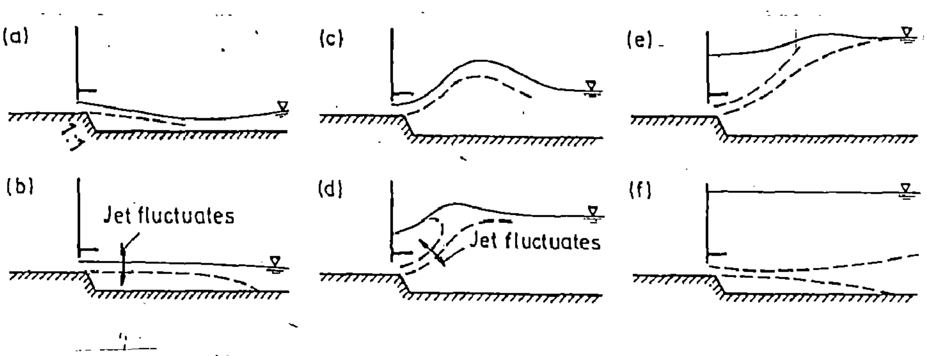


FIG. 4.47 Characteristic flow conditions for an apron form with flow separation (after Spiekermann, 1962).

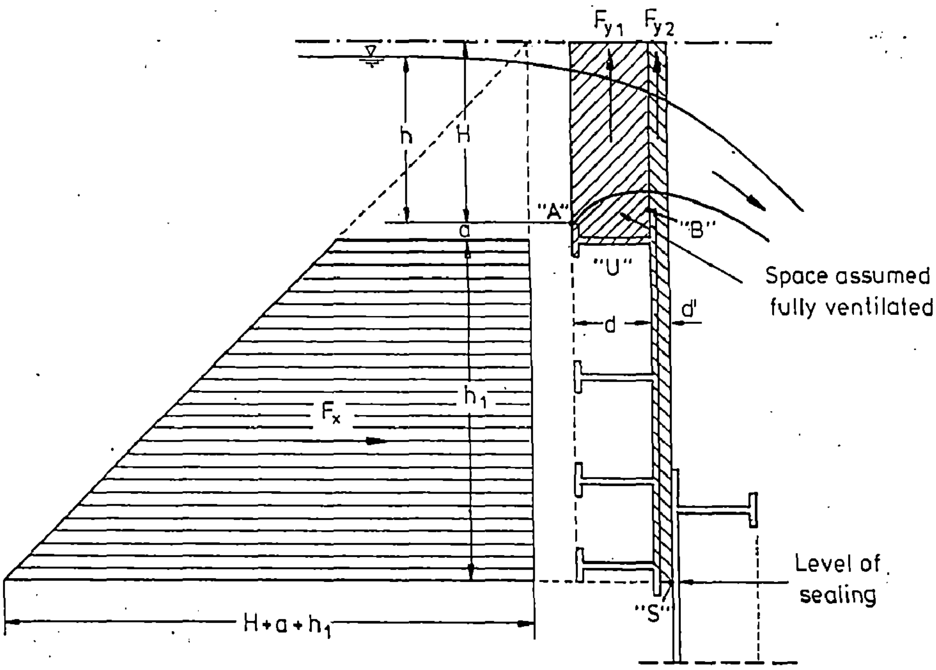


FIG. 4.48 Sketch of hydrodynamic forces acting on the upper leaf of a double-leaf gate during overflow (Figure 4.72).

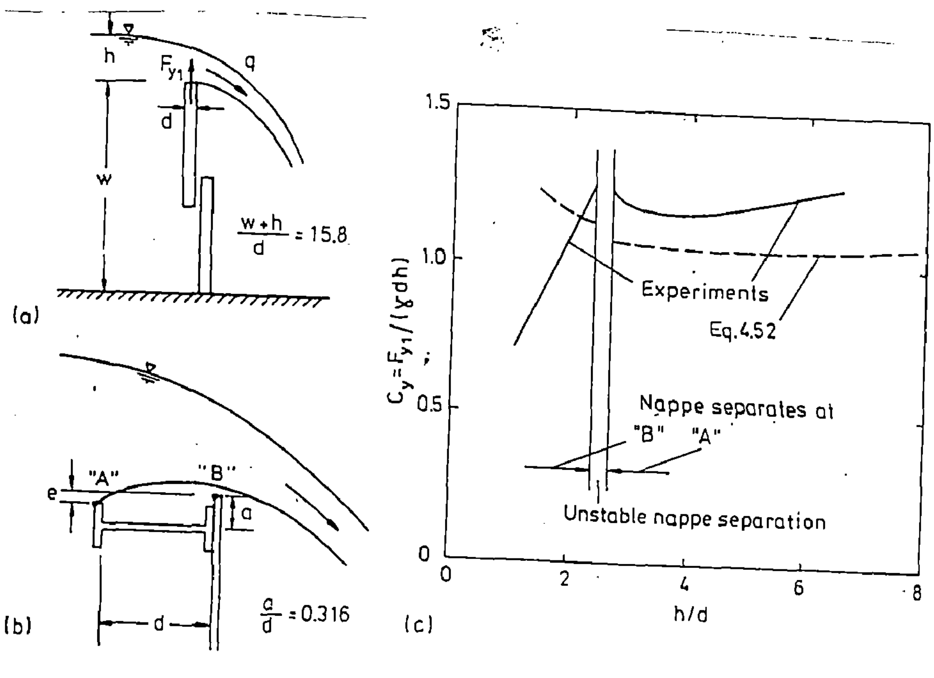


FIG. 4.49 Force coefficient C_y for a double-leaf gate (Figure 4.72) with flow fully ventilated downstream of point 'B'.

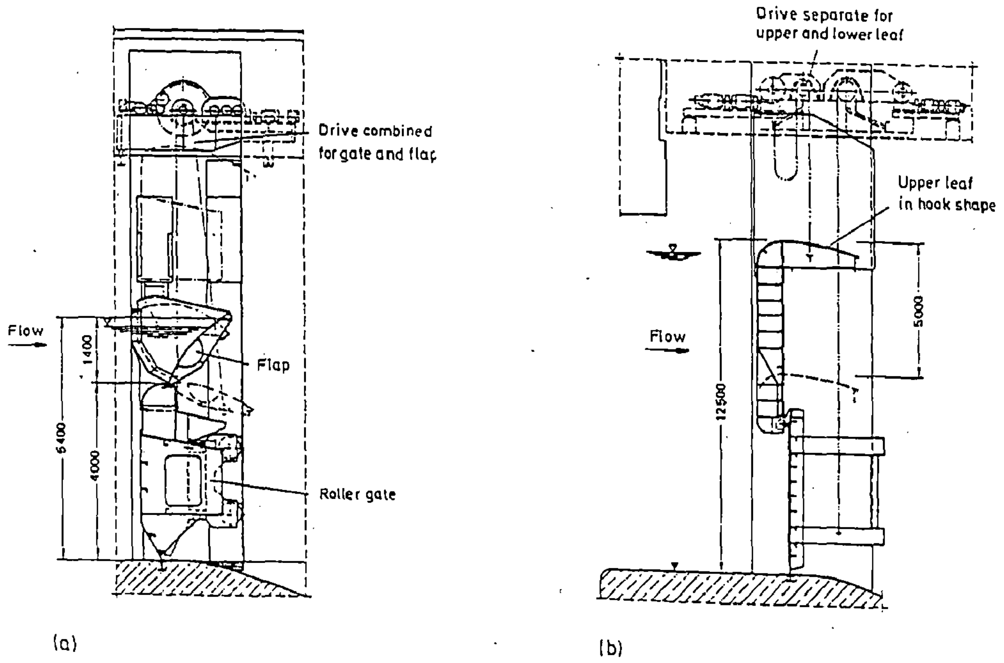


FIG. 4.50 (a) Leaf or roller gate with attached flap (B = 16 m); (b) Special double-leaf gate (B = 24 m)

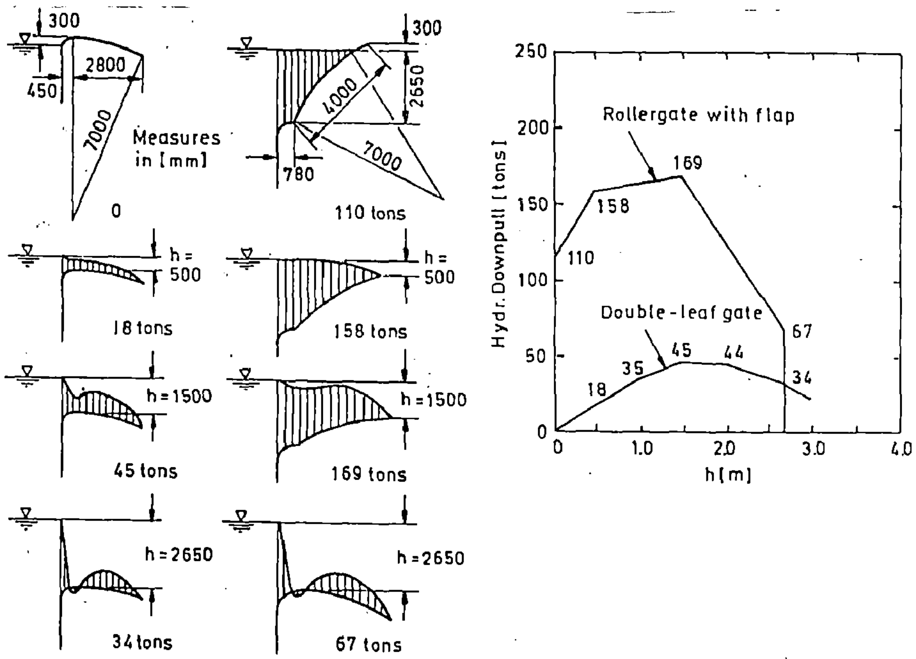


FIG. 4.51 Comparison of hydrodynamic downpull acting on upper part of gate for the two types of gates

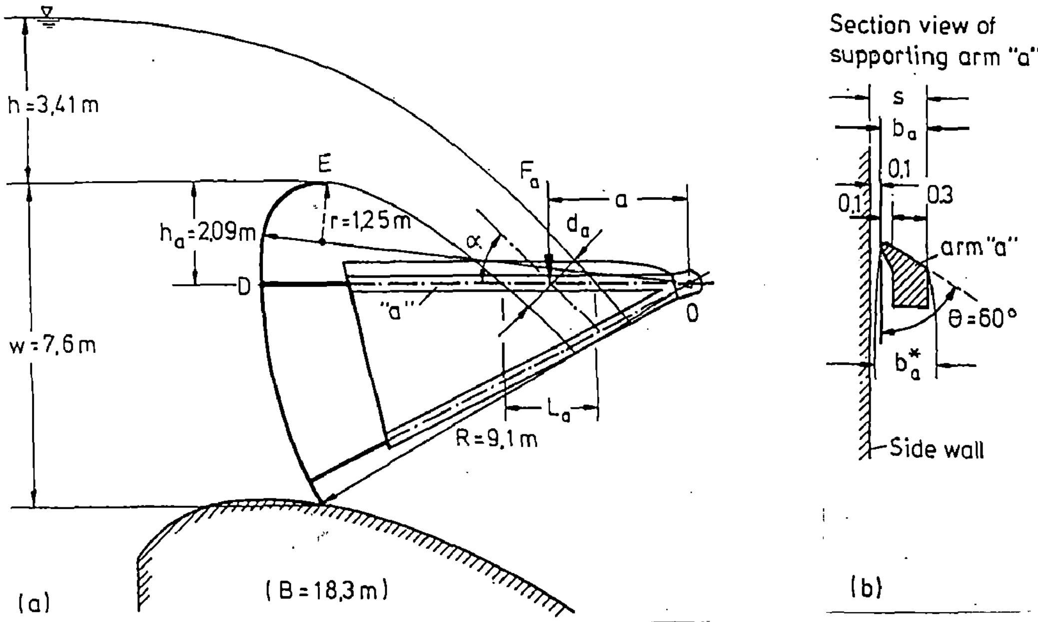


FIG. 4.52 Schematic of Tainter gate with overflow (after Böss, 1956).

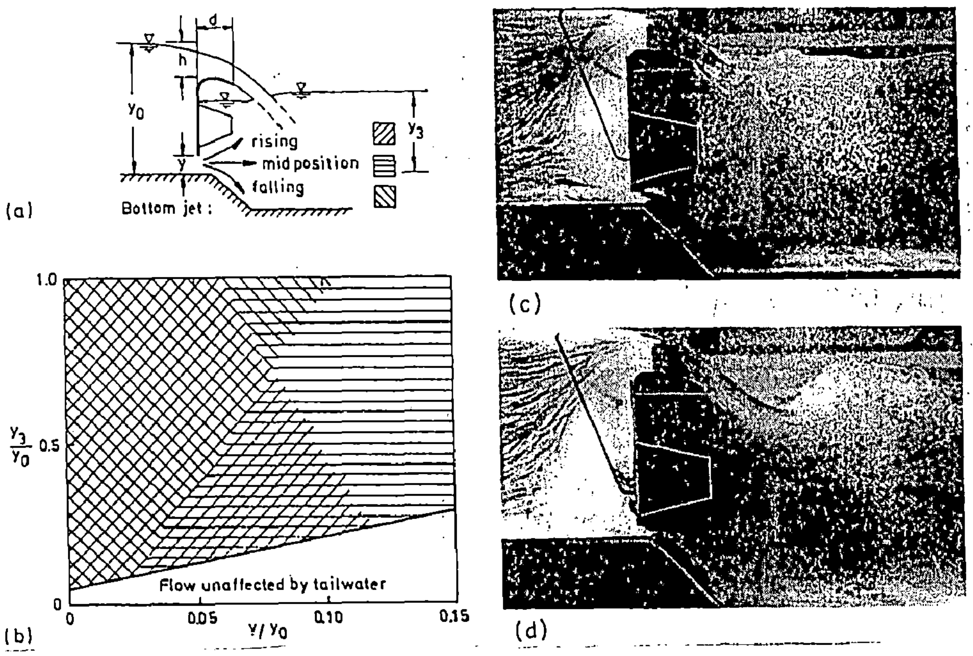


FIG. 4.53. Flow patterns observed with apron sh--
0.64).

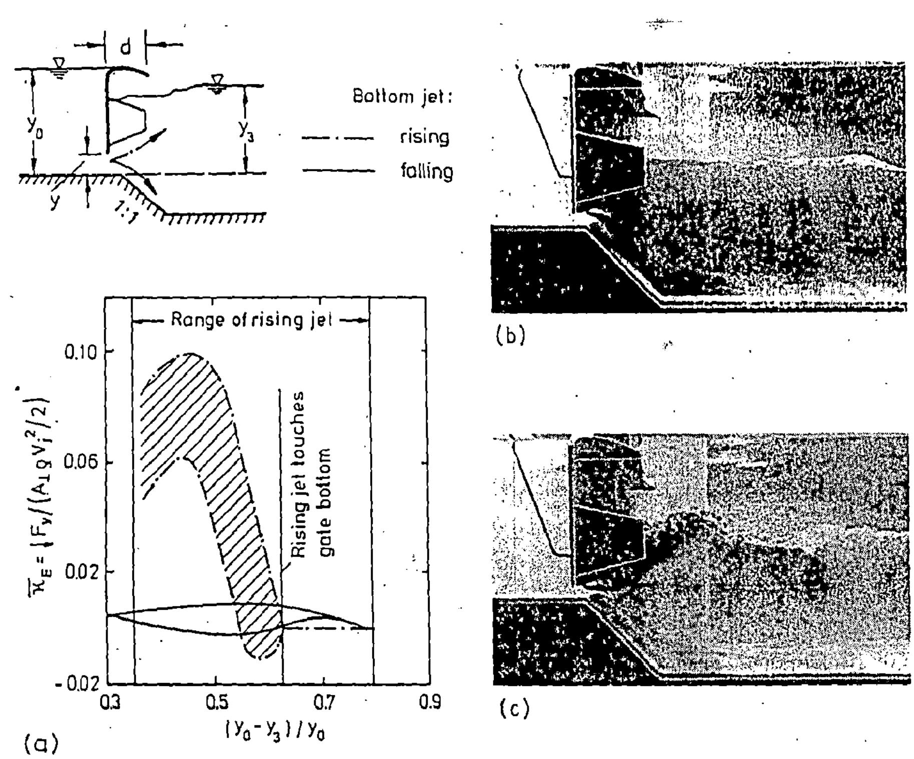


FIG. 4.54 (a) Coefficient $\bar{\kappa}_E$ of vertical hydrodynamic force on lower gate leaf (b, c) Flow patterns with bottom jet falling and rising ($y_o/d = 2.30$; $y/y_o = 0.07$).

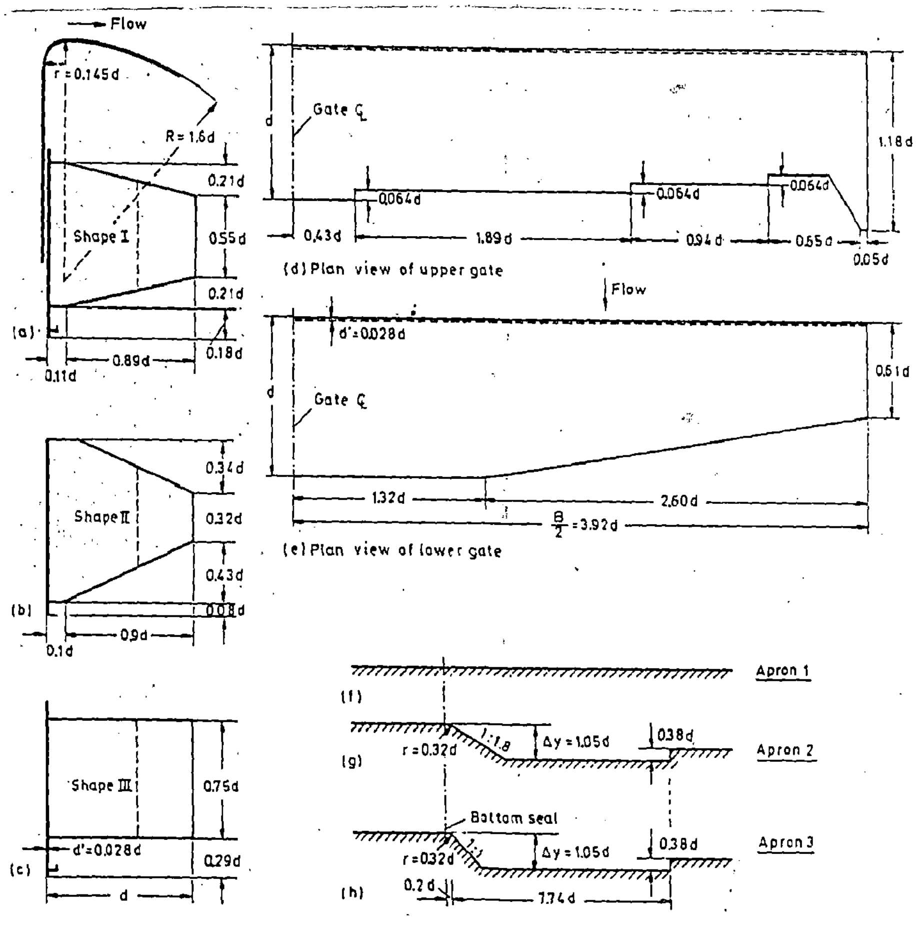


FIG. 4.55 Specific case of double-leaf gate. (a) Cross-section of gate; (b, c) Alternate shapes of lower gate leaf; (d, e) Plan view; (f, g, h) Apron shapes investigated.

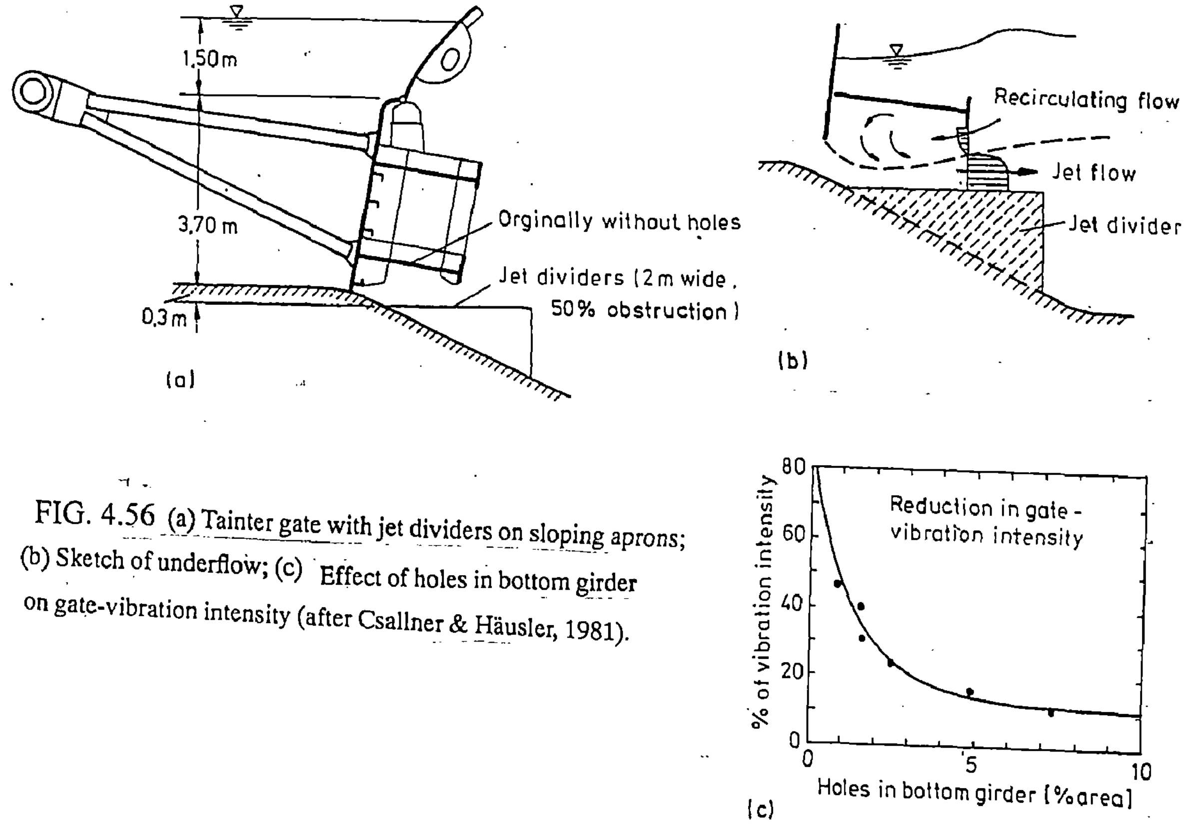


FIG. 4.56 (a) Tainter gate with jet dividers on sloping aprons; (b) Sketch of underflow; (c) Effect of holes in bottom girder on gate-vibration intensity (after Csallner & Häusler, 1981).

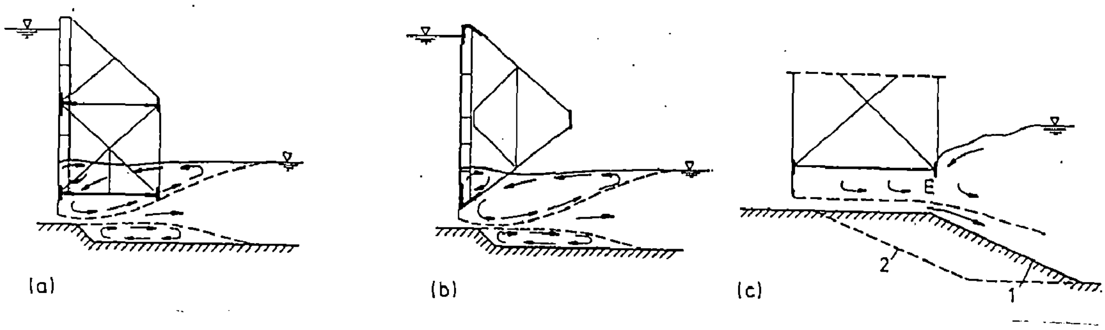


FIG. 4.57 (a, c_1) Unfavorable flow conditions leading to excessive fluctuations of the load on the gate; (b, c_2) Possible remedial designs.

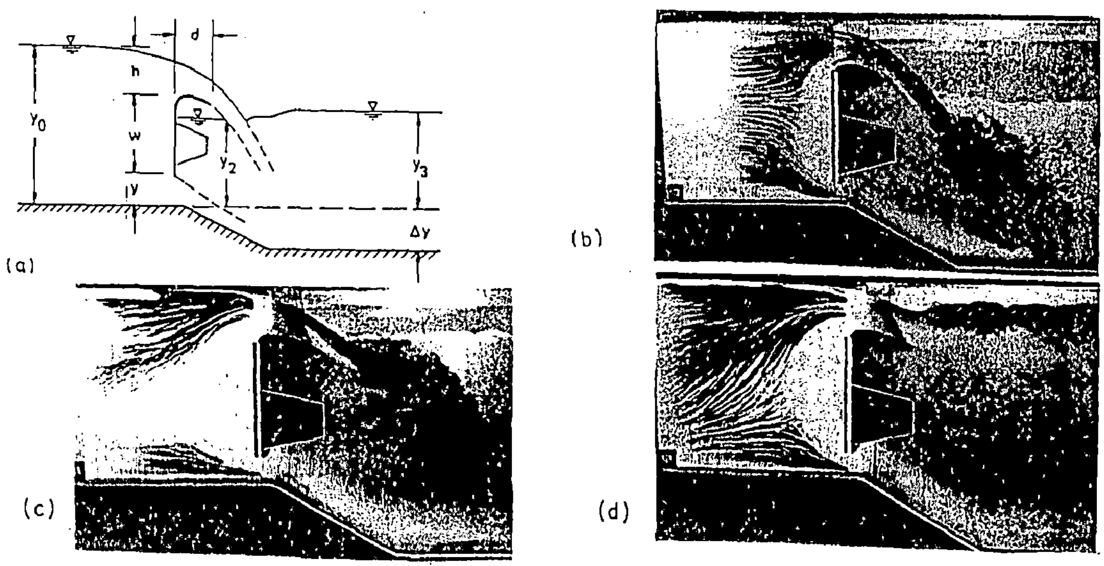


FIG. 4.58 Flow patterns observed for various tailwater conditions with apron 2 (y_o/d = 2.95; h/d = 0.64; y/d = 0.32).

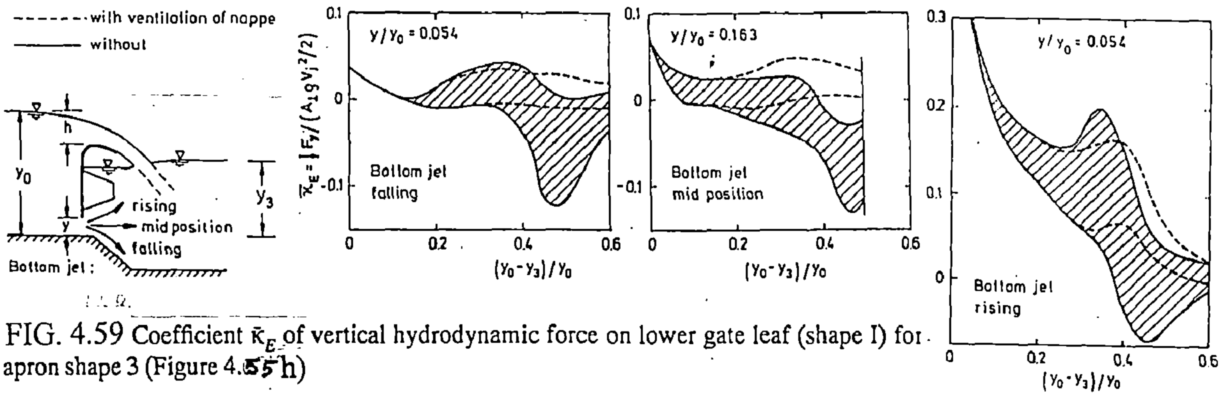


FIG. 4.59 Coefficient $\bar{\kappa}_E$ of vertical hydrodynamic force on lower gate leaf (shape I) for apron shape 3 (Figure 4.55h)

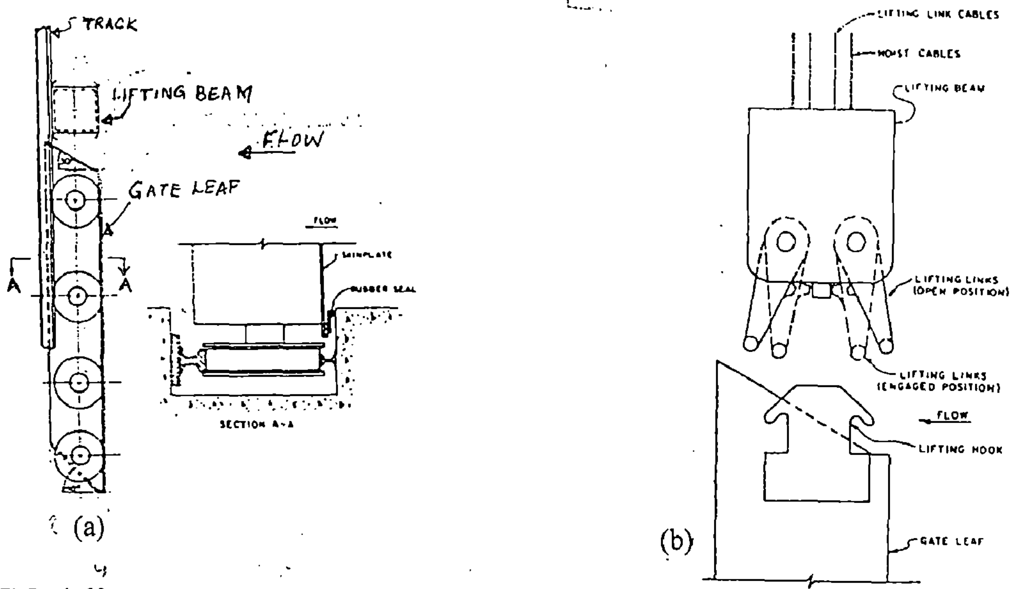
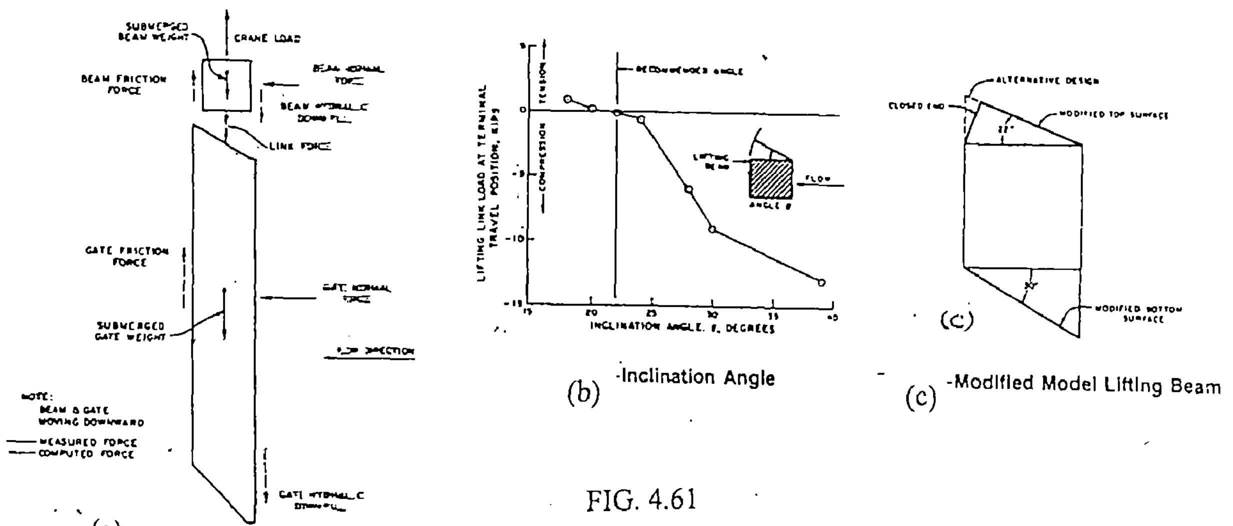


FIG. 4.60—Gate Leaf and Lifting Beam

Lifting Link Positions

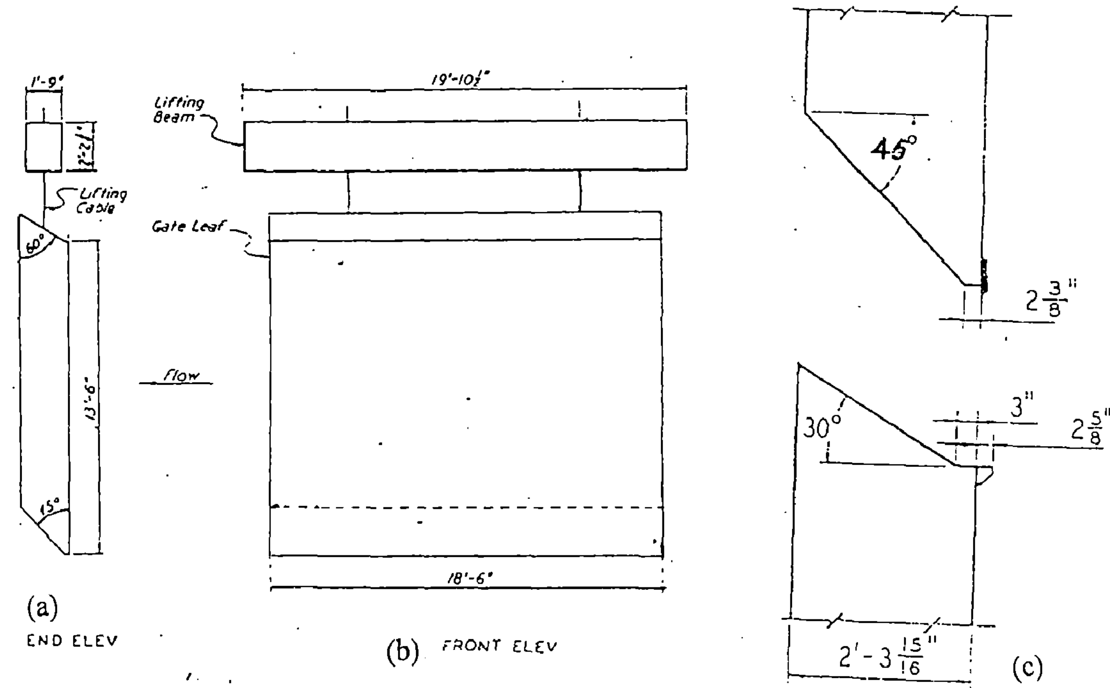


(a) Force Diagram

(b) -Inclination Angle

(c) -Modified Model Lifting Beam

FIG. 4.61



(a) END ELEV

(b) FRONT ELEV

(c)

FIG. 4.62 SCHEME ~~1—FINAL~~ GATE LEAF DESIGN

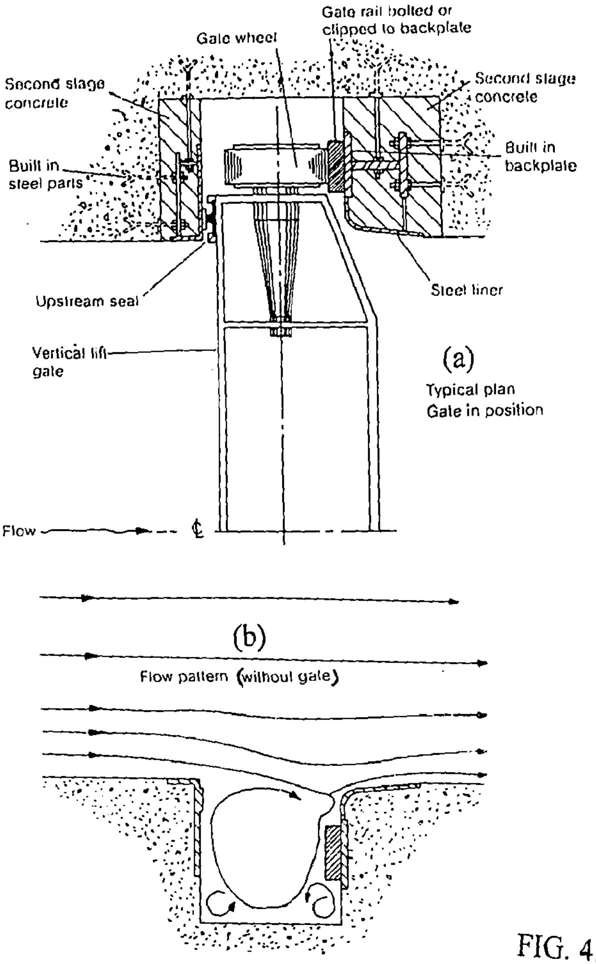


FIG. 4.63

Typical gate and slot arrangements with possible flow pattern

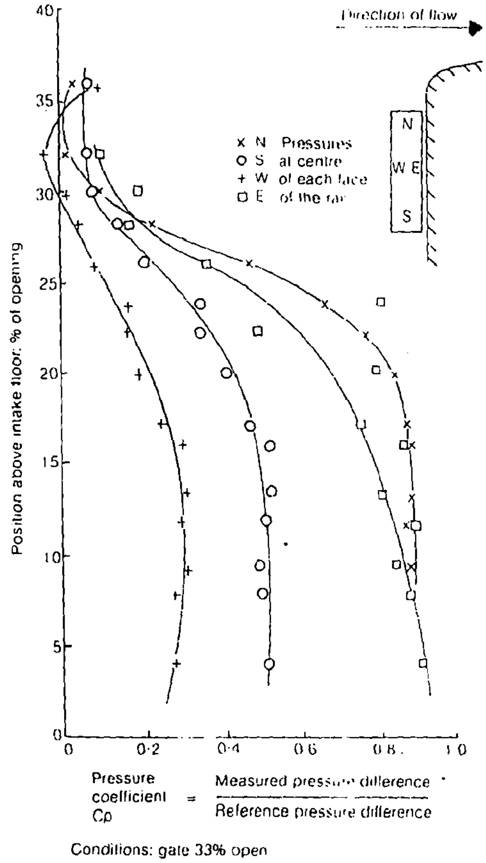


FIG. 4.64 *Typical summary diagram of pressure distributions*

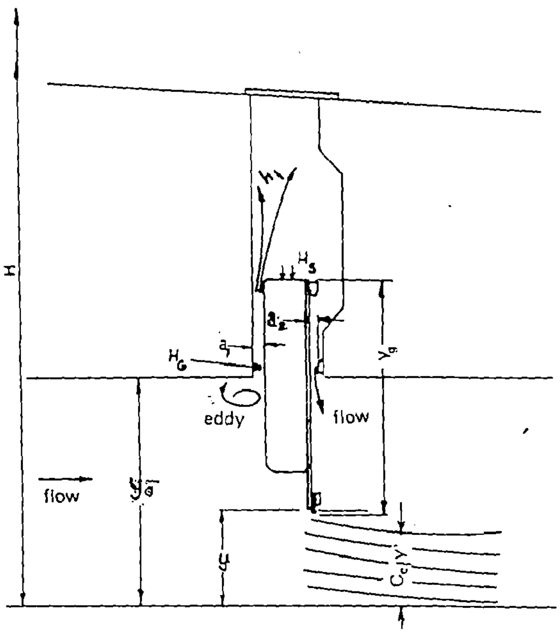


FIG. 4.65

Prediction of gate shaft pressure

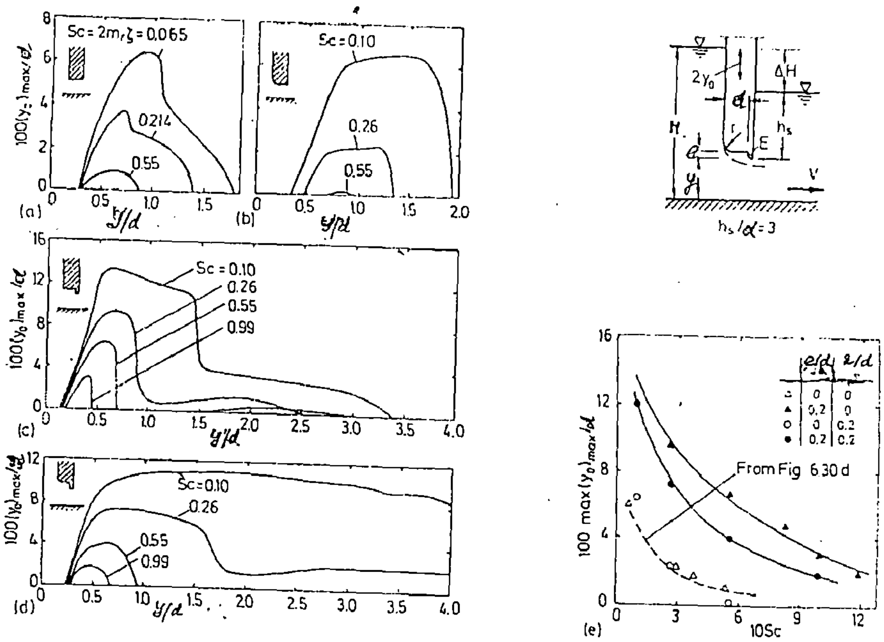


FIG. 4.66 . Ranges of instability-induced vertical excitation of gates and maximum amplitudes attained for various shapes of gate bottom (after Kanne, 1989). (a) $e/d = r/d = 0$; (b) $e/d = 0$, $r/d = 0.2$; (c) $e/d = 0.2$, $r/d = 0$; (d) $e/d = r/d = 0.2$; (e) Summary plot.

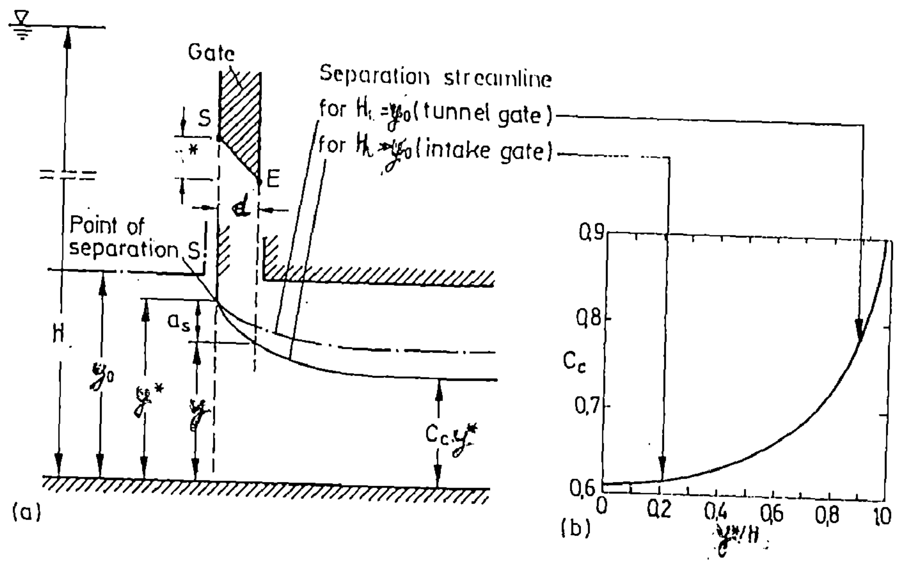


FIG. 4.67 (a) Schemes for assessing the susceptibility of a leaf gate to flow-induced vertical vibration. (b) Contraction coefficient C_c for submerged, turbulence-free flow. (For tunnel gates, $H = y_0$ if effect of corner eddy is disregarded.)

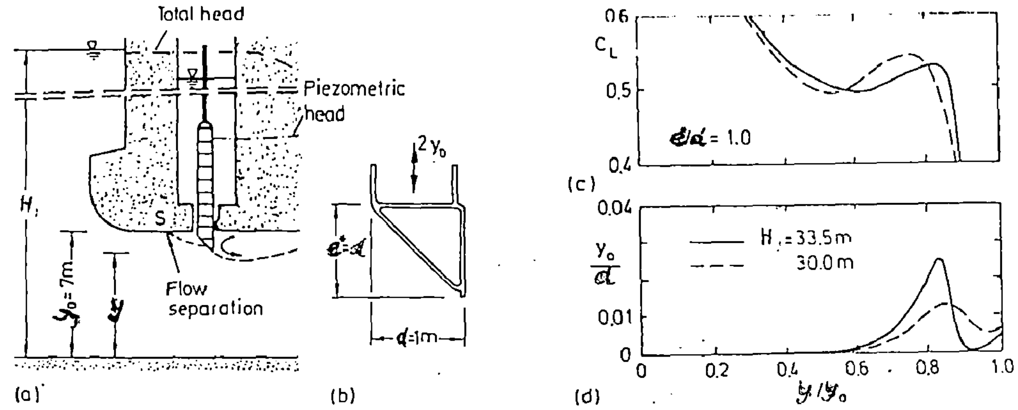


FIG. 4.68: Application of instability indicator to extraordinary case of leaf gate with destabilizing upstream flow separation (after Nguyen, 1990). (a, b) Gate arrangement and detail of gate bottom; (c) Corresponding mean-lift coefficient, and (d) response diagram for estimated values $V_r = 5$ and $Sc \equiv 2m_r\zeta \simeq 1$.

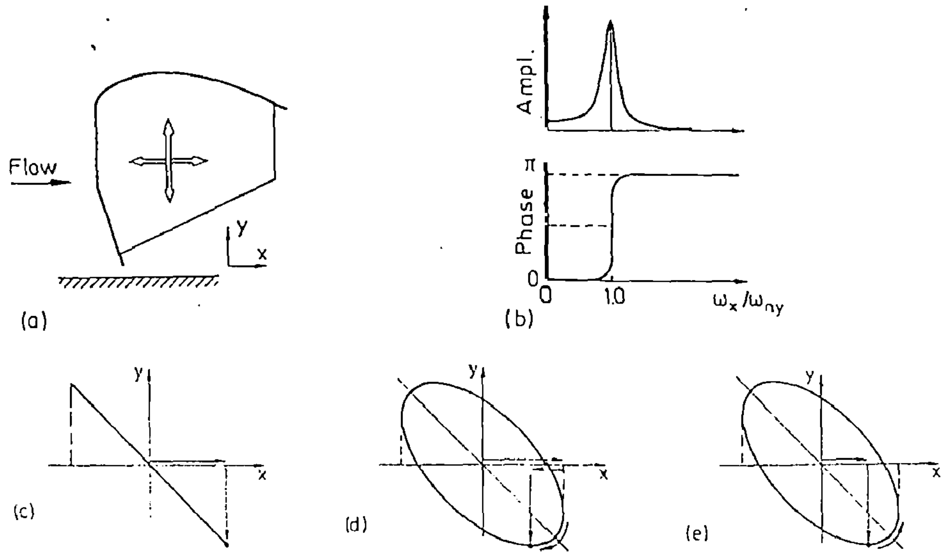


FIG. 4.69 (a) Shell-type long-span gate with degrees of freedom in vertical and horizontal directions. (b) Amplitude and phase response of a classical oscillator. (c-e) Traces of gate amplitudes for (c) $\omega_x = \omega_{ny}$, (d) ω_x slightly greater than ω_{ny}, and (e) ω_x slightly less than ω_{ny} (after Ishii et al., 1993).

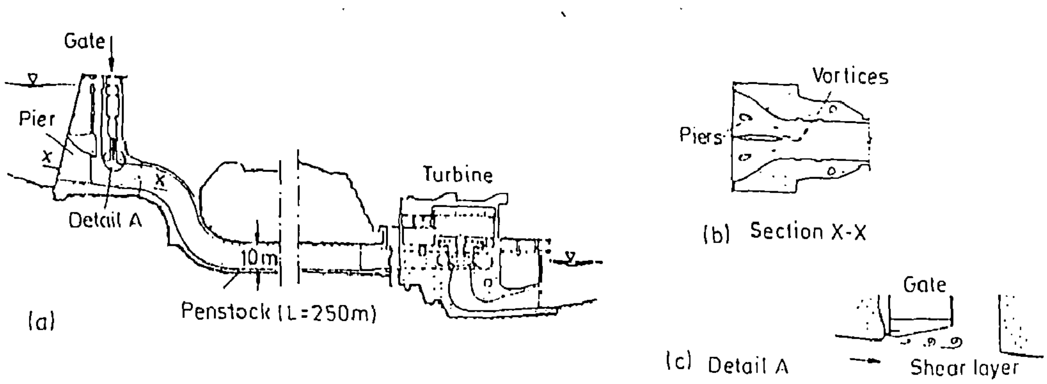


FIG. 4.70

Hydro-power system with gate vibrations associated with penstock resonance (after Hardwick et al., 1980).

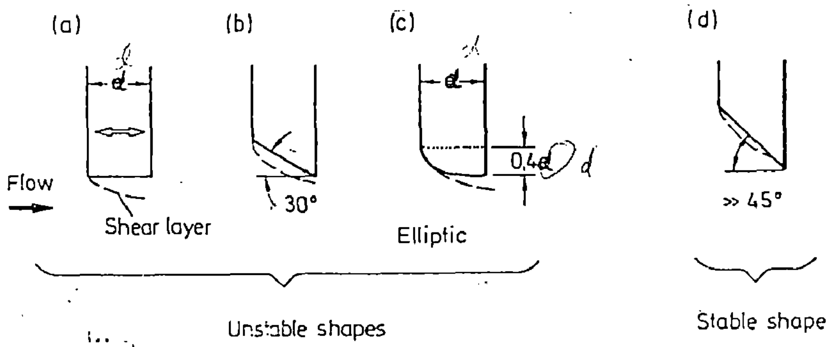


FIG. 4.71 Unstable and stable bottom shapes for gates free to undergo horizontal vibrations.

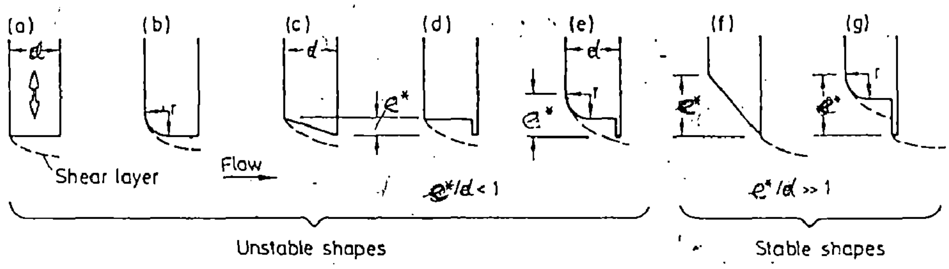


FIG. 4.72 Unstable and stable bottom shapes for gates free to undergo vertical vibrations

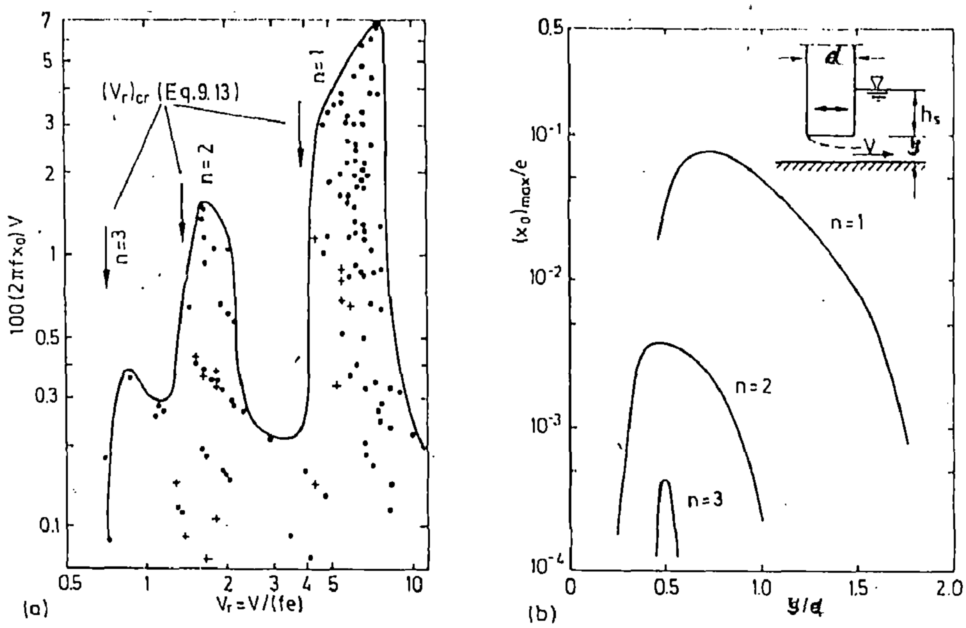


FIG. 4.73. Characteristics of instability-induced excitation of lightly-damped gate plates (after Jongeling, 1988). (a) Envelope of skinplate responses in horizontal direction (x_o = tip amplitude); (b) Ranges of excitation and maximum amplitudes attained for resonance with ILEV modes n = 1, 2, and 3. [e = 20 mm, h_s/e = 4 to 25, $\Delta H = V^2/2g$, $\zeta \simeq 0.0025$ in air.]

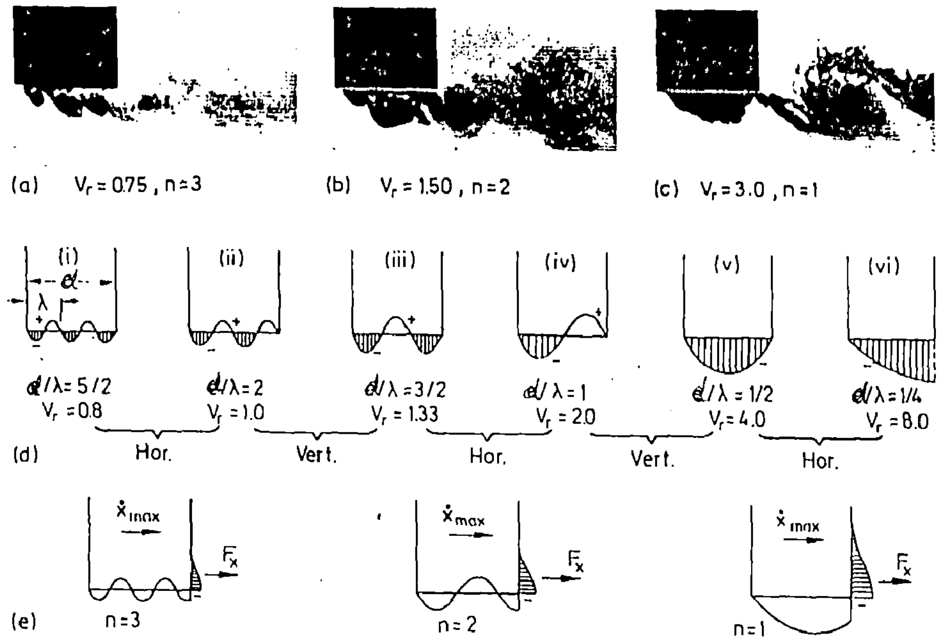


FIG. 4.74. (a-c) Instantaneous flow patterns at various reduced velocities V_r during controlled horizontal gate vibrations showing modes n = 3, 2, and 1 of impinging leading-edge vortices (ILEV) (after Nguyen, 1990). (d, e) Sketches of instantaneous pressure distributions (for $\dot{x} = \dot{x}_{max}$) characterizing (d) onsets of horizontal and vertical gate vibrations and (e) typical resonance conditions of a gate vibrating horizontally with ILEV modes n = 3, 2, and 1.

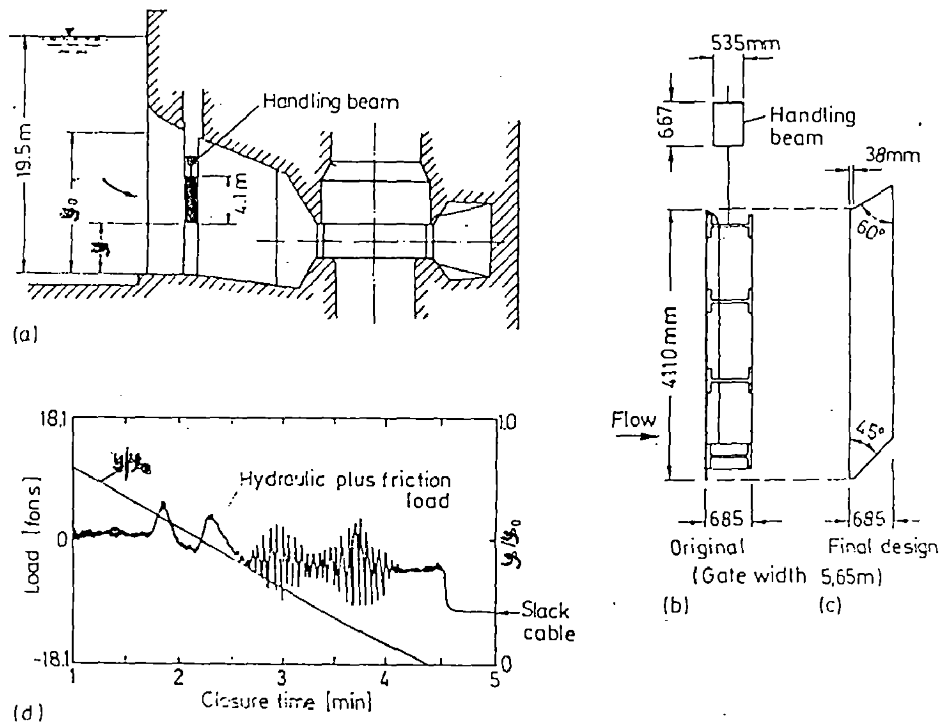


FIG. 4.75. (a) Section of power house with first of three leaf gates in half-lowered position; (b, c) Cross-section of leaf gates tested in a model. (d) Combined hydrodynamic and friction load acting on original design of leaf gate and handling beam during closure of the first leaf (Elder & Garrison, 1964).

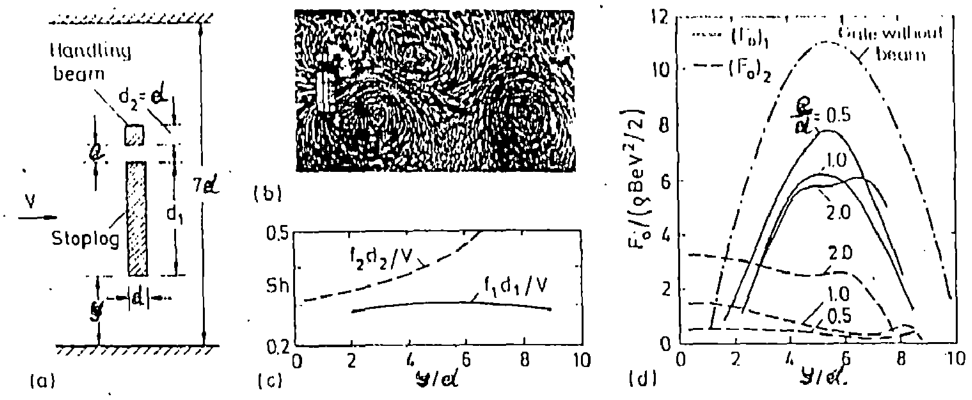


FIG. 4.76. (a) Definition sketch of stoplog (height d_1) and handling beam (height $d_2 = e$). (b) Visualization of shed vortices (camera moving). (c) Strouhal numbers $Sh_{1,2}$ and (d) maximum amplitudes $(F_o)_{1,2}$ of major components of fluctuating vertical load as a function of position (after Naudascher & Farell, 1965).

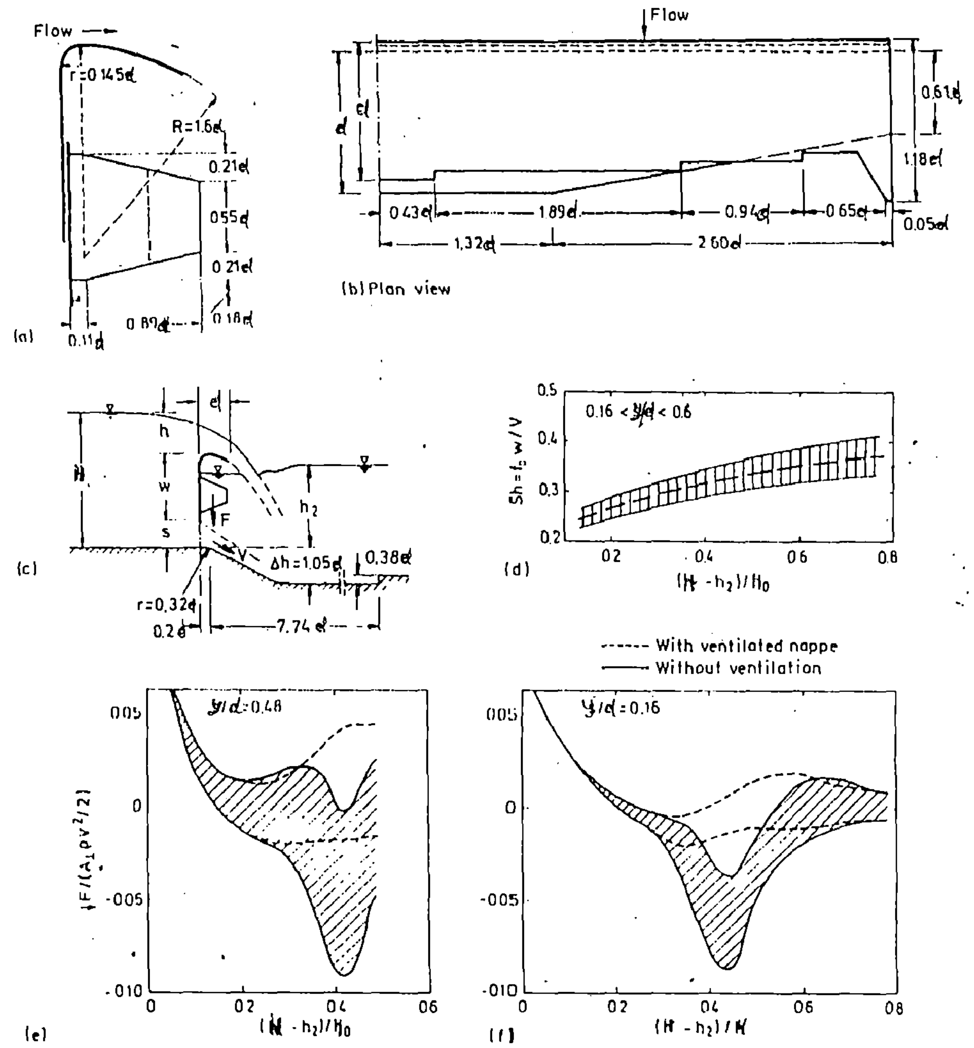


FIG. 4.77. (a, b) Hook-type double-leaf gate. (c) Sketch of gate and stilling-basin arrangement. (d) Strouhal number for stationary gate with ventilated nappe. (e, f) Normalized hydrodynamic force F acting vertically on lower gate leaf (after Naudascher, 1959). [$H/e = 2.95$; $h/d = 0.64$; $d = 125$ mm; Re $= d\sqrt{2gh}/\nu = 1.4\times10^5$; $A_\perp = 53380$ mm^2 = area of loading.]

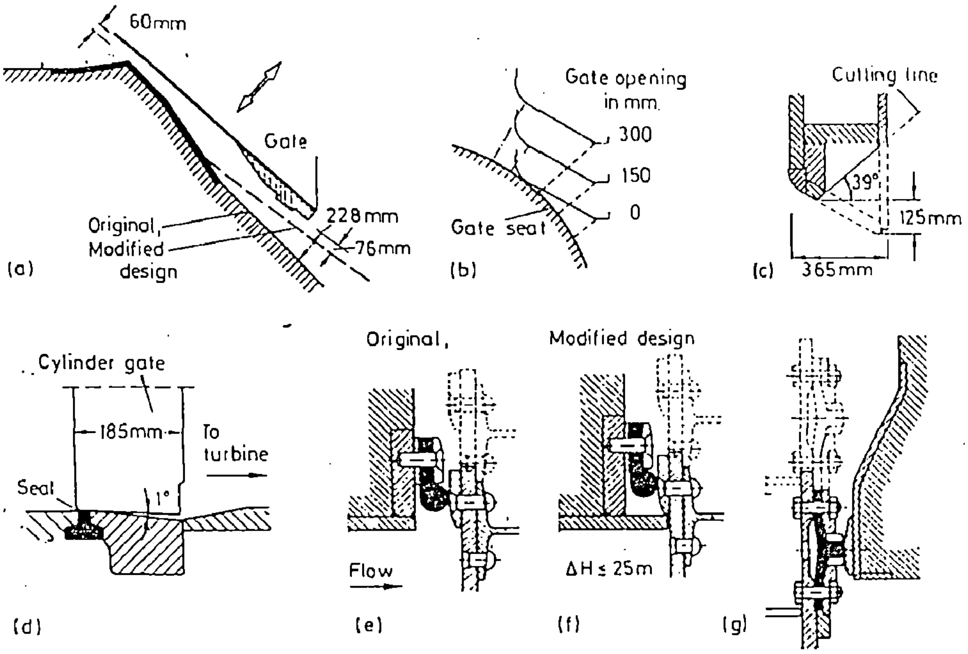


FIG. 4.78 Examples of vibration problems and vibration control involving various gates and gate seals. (a) Bottom seal of submersible Tainter gate (after Brown, 1961). (b, c) Bottom of cylinder gate in intake tower (after Martin & Ball, 1955): (b) before and (c) after modification. (d) Bottom of cylinder gate for turbine entrance. (e-g) Top seals of tunnel gates (after Petrikat, 1980).

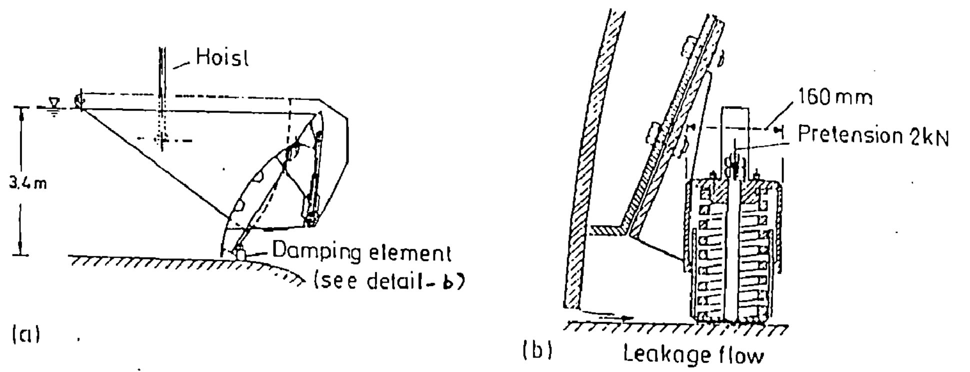


FIG. 4.79. Damping cylinder fixed at the center of a 22.5 m-span reversed Tainter gate. Gate had vibrated during leakage flows at gate openings between 8 and 25 mm (after Petrikat, 1980).

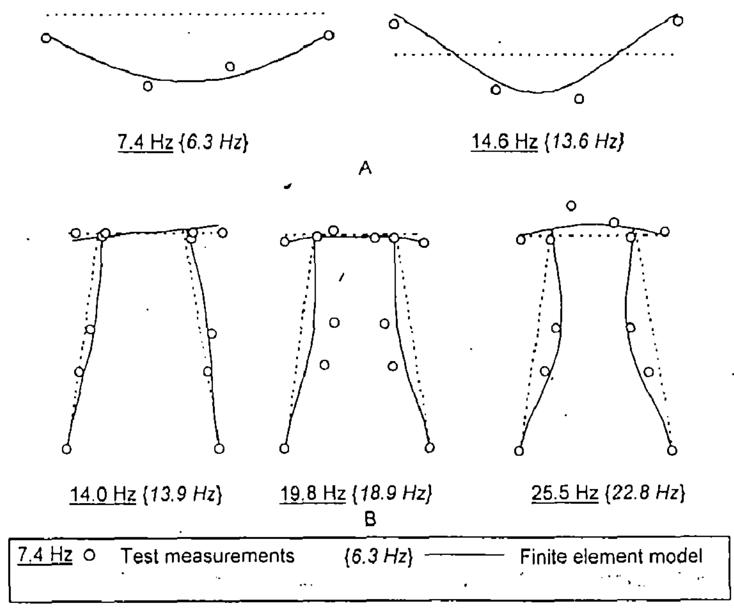


FIG. 5.1

Mode shapes from hammer tests and three-dimensional finite element model

A. At top of stiffened plate
B. On upper cross-girder and struts

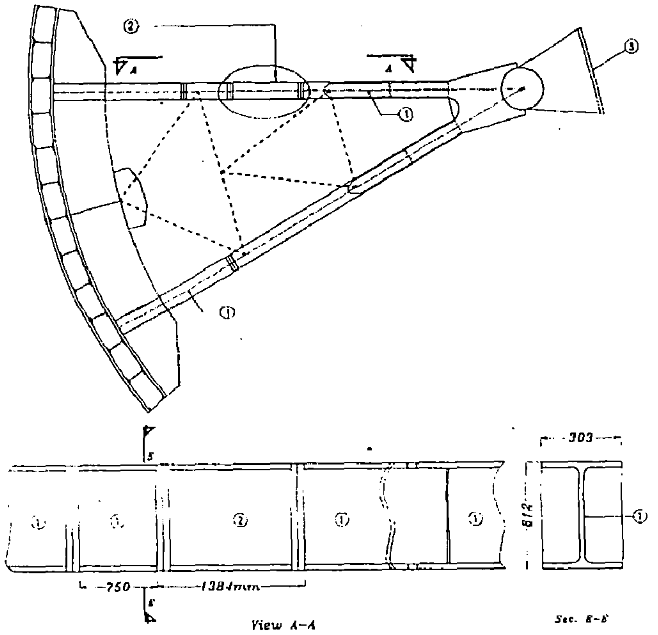
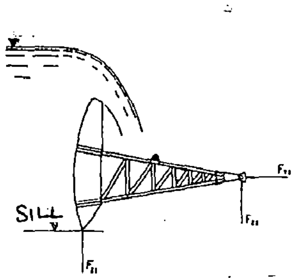


FIG. 5.2 Damaged beam of Sefidrud dam

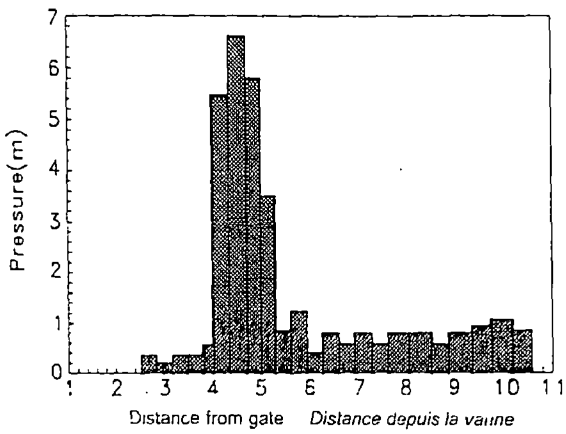
- Radial gate and rehabilitation measures after earthquake

(1) Main beam of arm, IPBV 800
(2) Substituted part at damaged section of the upper arm
(3) Base plate 40 mm thick

FIG. 5.3
Damaged part of upper beam of the right gate



(a) FORCES DUE TO OVERTOPPING



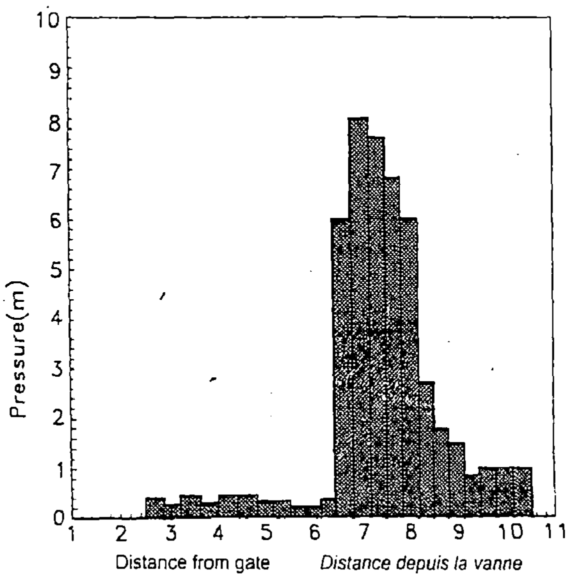
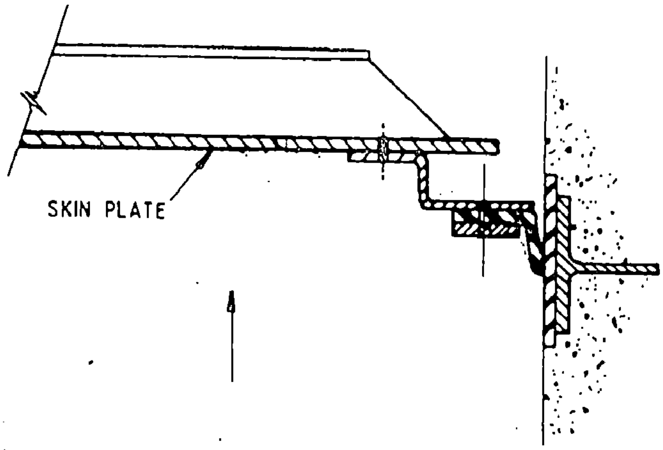


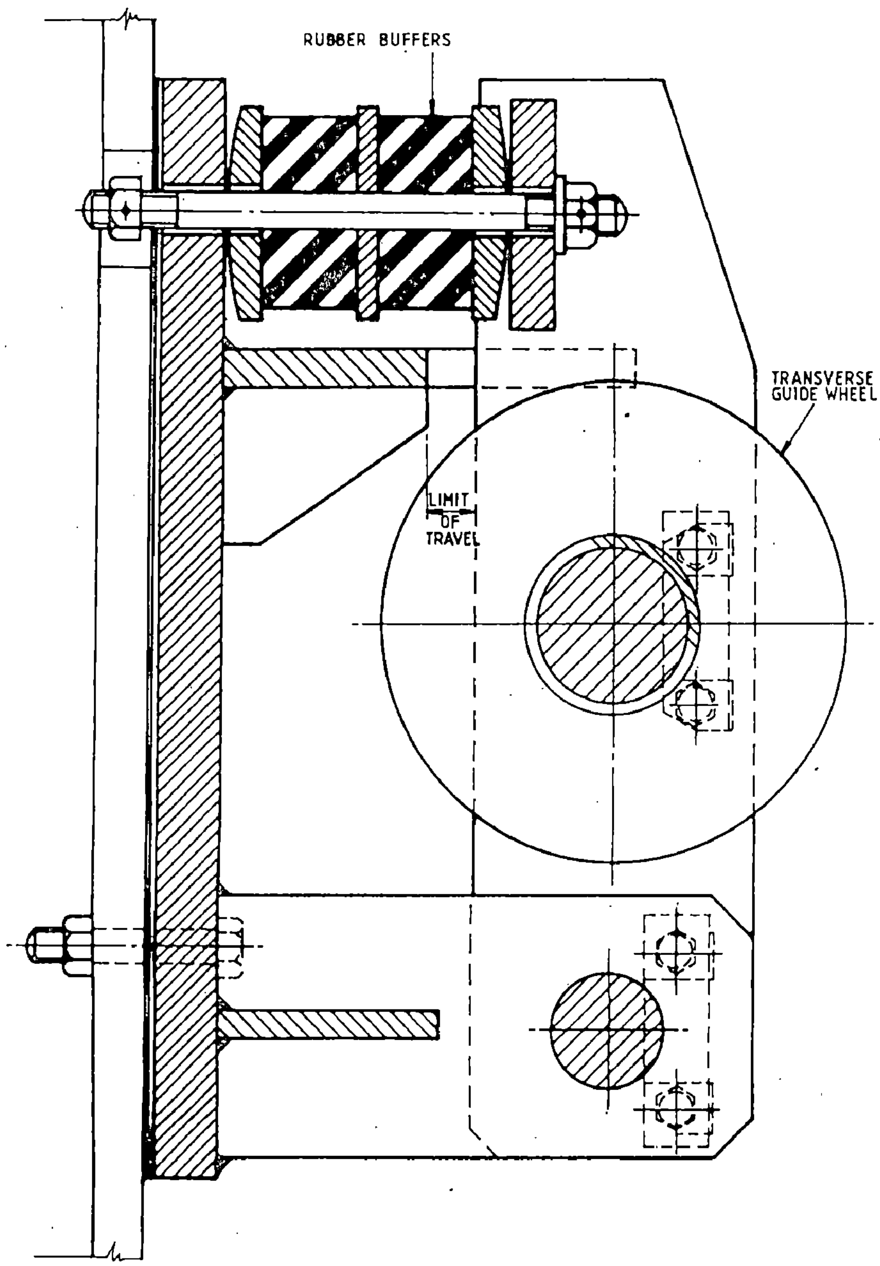
FIG. 5.4

(b) Pressure distribution on the gate arms (overtopping = 2.5 m)

(c) Pressure distribution on the gate arms (overtopping = 4 m)



(a) *Side seal mounting of a radial gate to provide a collapse zone in the event of a transverse movement of a sluiceway pier due to an earthquake*



(b) *Arrangement of spring loaded transverse guidewheel of a tunnel gate to absorb an earthquake shock*

FIG. 5.5

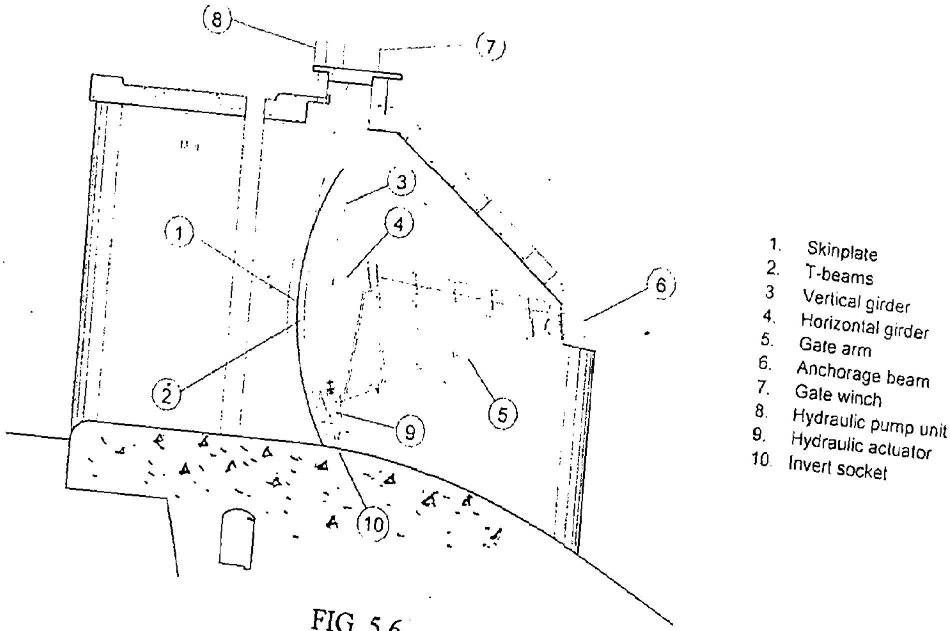


FIG. 5.6
Spillway gate - Section

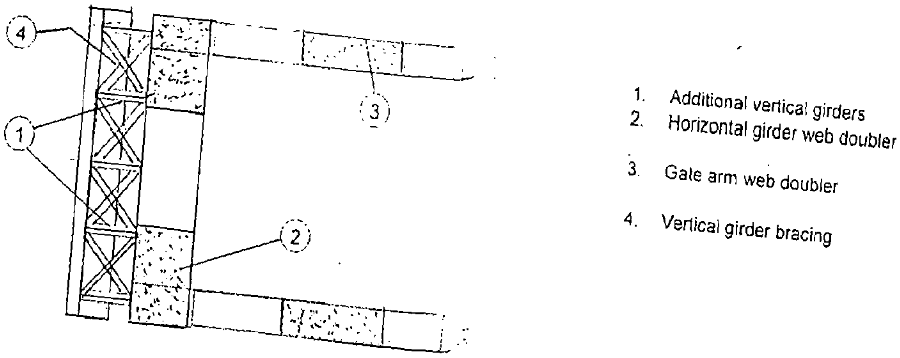


FIG. 5.7
Strengthened spillway gate - Sectional plan

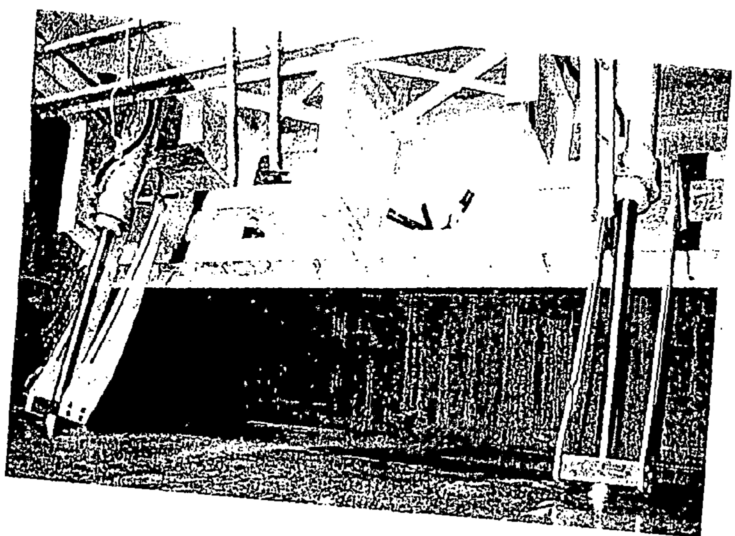


FIG. 5.8
Auxiliary lifting system

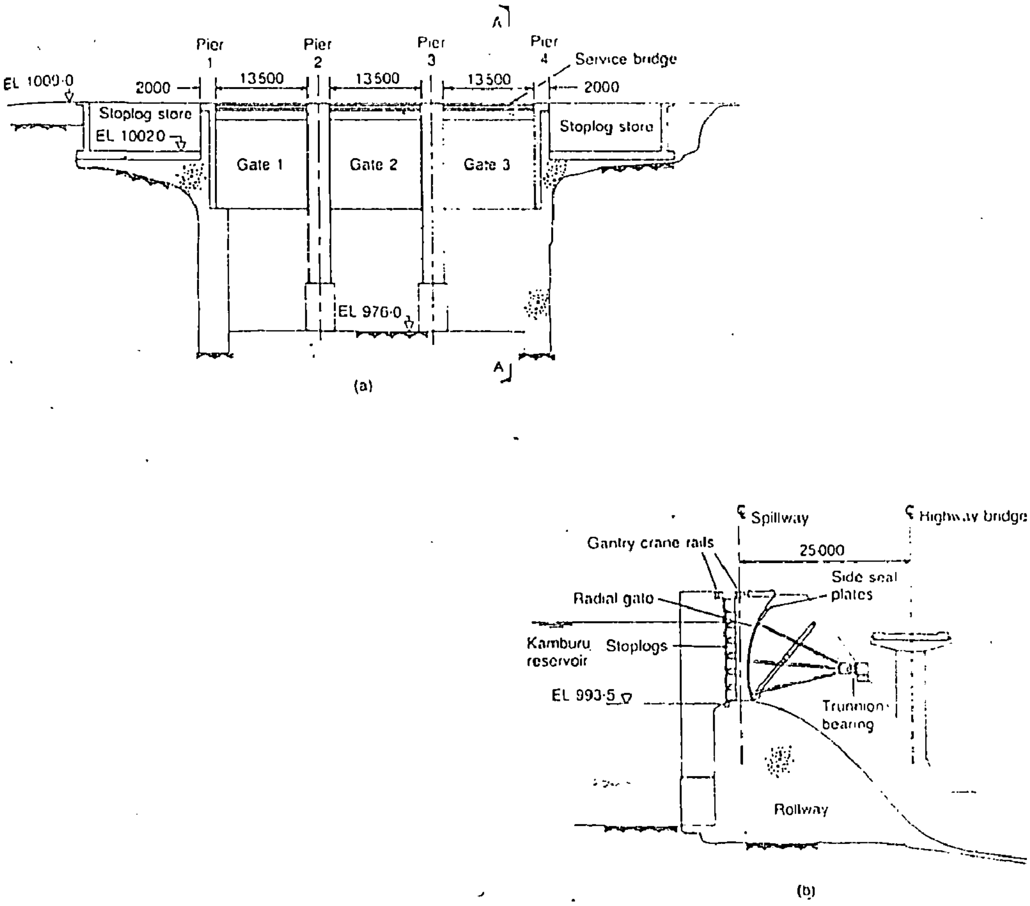


FIG. 5.9 *Kamburu spillway: (a) upstream elevation; (b) section A–A*

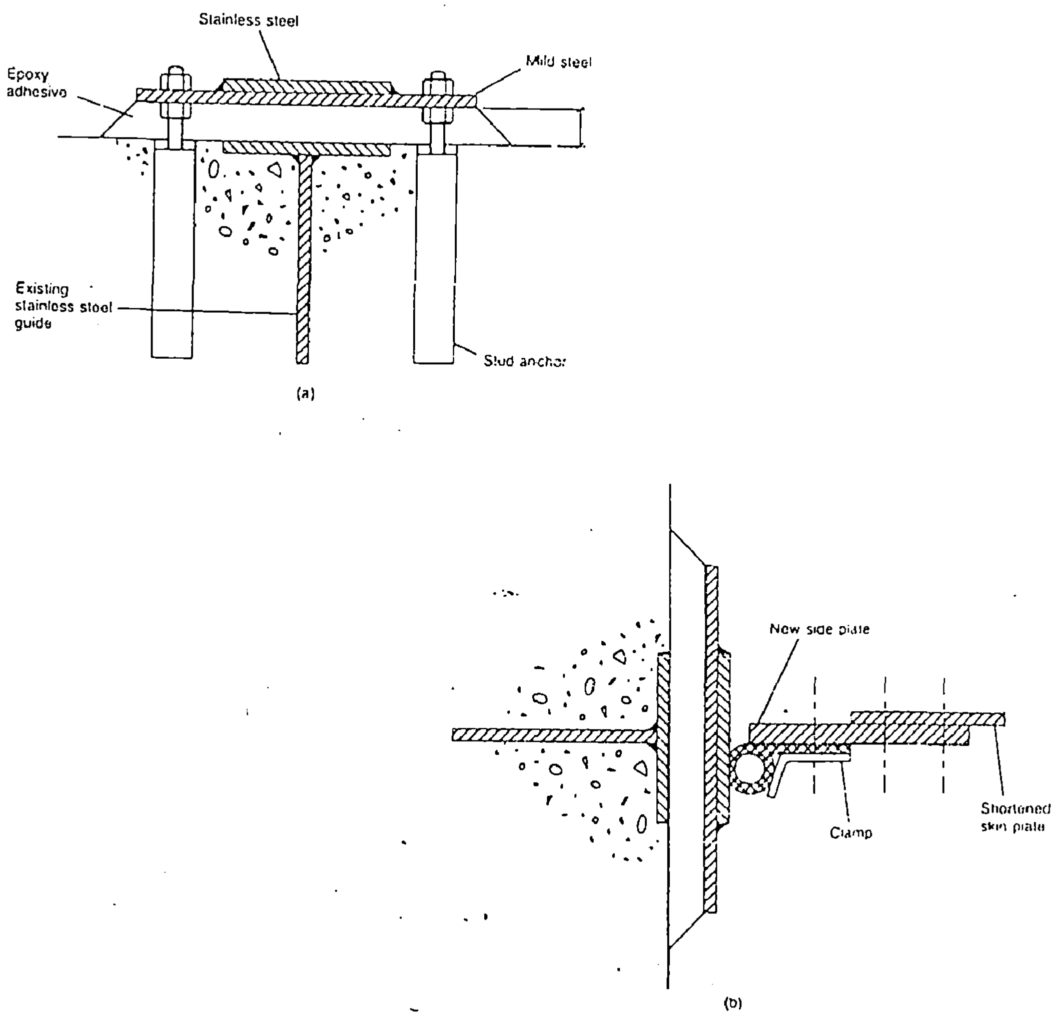


FIG. 5.10 *Modifications to radial gate: (a) embedded parts; (b) skin plate*

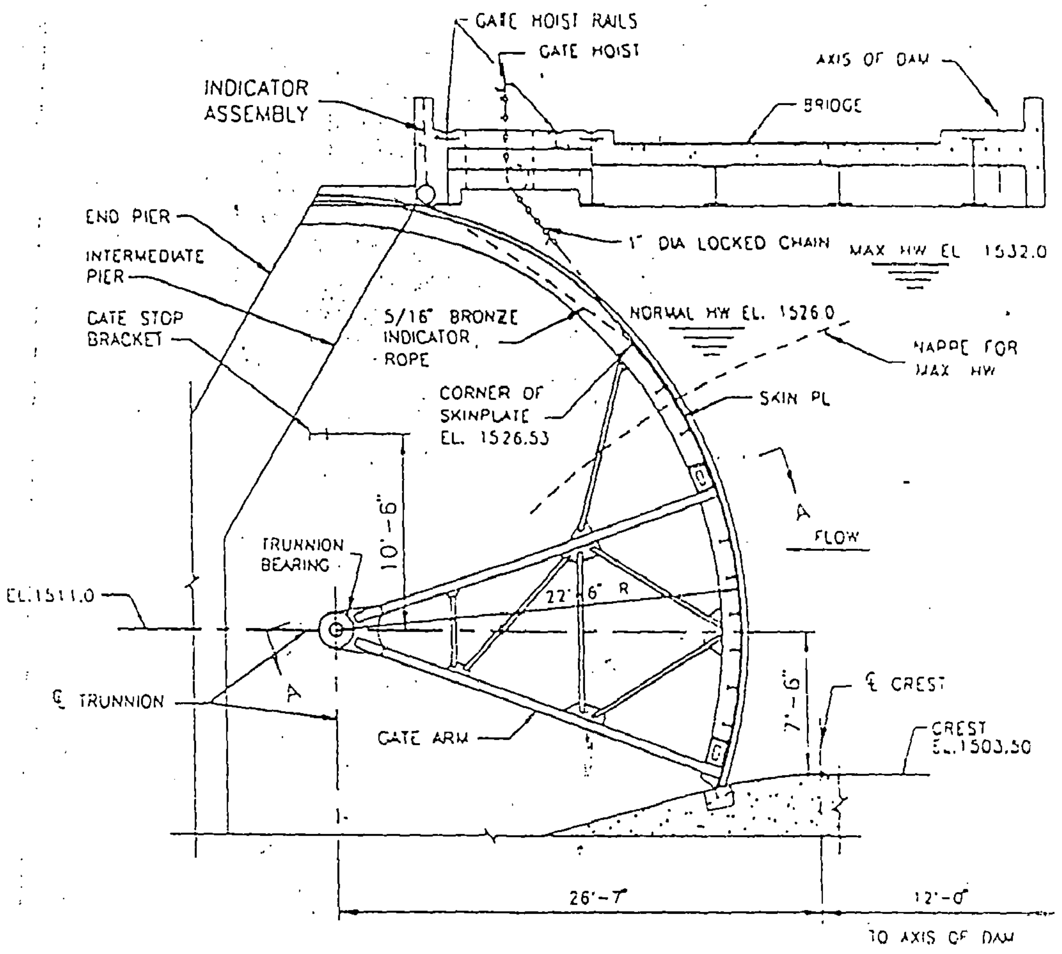


FIG. 5.11 General arrangement of the existing gate

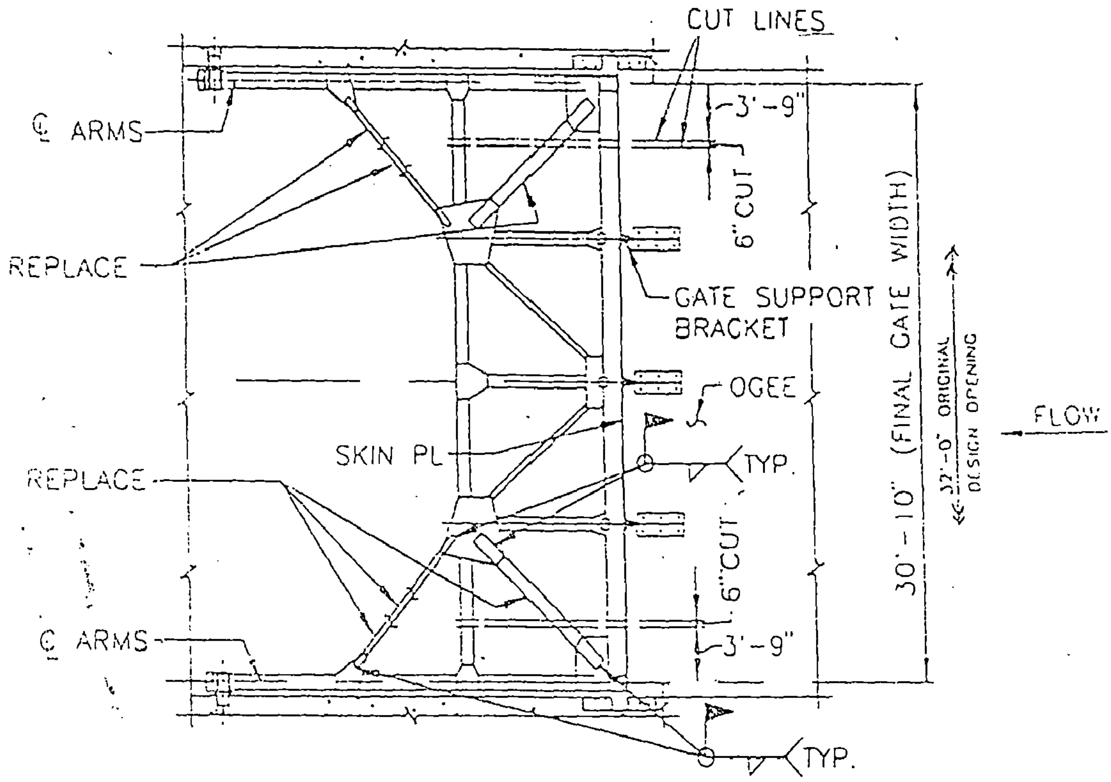
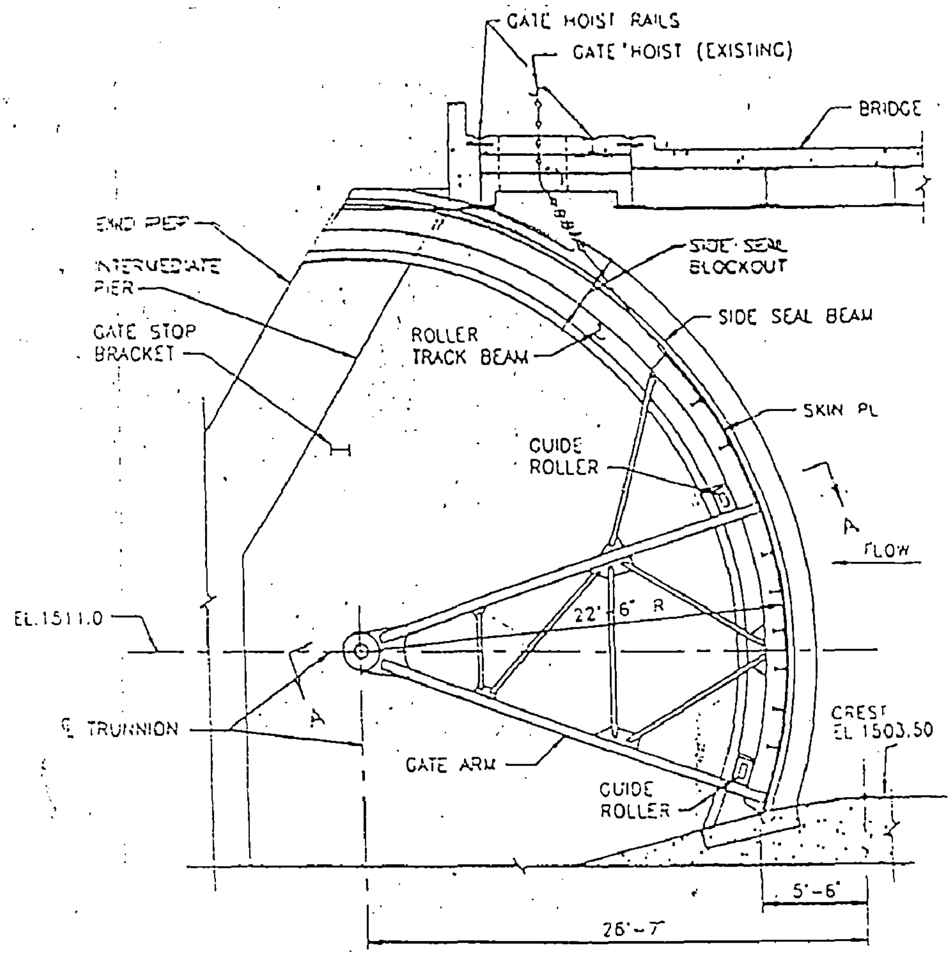
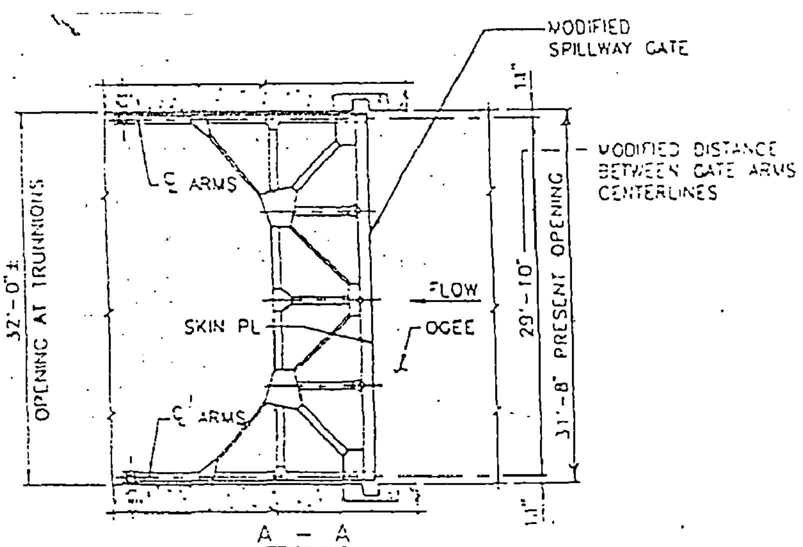


FIG. 5.12 Reduction of gate width



(a)



(b)

FIG. 5.13 General arrangement of the modified gate

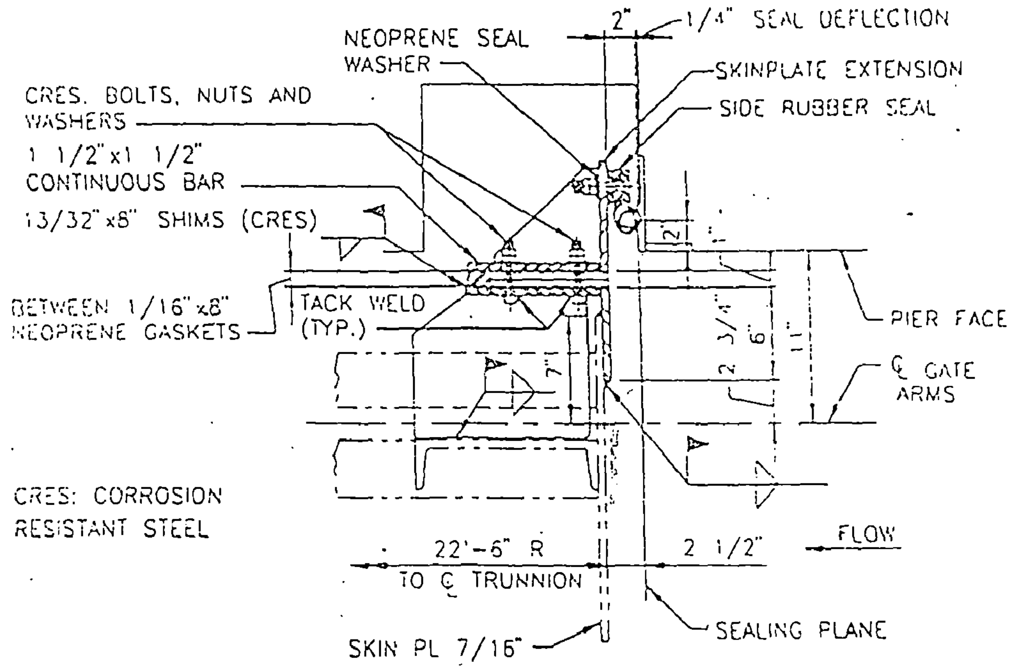


FIG. 5.14 New gate side seal arrangement

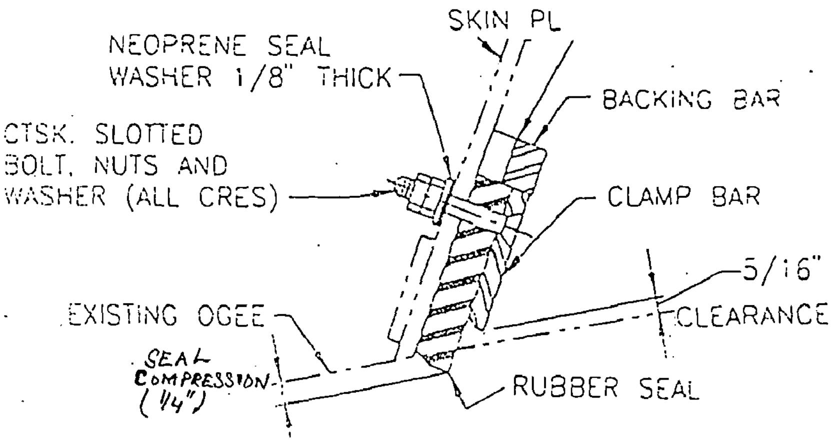


FIG. 5.15
New bottom seal arrangement

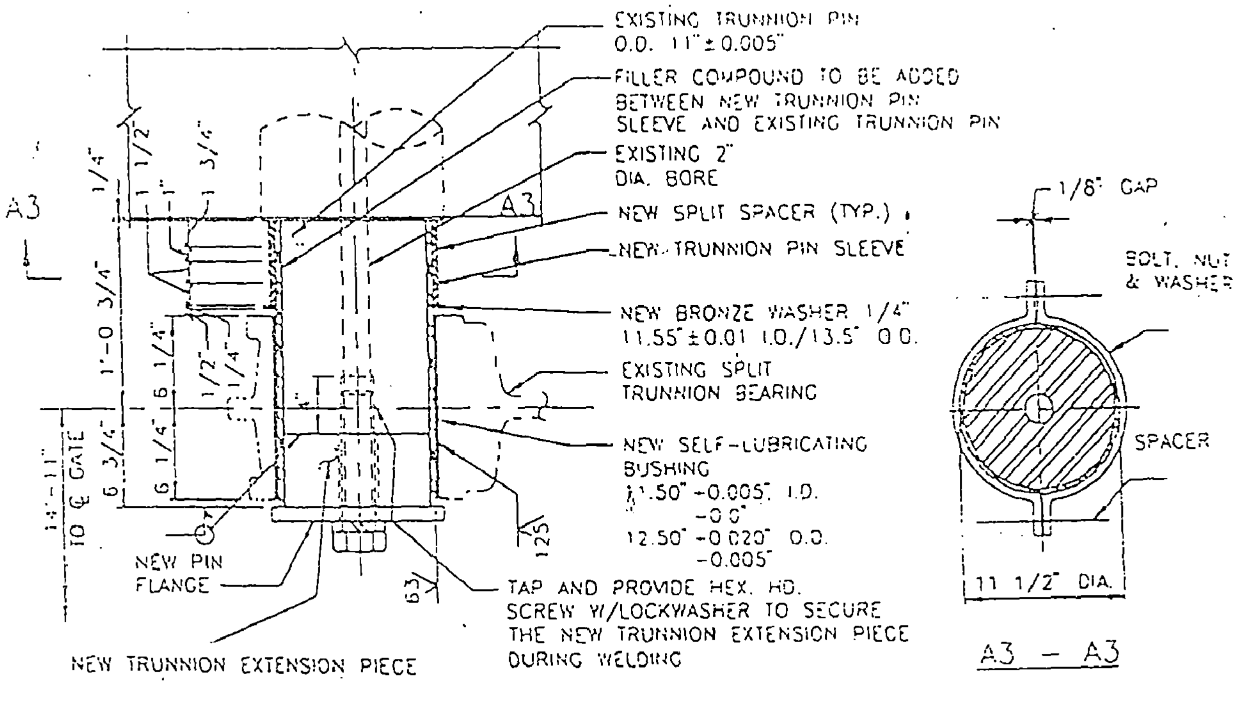


FIG. 5.16 Detail of trunnion modification and split spacers

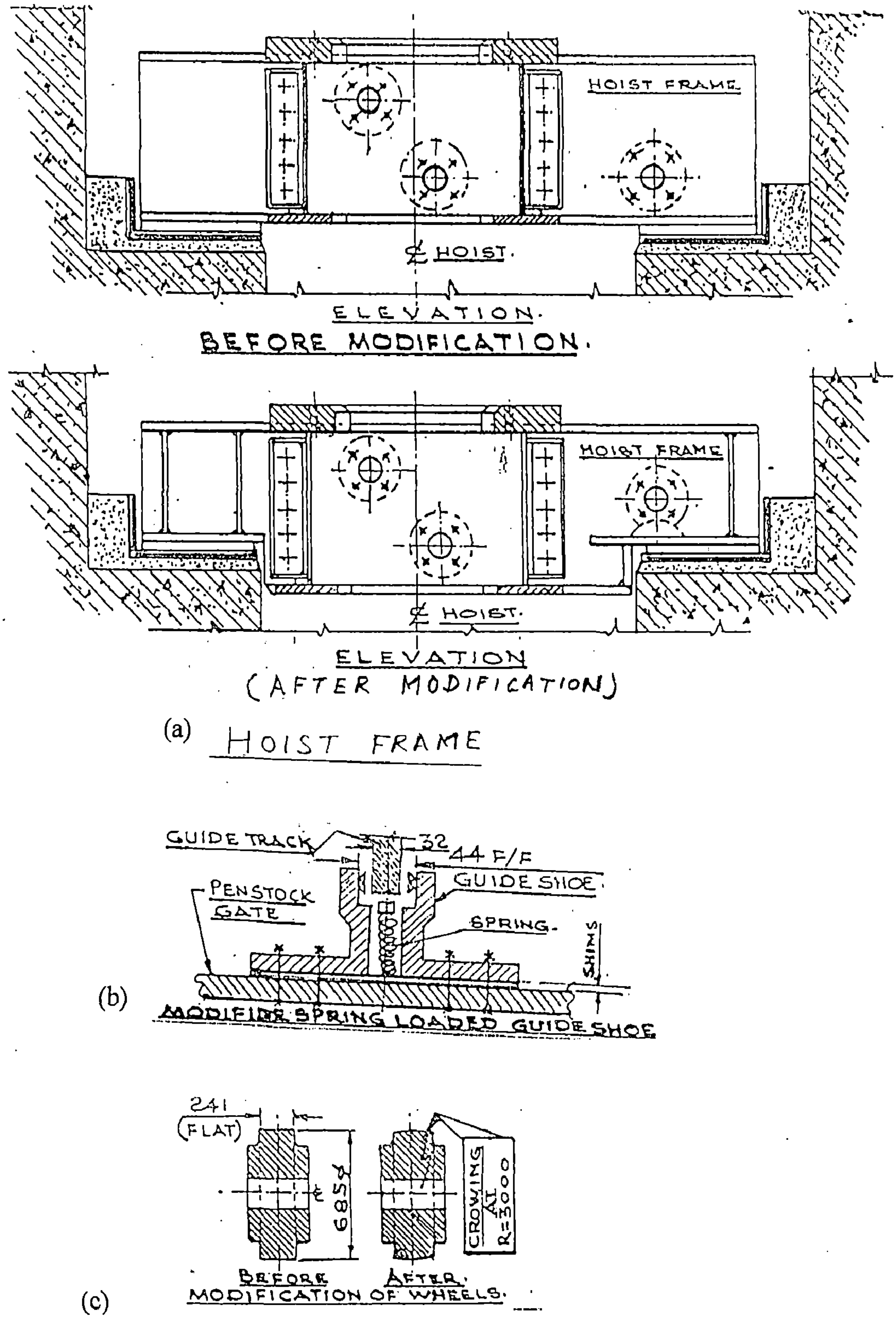
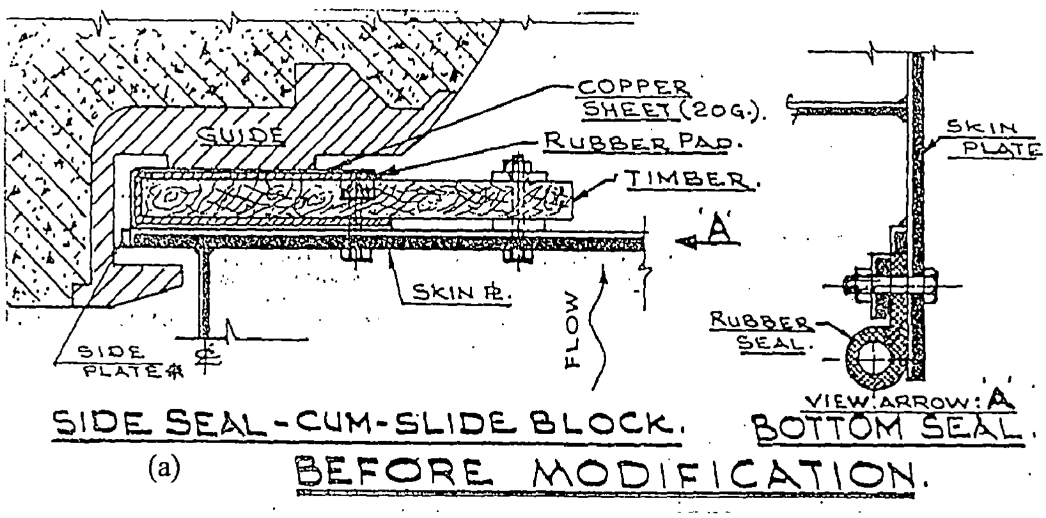
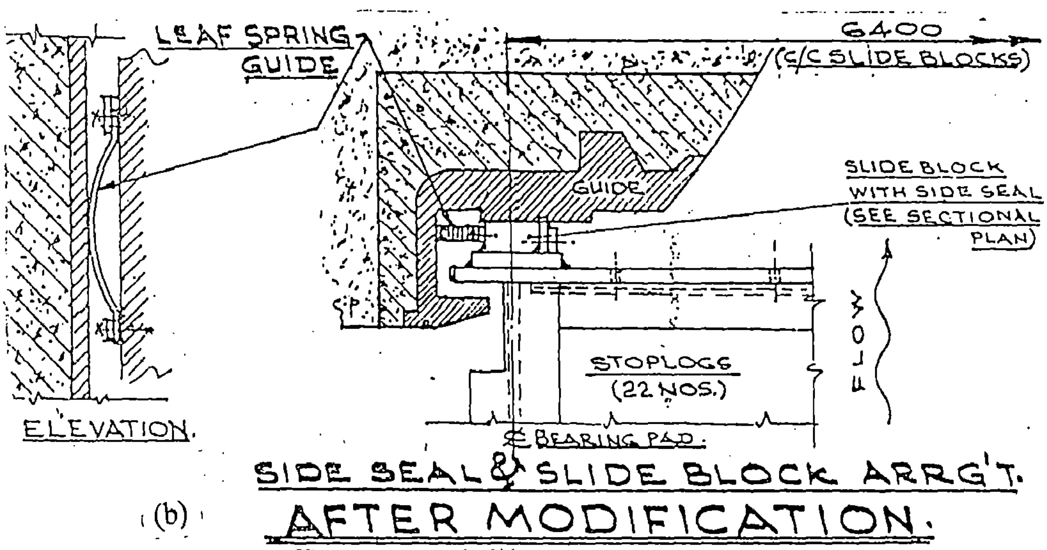


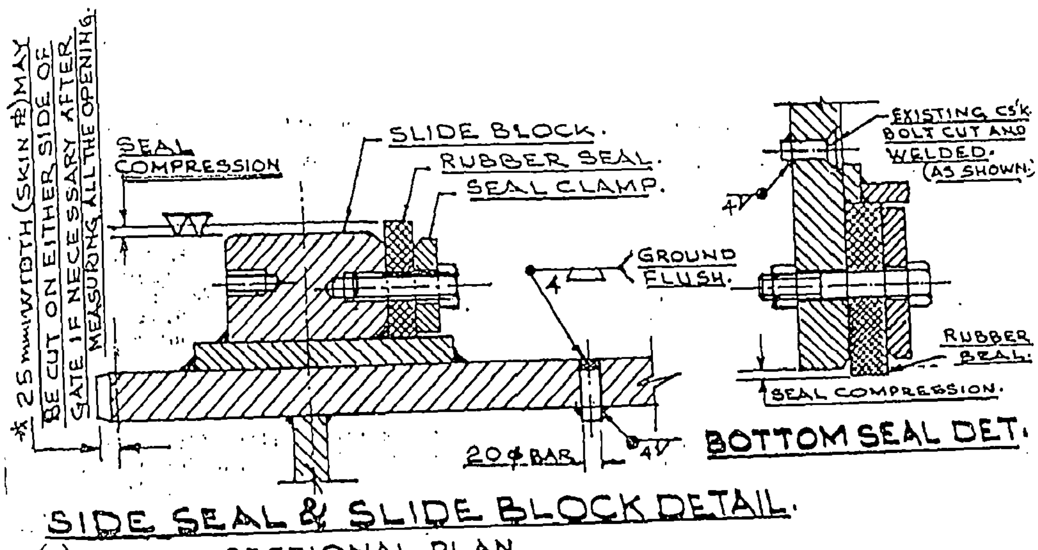
FIG. 5.17 PENSTOCK GATE & HOIST FRAME.



(a)



(b)



(c)

FIG. 5.18 PENSTOCK STOPLOG

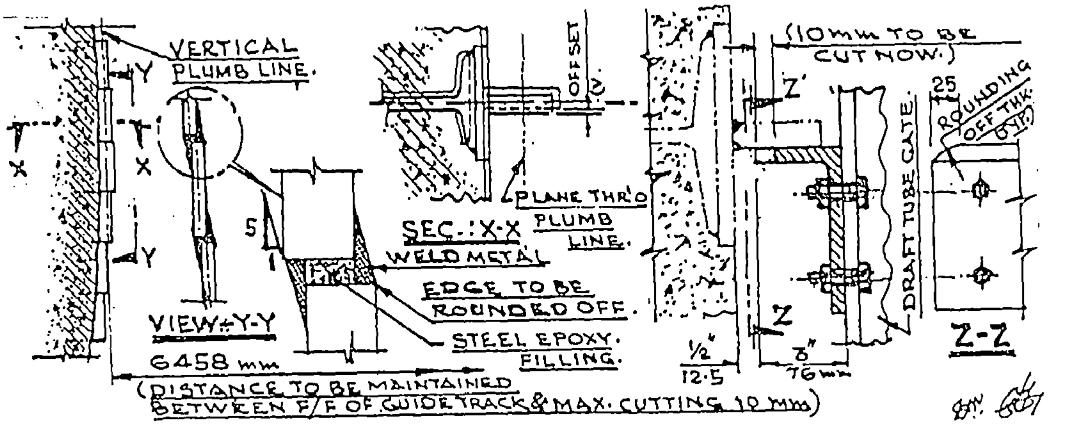
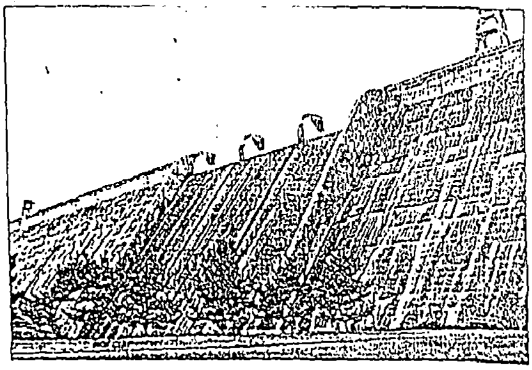
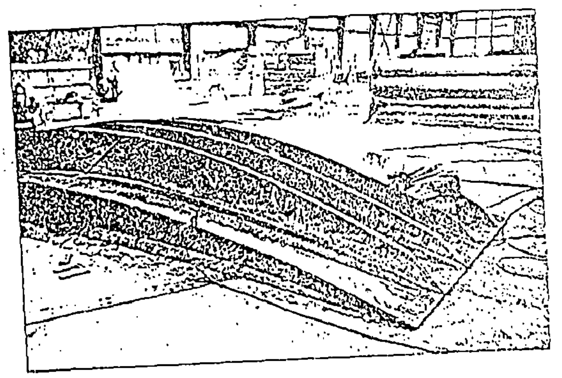


FIG. 5.19 MODIFICATIONS IN GUIDE TRACK & DRAFT TUBE GATE

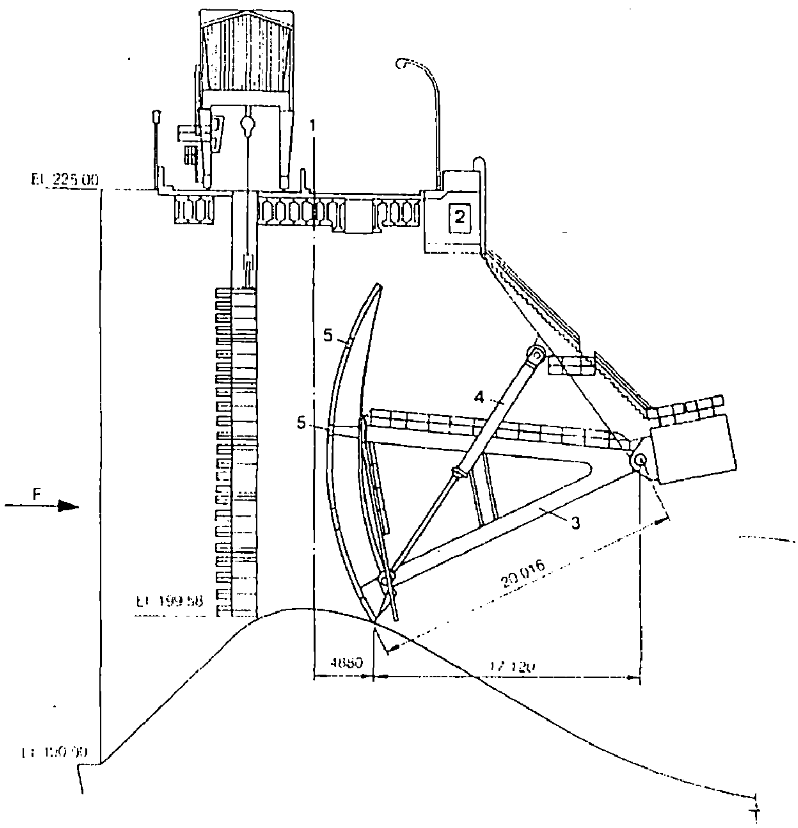


(a) DAM PRIOR TO REFURBISHMENT

FIG. 5.20



(b) PANEL OF RUBBER DAM (TOP PROFILE TO MATCH WITH THE SHAPE OF EXISTING GATES)



(1) Center spillway crest
(2) Control room
(3) Arms
(4) Oil dynamic mechanism
(5) Bearing pads
(F) Flow direction

FIG. 5.21

Spillway gates arrangement - Lateral view

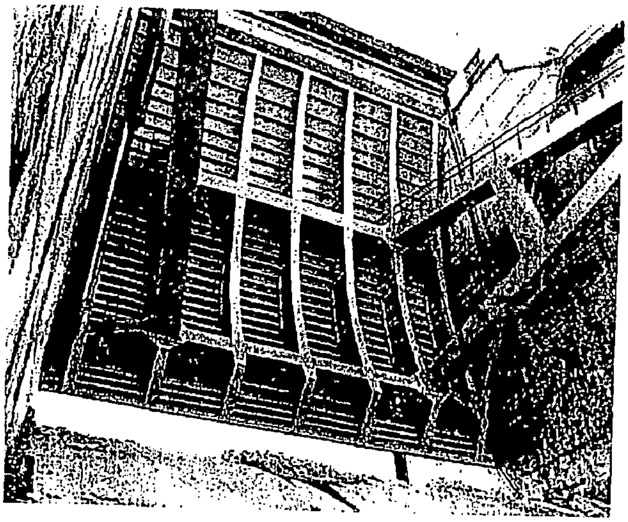
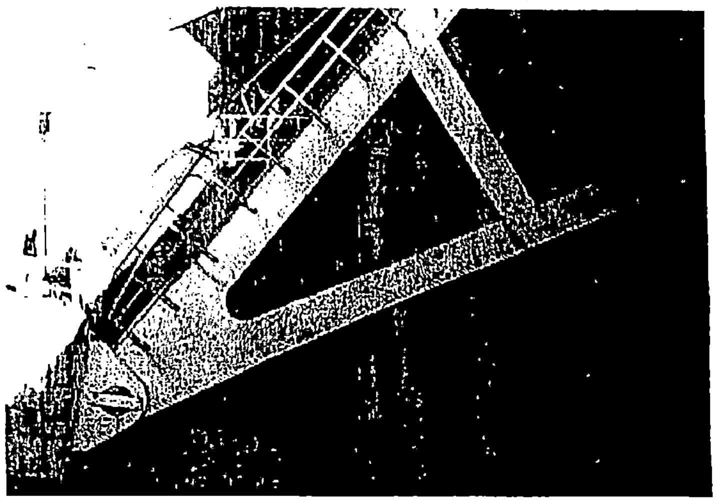


FIG. 5.22

Spillway gate

FIG. 5.23

Situation of H. HOIST gate after the accident



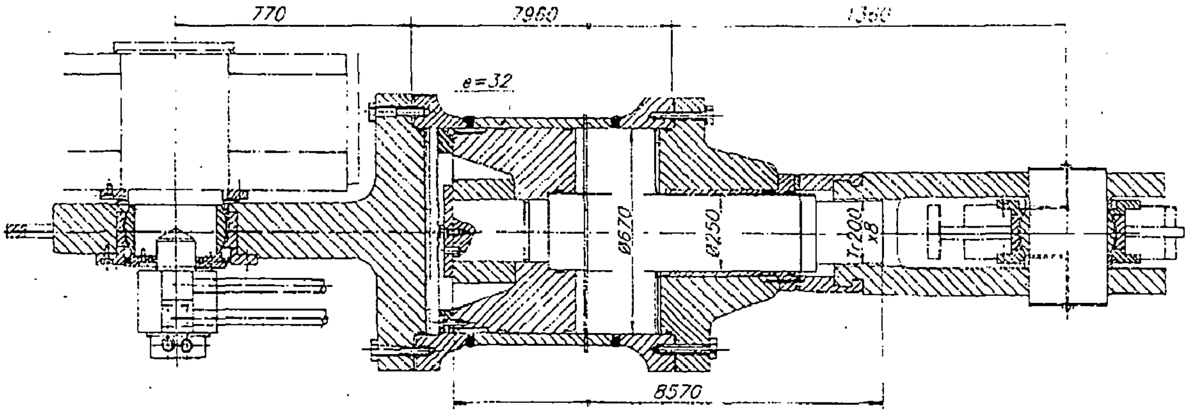


FIG. 5.24
HYDRAULIC CYLINDER (Assembly)

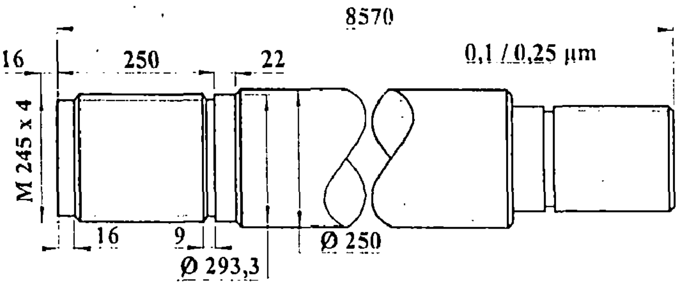


FIG. 5.25 – MODIFIED ROD
(Detail of end of rod replacing the broken one)

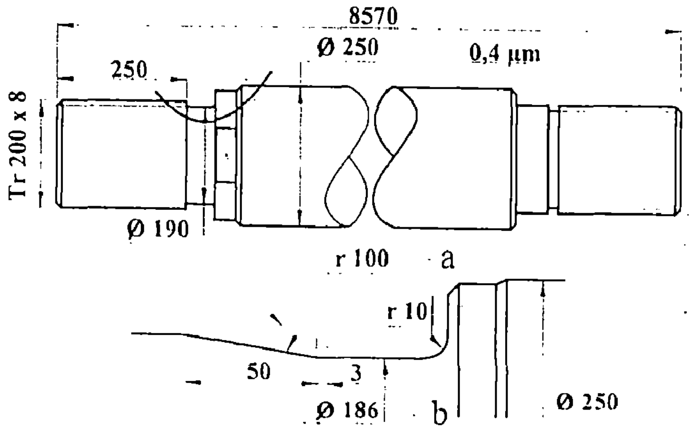


FIG. 5.26 .
Modification of the original profile of the existing rods

(a) Original profile
(b) Modified profile

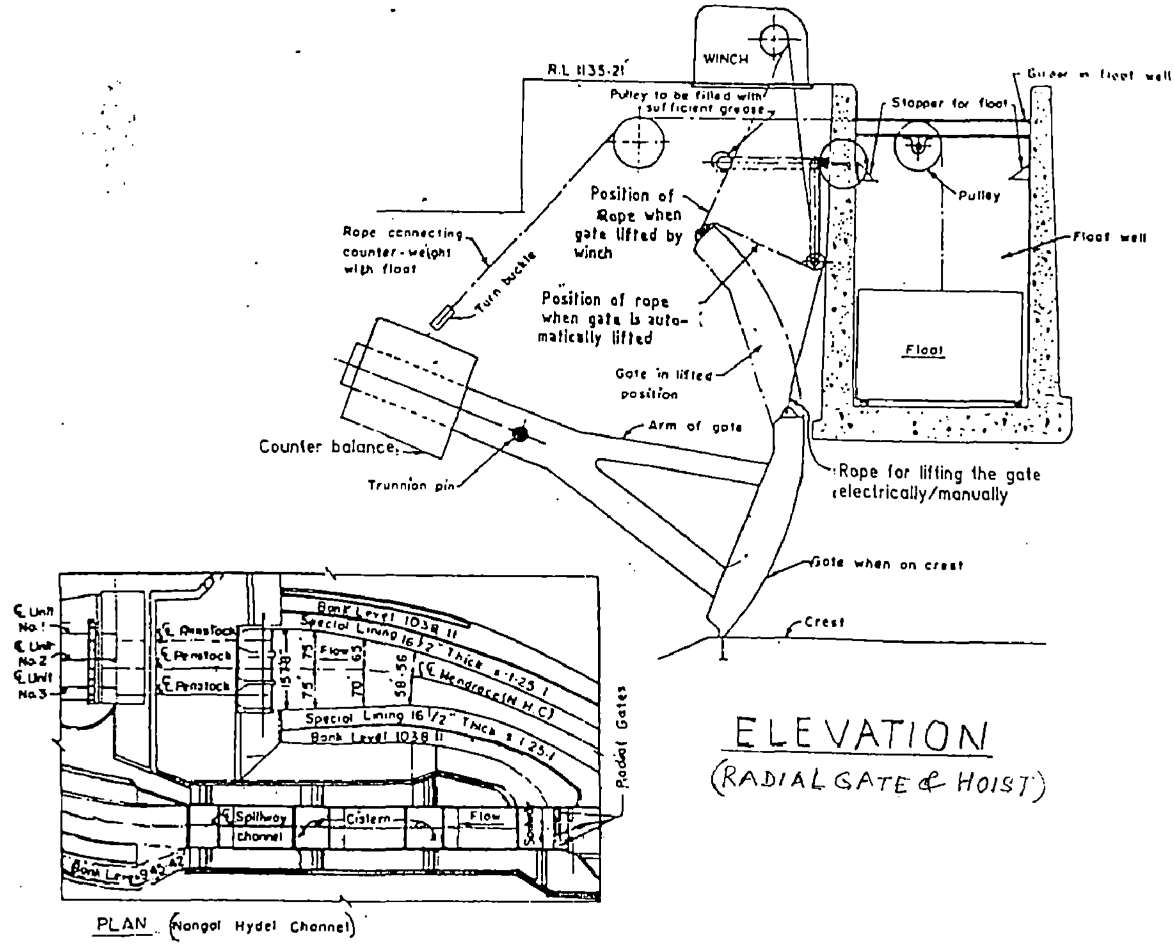
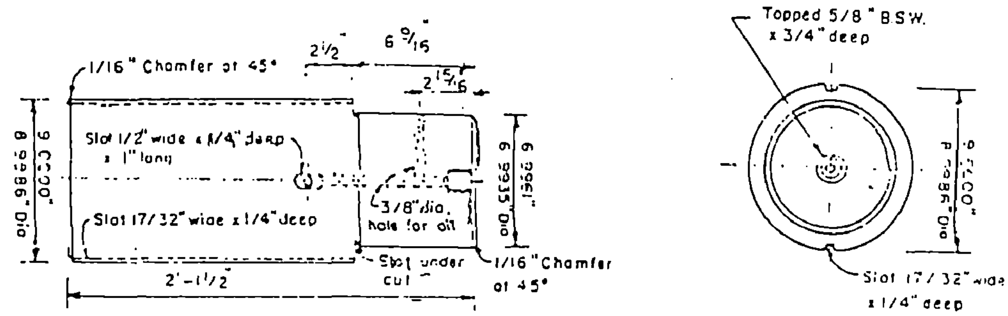
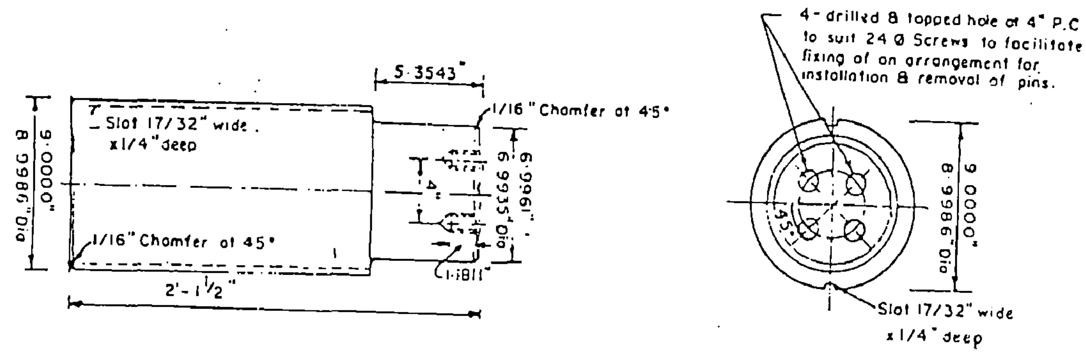


FIG. 5.27 KOTLA SPILLWAY GENERAL LAYOUT



(a) M.S. TRUNNION PIN ORIGINAL



(b) MODIFIED TRUNNION PIN STAINLESS STEEL

FIG. 5.28 DETAIL OF PIN

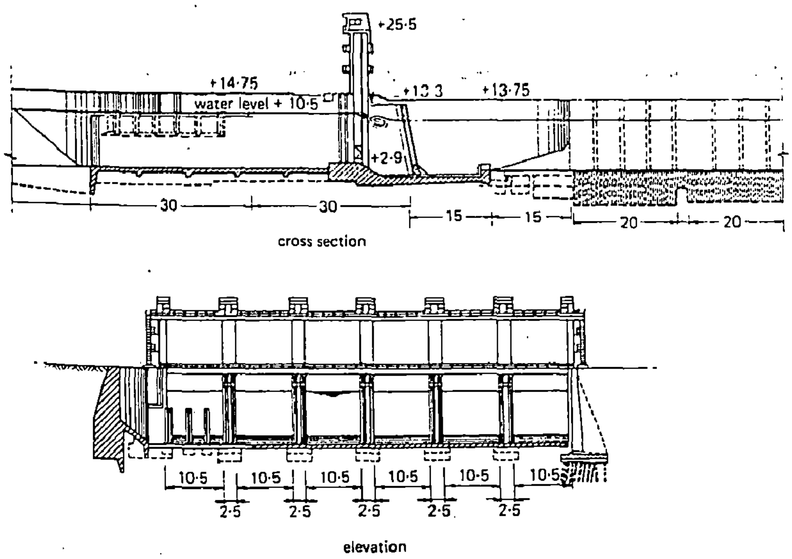


FIG. 5.29 Cross section and upstream elevation of spillway gates at Manganti dam, Indonesia.

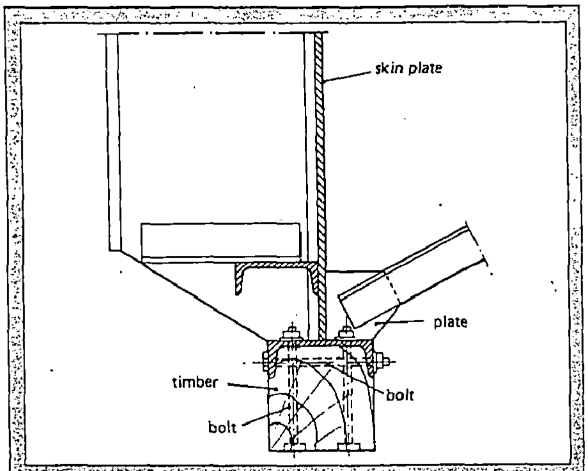


FIG. 5.30 The original gate bottom and seal arrangement.

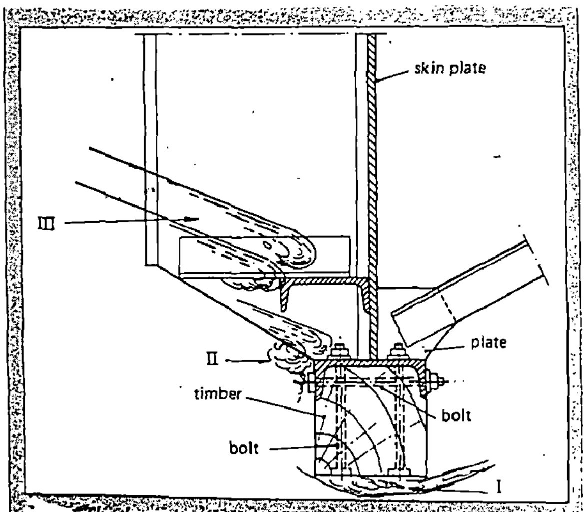


FIG. 5.31 The three sites (I, II and III) causing severe vibrations in the original gate arrangement.

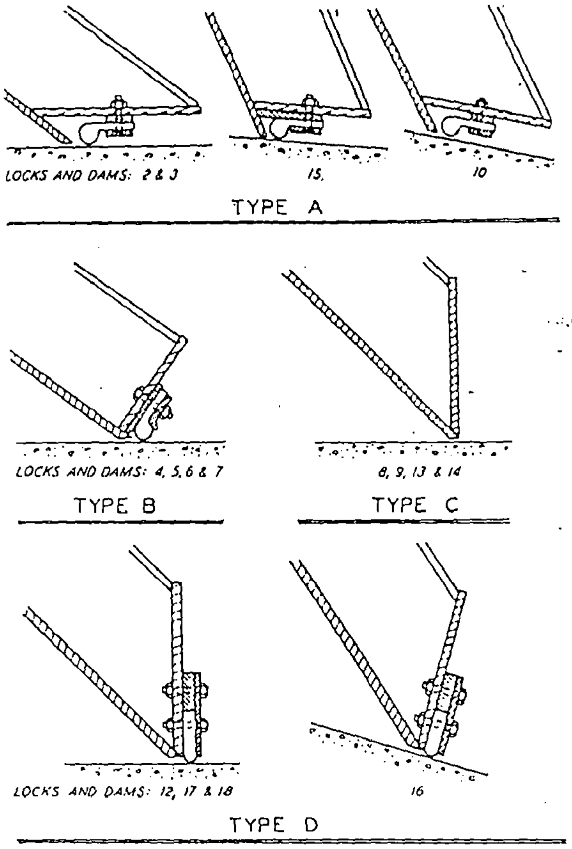


FIG. 5.32 ORIGINAL GATE LIP DESIGNS

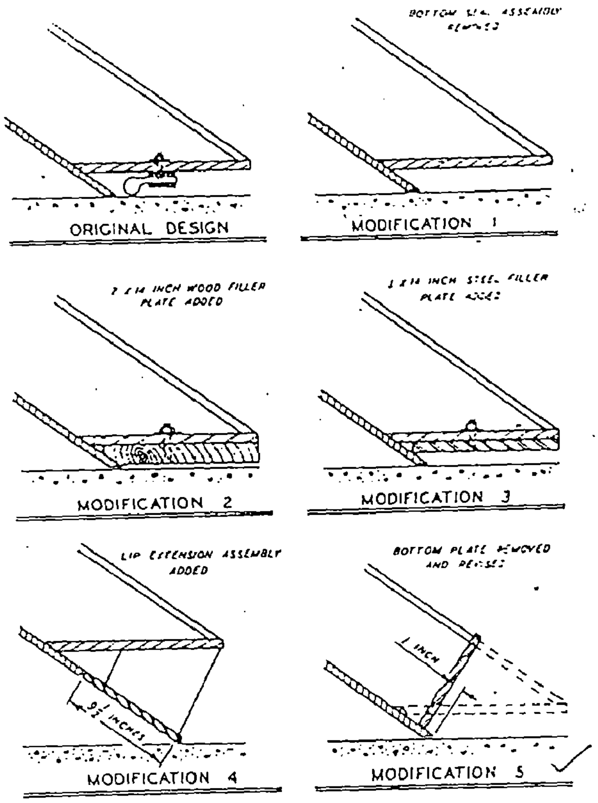


FIG. 5.33 TYPE A GATE LIP MODIFICATIONS

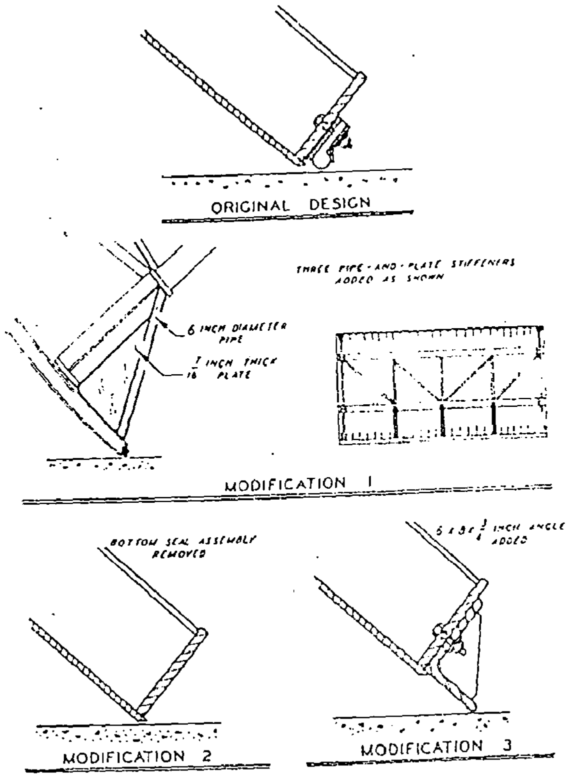


FIG. 5.34 TYPE B GATE LIP MODIFICATIONS

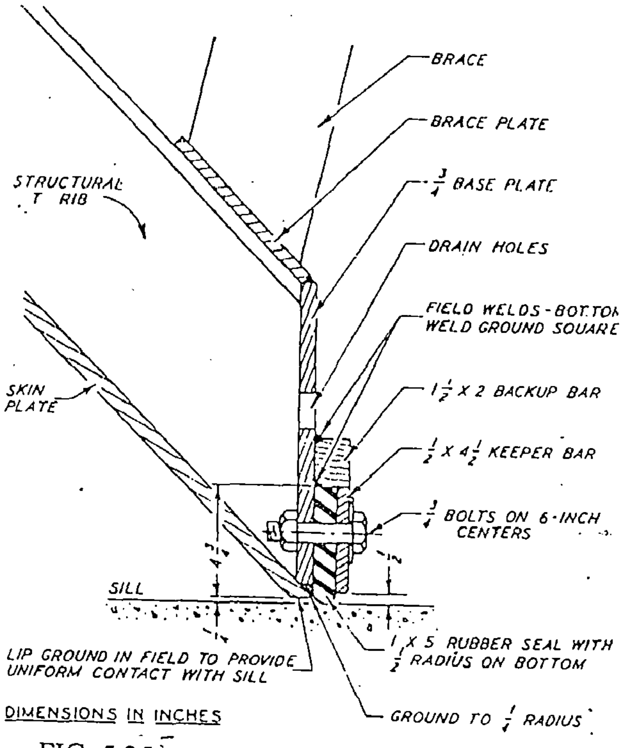


FIG. 5.35 GATE BOTTOM SEAL, MODIFIED DESIGN

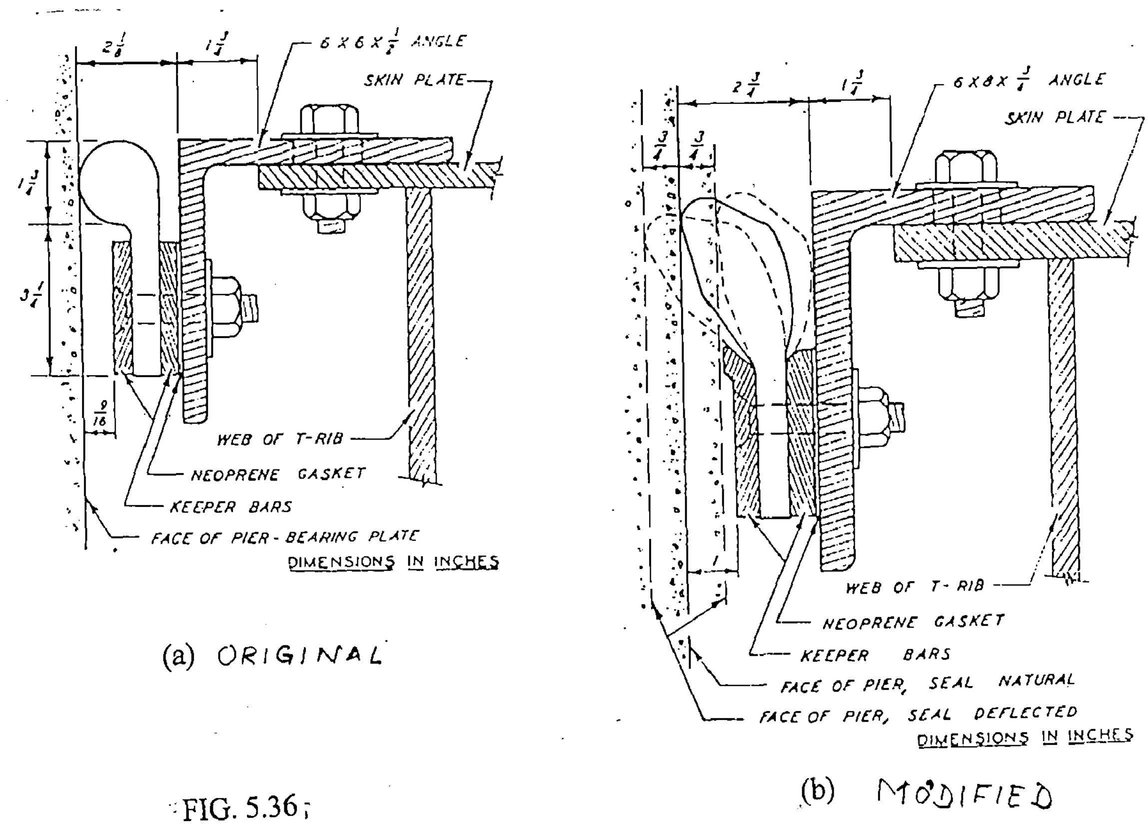


FIG. 5.36

GATE SIDE SEAL DESIGN

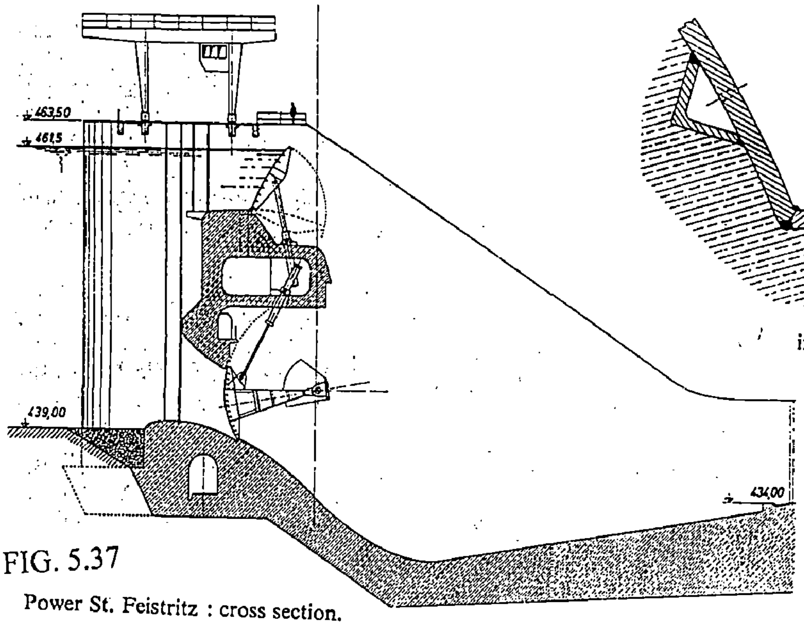
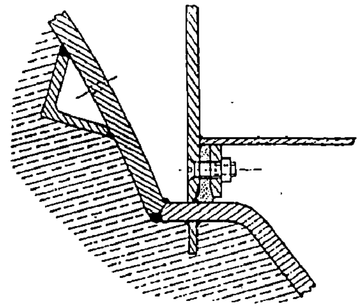
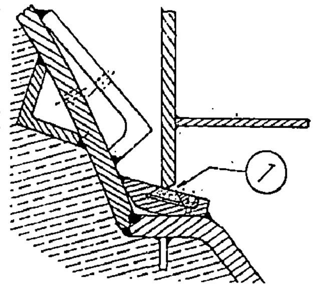


FIG. 5.37

Power St. Feistritz : cross section.



initial bottom sealing.



final bottom sealing.

FIG. 5.39

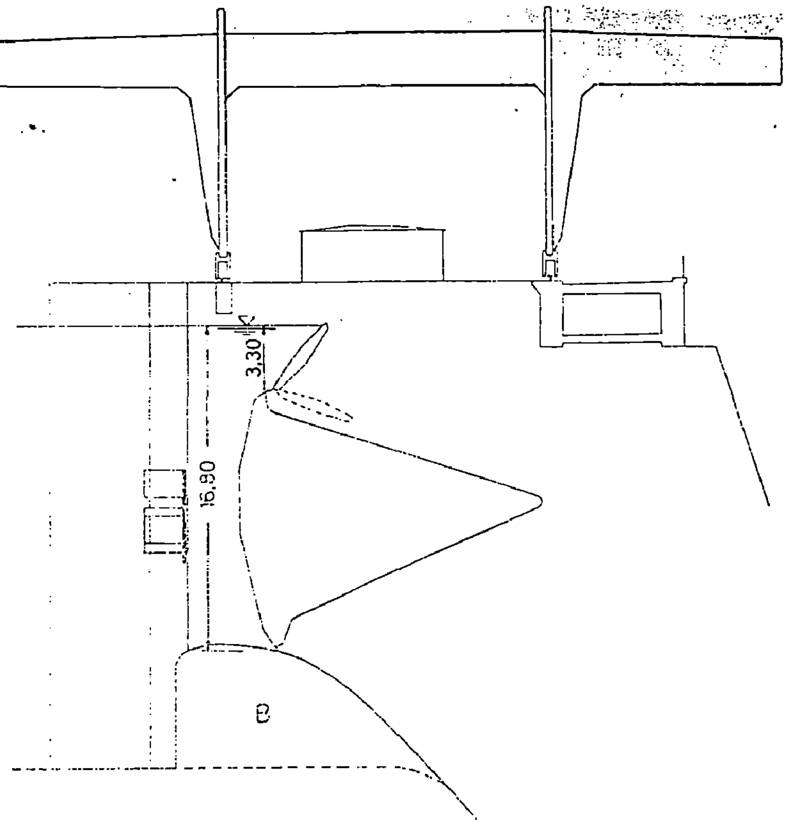


FIG. 5.38 Vertical cross-section through the spillway of the Edling Plant

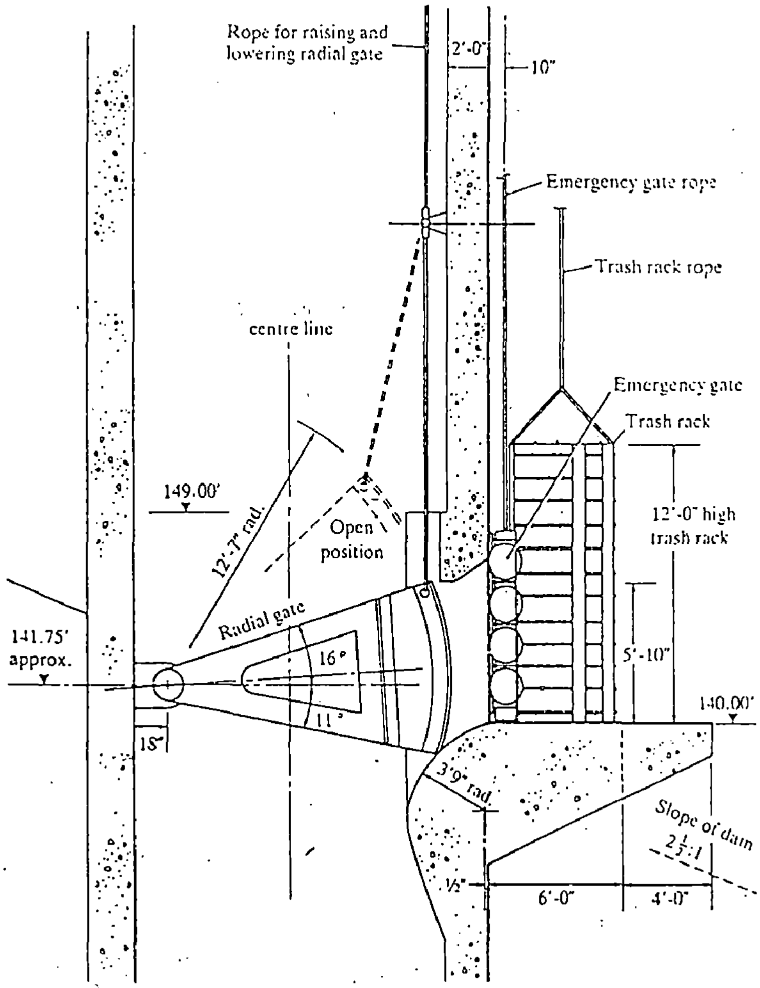


FIG. 5.40 Sectional elevation—INTAKE

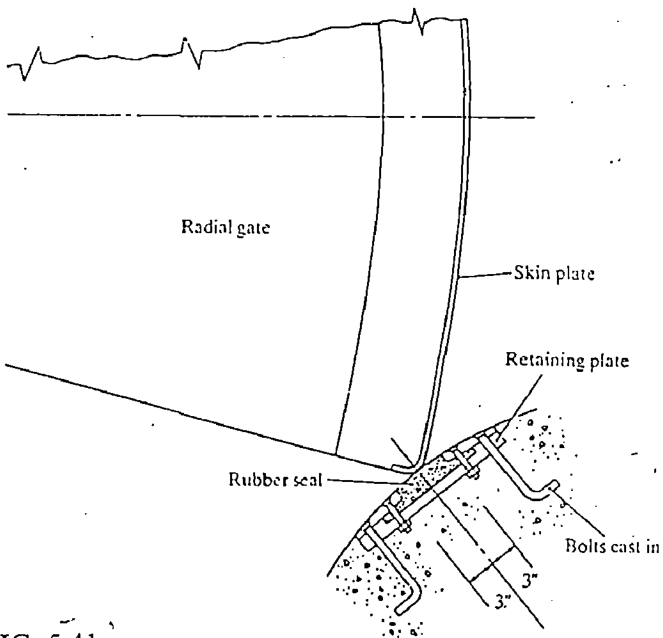


FIG. 5.41 Unsatisfactory bottom seal

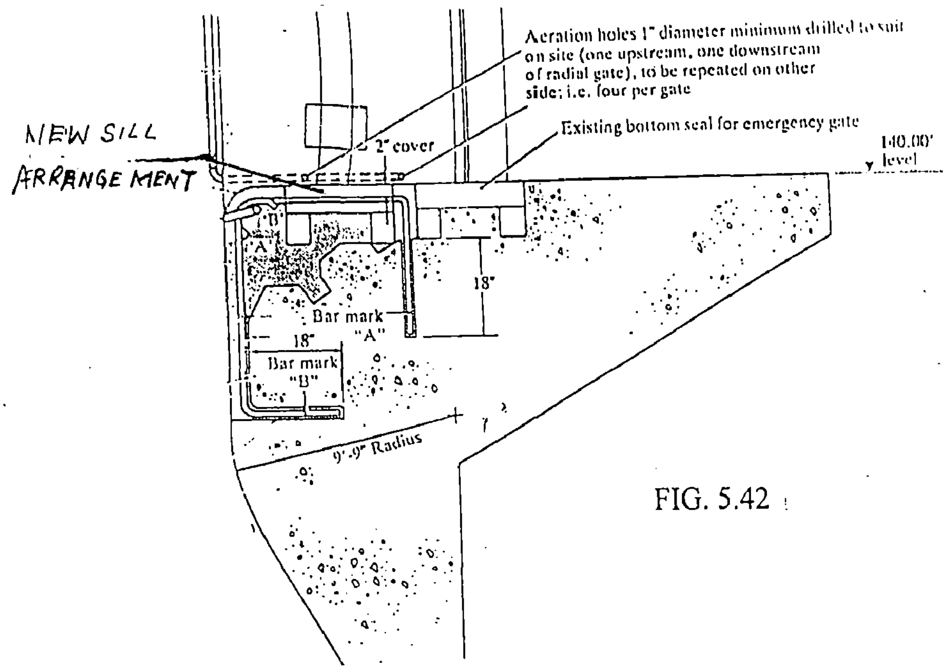


FIG. 5.42

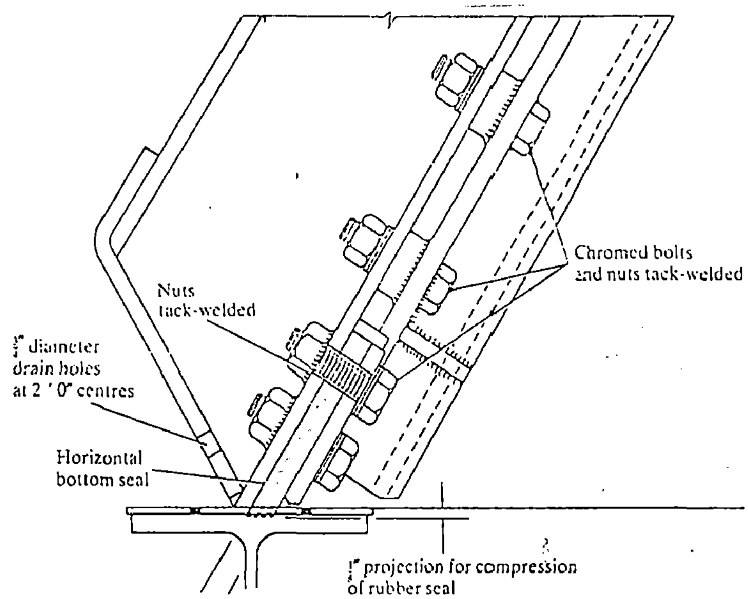


FIG. 5.43

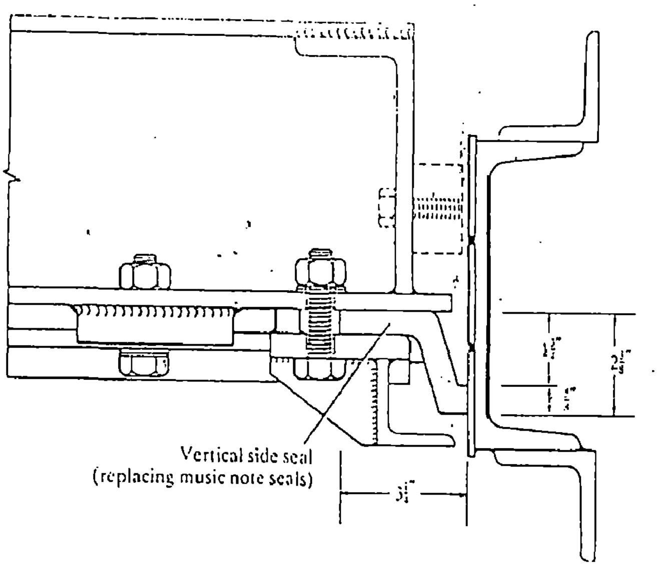
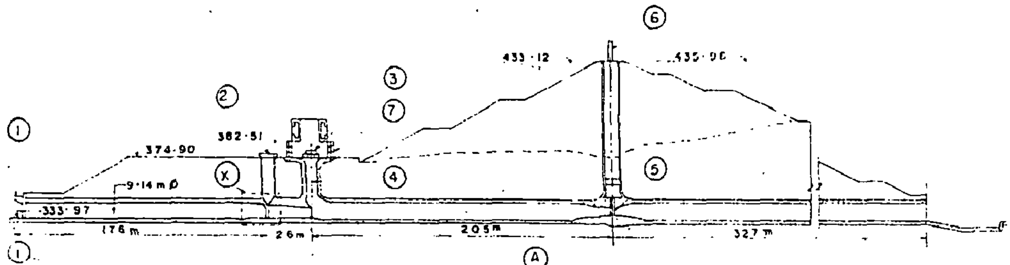


FIG. 5.44



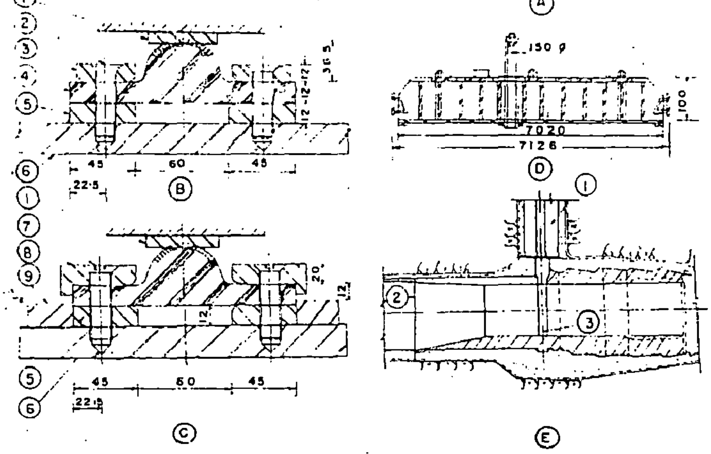


FIG. 5.45

Beas project — Pong dam power tunnel gate

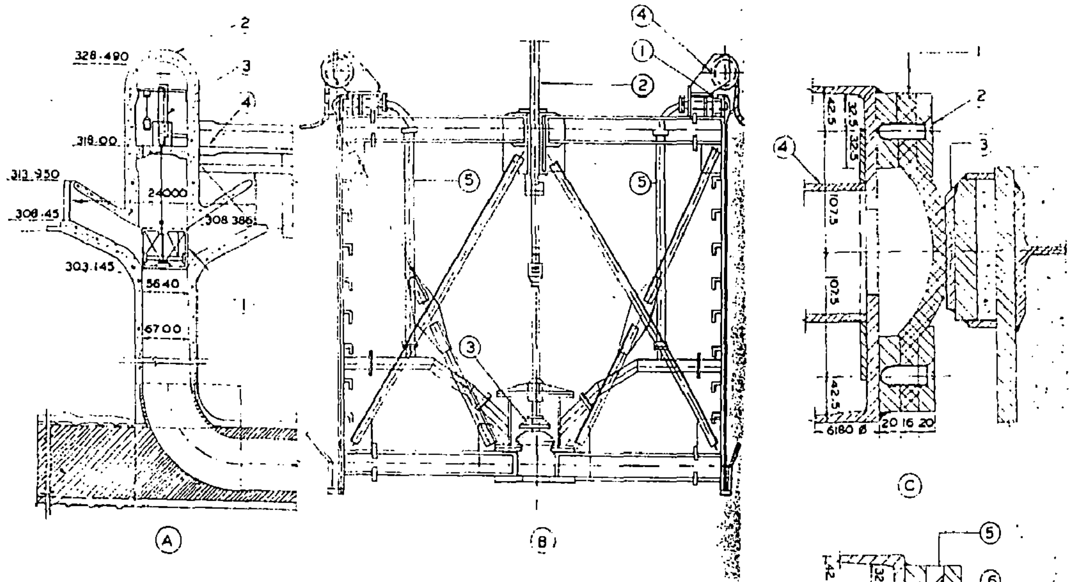
Layout of P 3 power tunnel. (A)
Inlet portal P 3. (1)
Closure shaft. (2)
Flat bulk-head gate. (3)
Intake shaft. (4)
P 3 Emergency gate. (5)
Gate hoist. (6)
Trash rack. (7)
Seal assembly before failure. (B)

Seal assembly after rectification. (C)

Seal seat. (1)
12 mm dia. slotted stainless steel screw. (2)

12 mm thick clamp plate. (3)
Teflon clad rubber seal. (4)
Seal base plate. (5)
Skin plate. (6)
New hexagonal (socket) headed 16 mm dia. stainless steel screws. (7)
New 20 mm thick clamp plate with turned edges. (8)
Stopper plate. (9)
Flat bulkhead gate (Item 3 in (A)). (D)

Junction of closure shaft with P 3 (Detail at (X) in (A)). (E)
Closure shaft. (1)
P 3 tunnel. (2)
Bulkhead gate slot. (3)



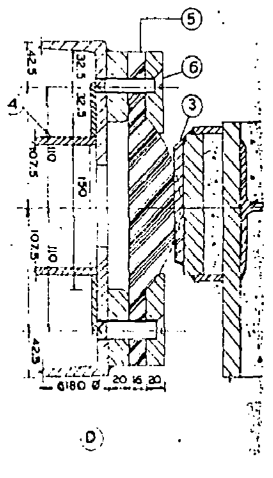


FIG. 5.46

Ramganga project power intake.

(A) Power intake shaft.
(1) Cylindrical gate.
(2) Underwater hoist chamber.

(3) hydraulic Hoist.
(4) Access gallery.
(B) Cylindrical gate.
(1) Top rubber seal.

(2) Stem rod.
(3) Filling valve.
(4) Guide rollers.
(5) Top Seal pressurising pipe.

(C) Top seal assembly before failure.

(D) Top seal assembly after modifications.
(1) Rubber seal.
(2) 12 mm dia. 50 mm long slotted stainless steel screws.

(3) Seal seat.
(4) Seal pressurising pipe.

(5) New rubber seal.

(6) New 16 mm dia. 55 mm long socket headed stainless steel screws.

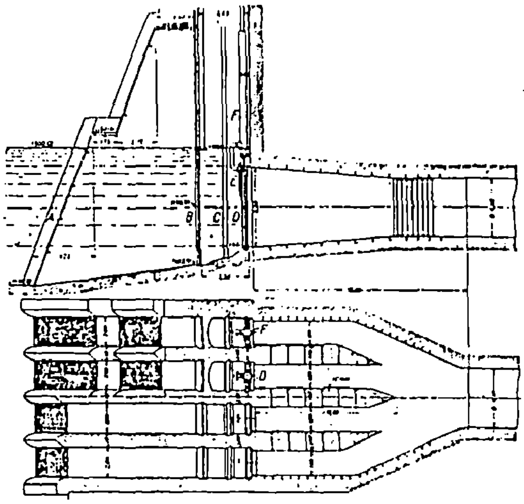


FIG. 5.47

Plan and section across of intake

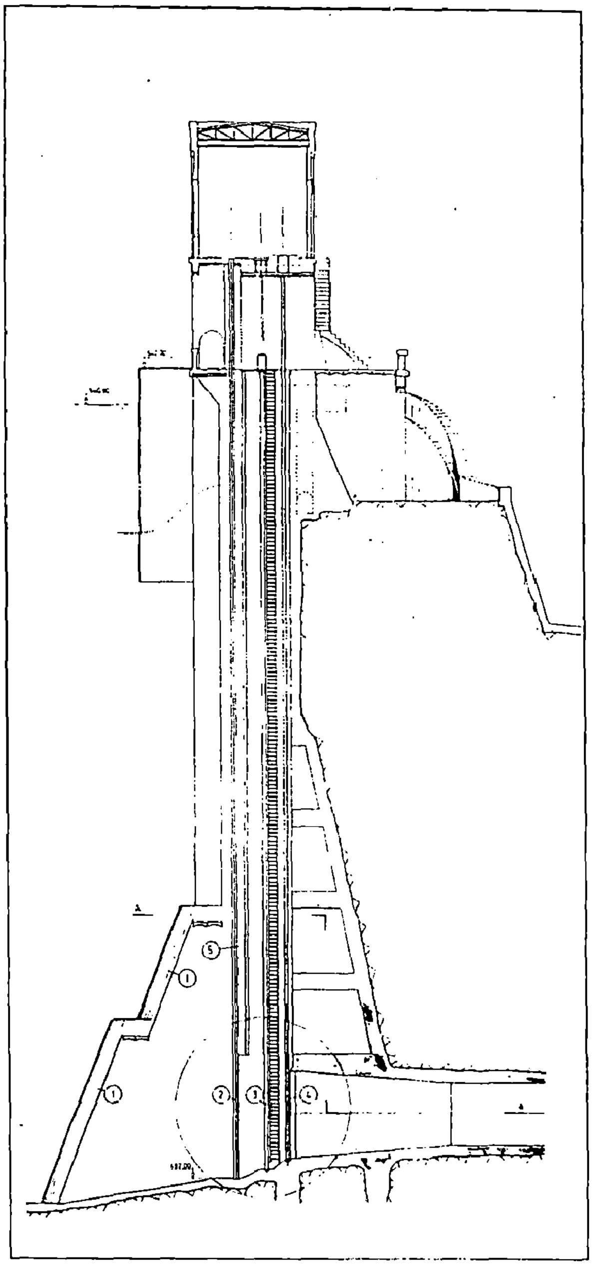


FIG. 5.48

Intake cross section

(1) Coarse screens
(2) Fine screens
(3) Guide rail stoplogs
(4) Guide rail gate
(5) Front wall

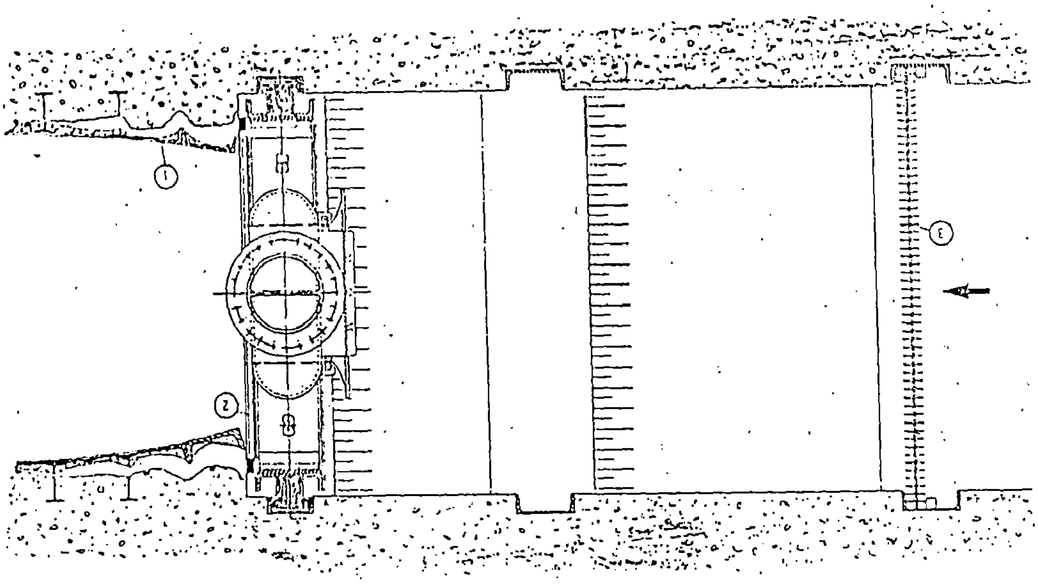


FIG. 5.49

~~Draw of~~ collapsed steel lined branch

(1) Steel lined
(2) Gate
(3) Fine screen
(4) Guide rail stoplogs

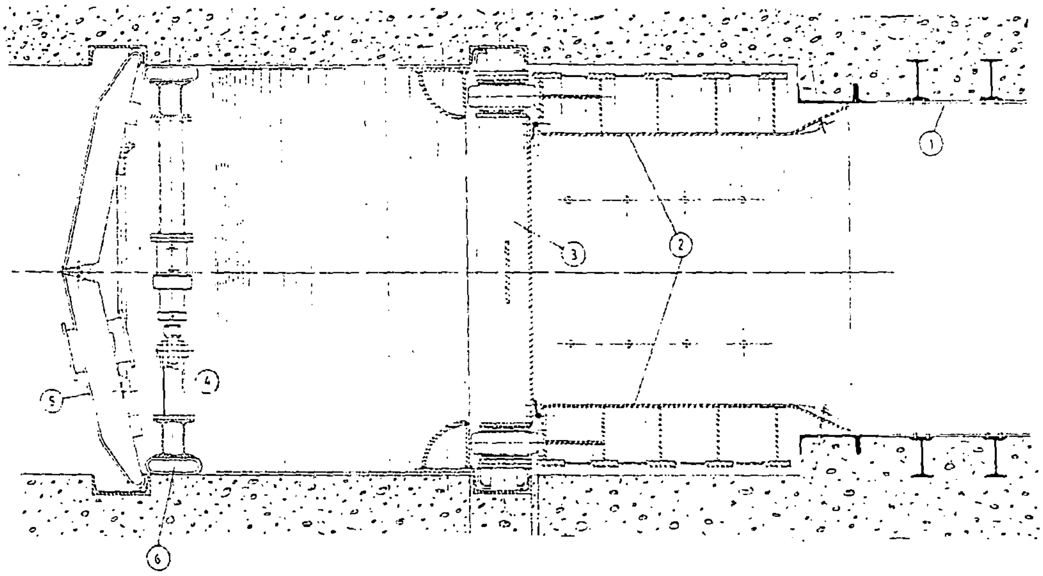


FIG. 5.50

Provisional elements and new gates

(1) Old steel lined
(2) New steel lined
(3) New gate
(4) Expanders
(5) Cofferdam
(6) Grouted rubber pipes

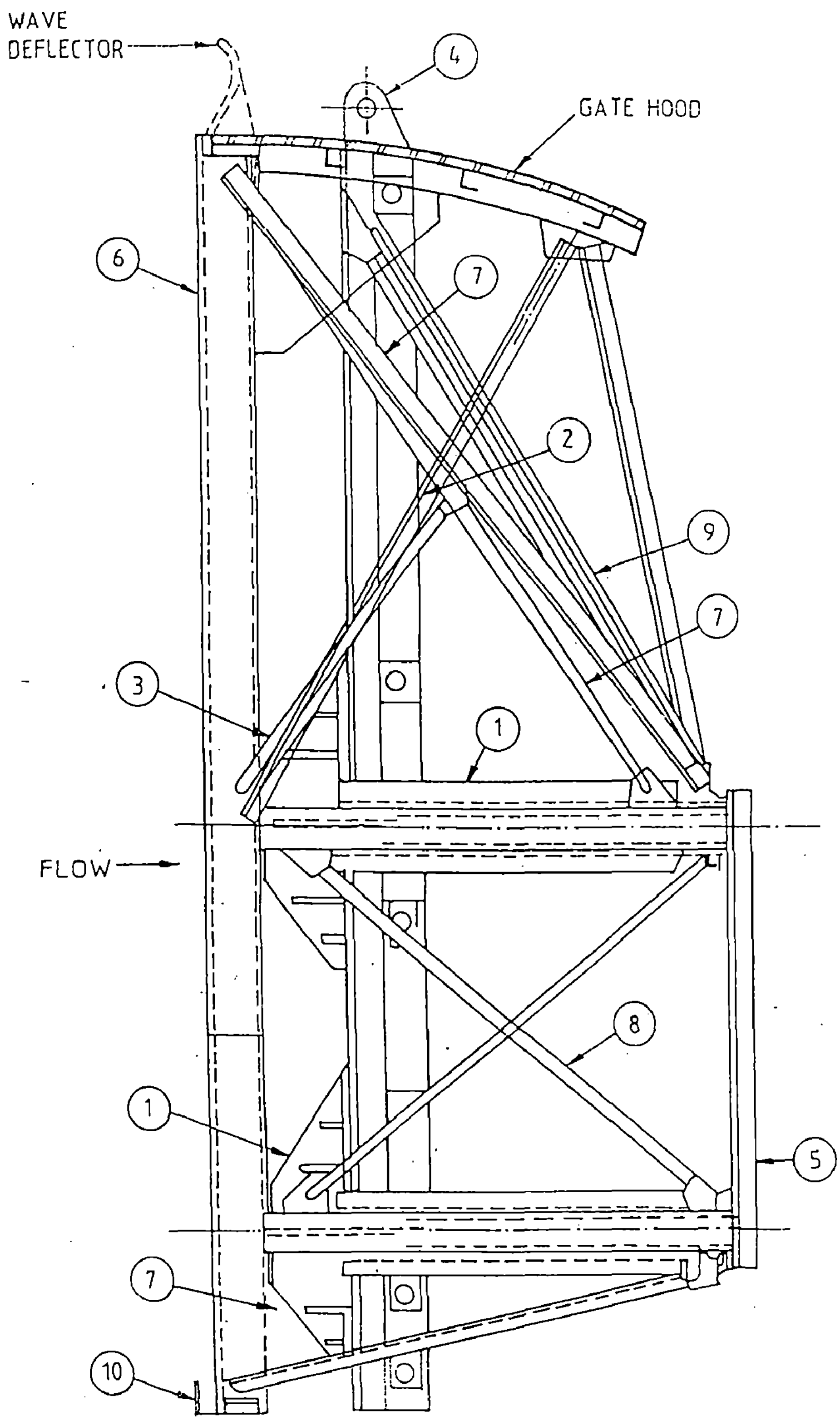


FIG. 5.51 Overtopping of vertical lift spillway gates

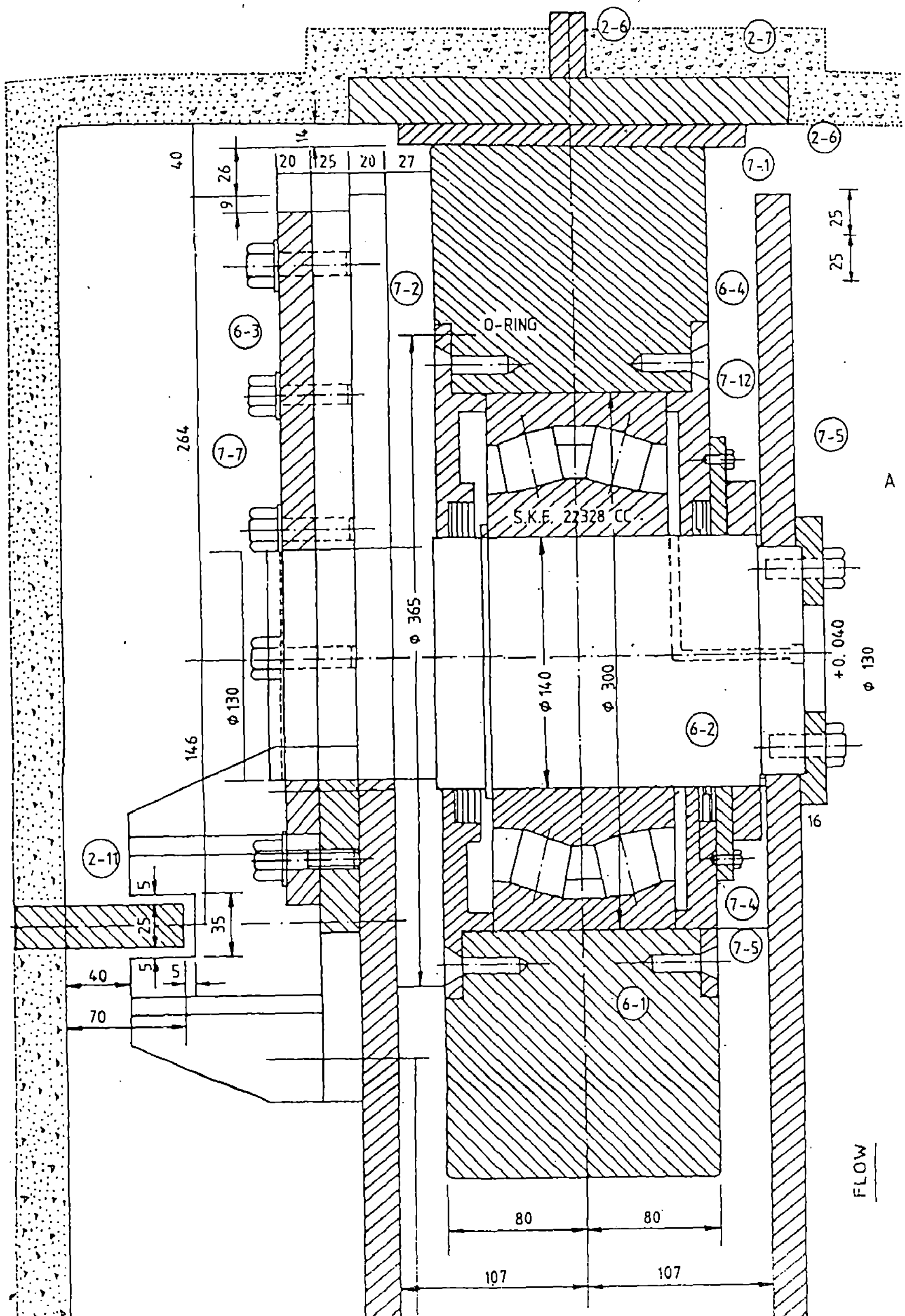


FIG. 5.52 Jamming of spherical roller bearings

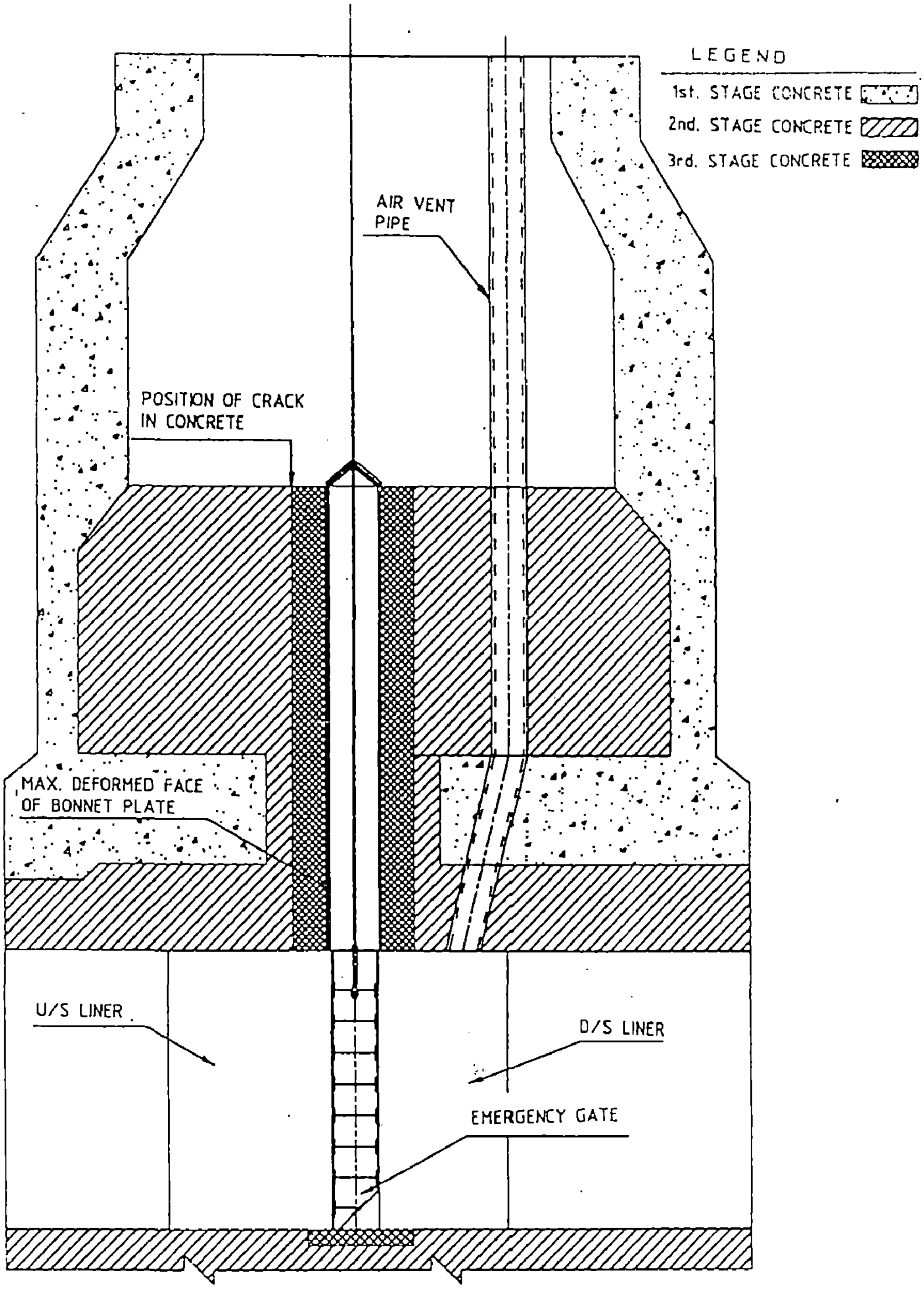


FIG. 5.53 : Building of gate shaft liners of penstock gate

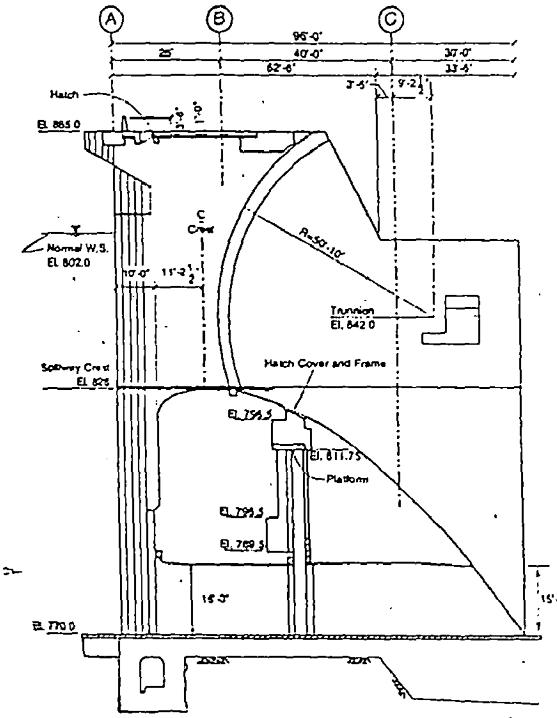


FIG. 5.54 Section Through Spillway and Sluice Conduit

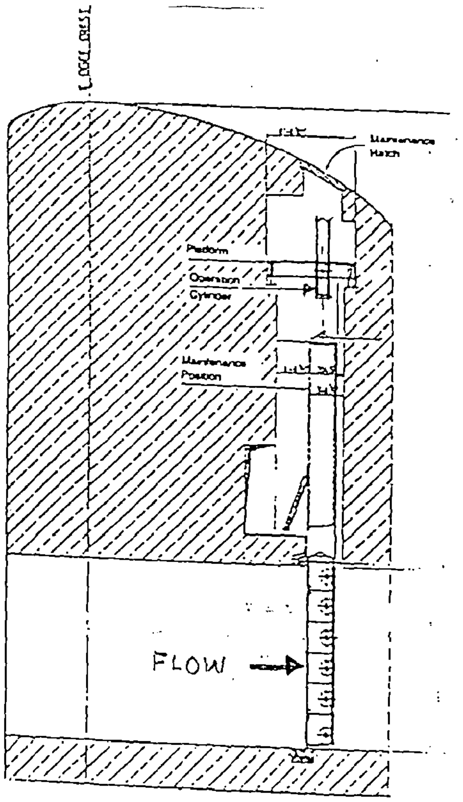


FIG. 5.55
Upstream Sealing Roller Gate and Gate Chamber

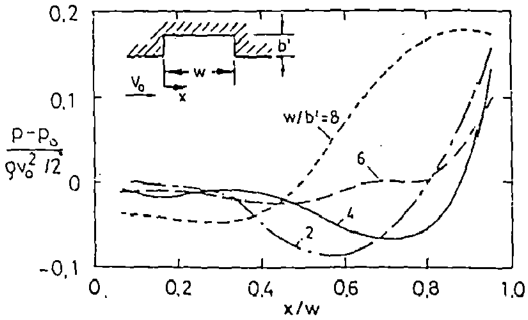


FIG. 5.56 Pressure distribution in a rectangular cutout (or gate-slot) with flow past it (according to Rossiter).

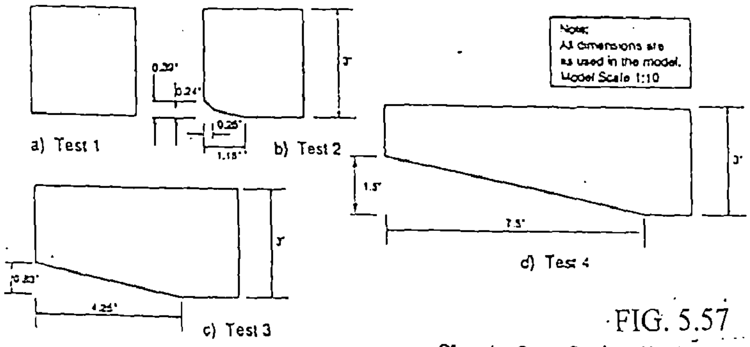


FIG. 5.57
Chamfer Cross Sections Used in Test

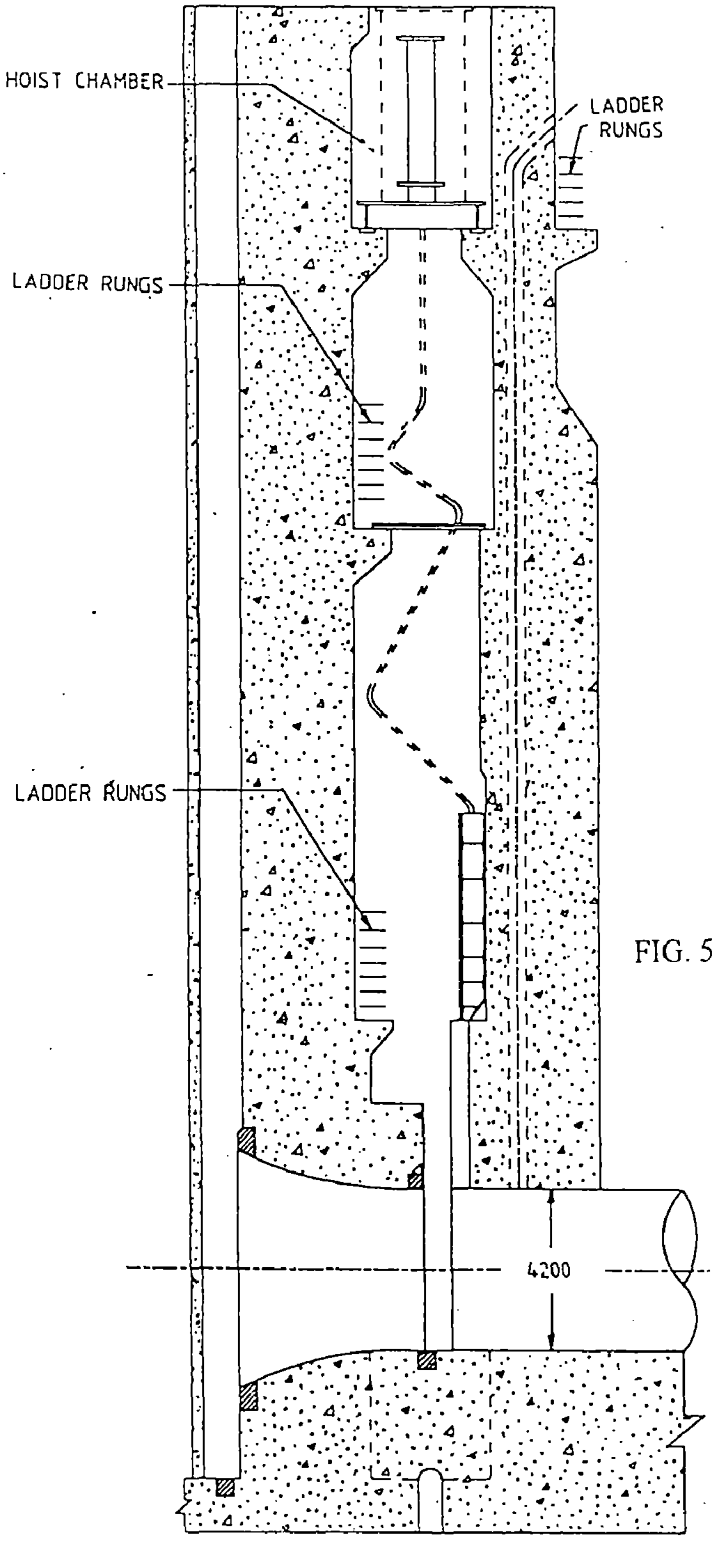


FIG. 5.59 : Catapulting of service gate

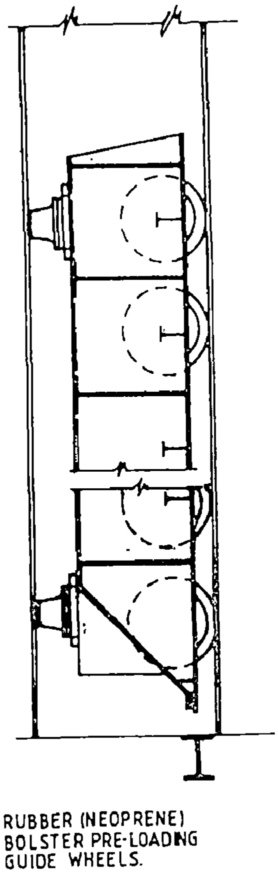
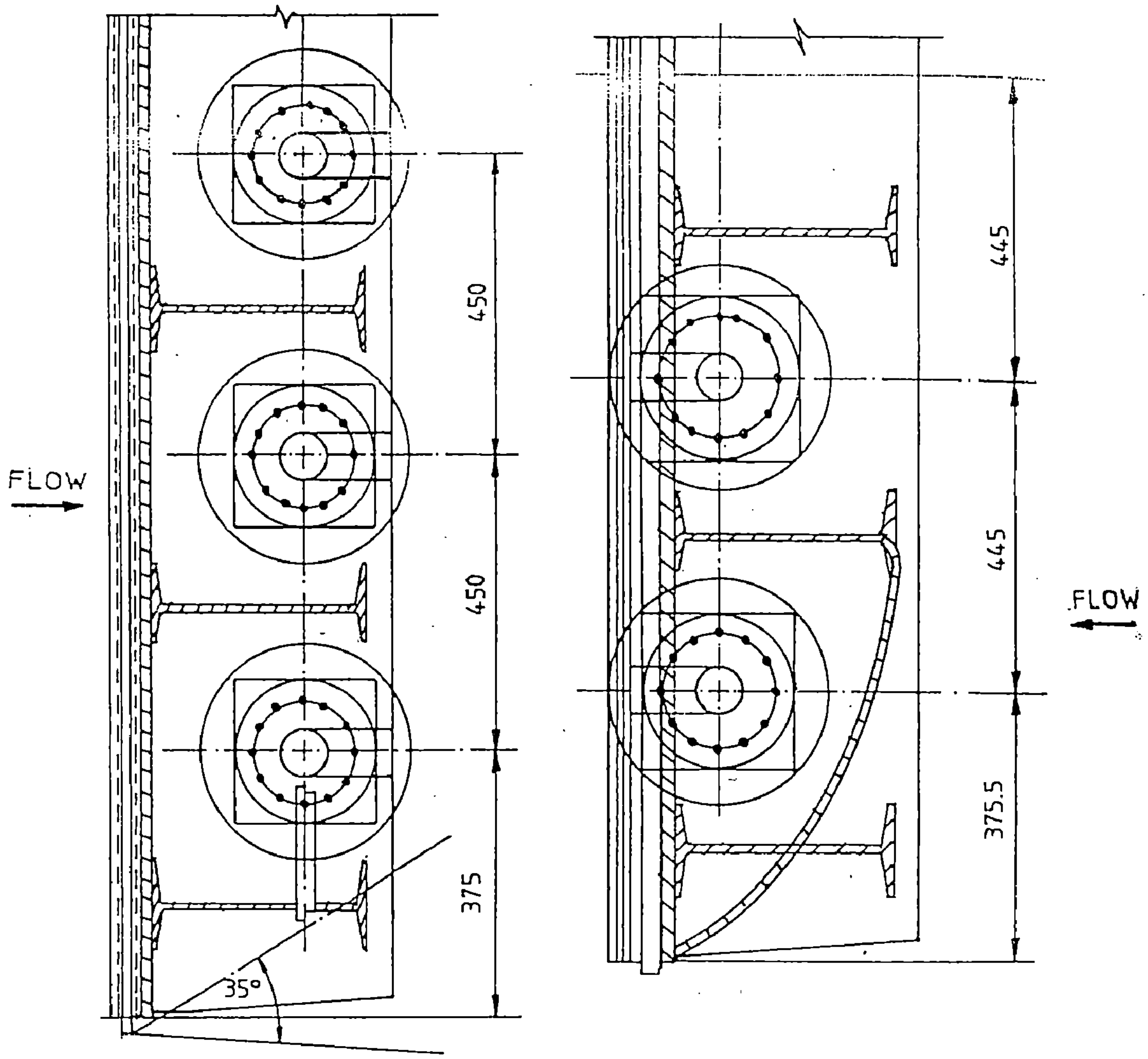


FIG. 5.58 *Pre-loading of the guide wheels of a vertical lift gate*



Service gate
Proposed bottom shape
(for u/s sealing case)

Emergency gate
Proposed bottom shape
(for d/s sealing case)

FIG. 5.60 Modifications of gate bottoms

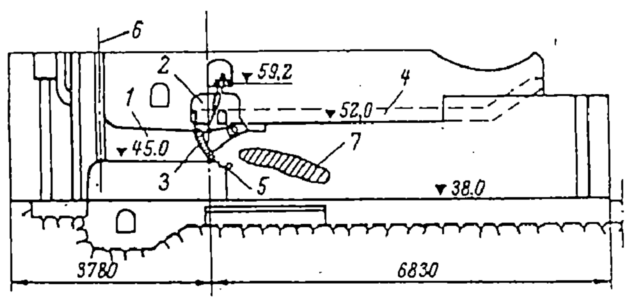


FIG. 5.61 Bottom outlet. 1) Outlet [illegible]; 2) chamber of radial gate; 3) radial gate; 4) ventilation gallery; 5) ventilation pipe; 6) groove of vertical emergency gate; 7) scour zone.

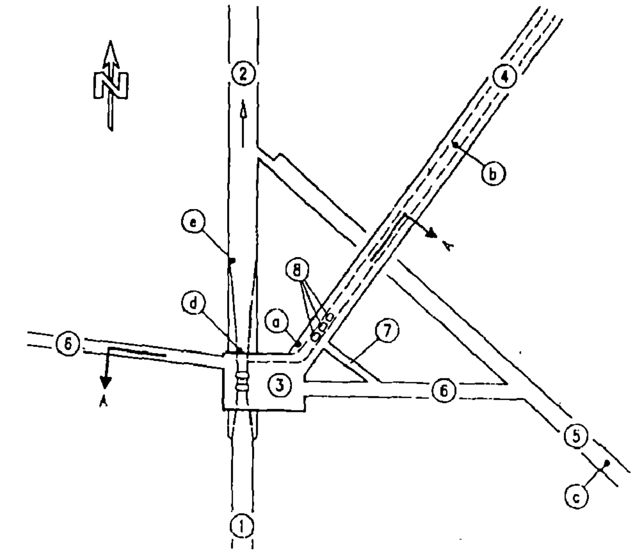


FIG. 5.62

Layout of the bottom outlet

(1) Upstream tunnel (pressurized part)
(2) Downstream tunnel (free flow part)

(3) Gate chamber
(4) Inclined access shaft with aeration channel
(5) Drainage gallery
(6) Access tunnel
(7) Connection for additional air supply from the gallery system of the dam to the inclined access shaft
(8) Additional openings for aeration
(a-c) Measurement locations

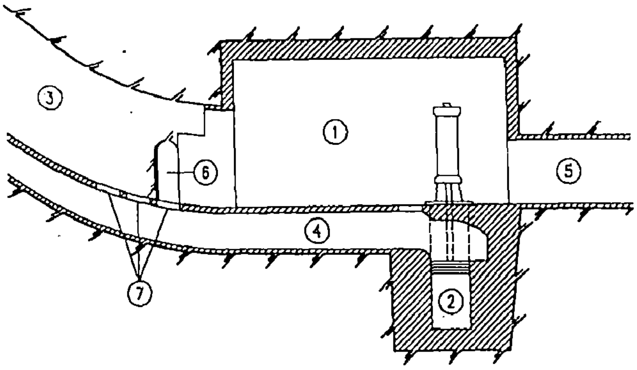


FIG. 5.63

Cross section A-A through the gate chamber

(1) Gate chamber
(2) Slide gate
(3) Inclined access shaft
(4) Aeration channel
(5) Access tunnel
(6) Connection for additional air supply for the gallery system of the dam to the inclined access shaft
(7) Additional openings for aeration

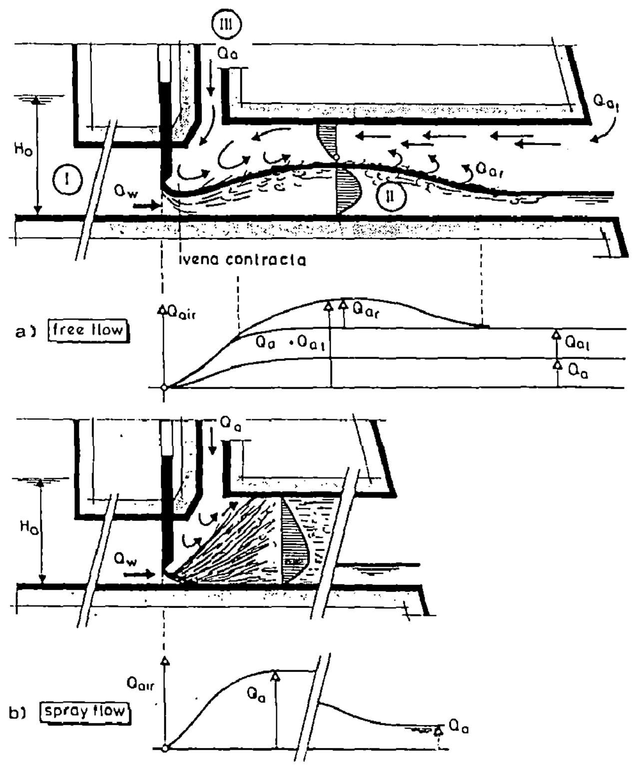


FIG. 5.65

Typical longitudinal section through a bottom outlet

I Approaching flow (Q_w) with pressure head H_o
II Air entrainment and mixture zone
III Aeration channel (Q_a)

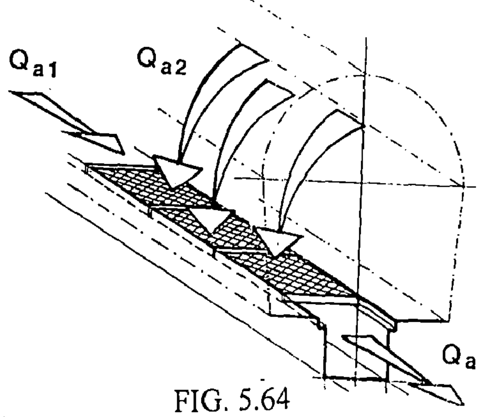


FIG. 5.64

Air flow in the aeration channel and the additional openings

Q_{a1} Original air flow from the aeration channel intake
Q_{a2} Air flow through openings (supplied by drainage gallery)
Q_a Total air flow to the bottom outlet tunnel

a) " Free flow " downstream of the gate
$Q_{air} = Q_a + Q_{ar} + Q_{at}$
Q_a : Air flow in the aeration channel
Q_{ar} : Air escaping from the water
Q_{at} : Air flow from the free atmosphere

b) " Spray flow " at small openings (< 10 %)

$Q_{air} = Q_a$
Because the air flow at the tunnel roof is interrupted, the air demand in the aeration channel (Q_a) reaches a first peak

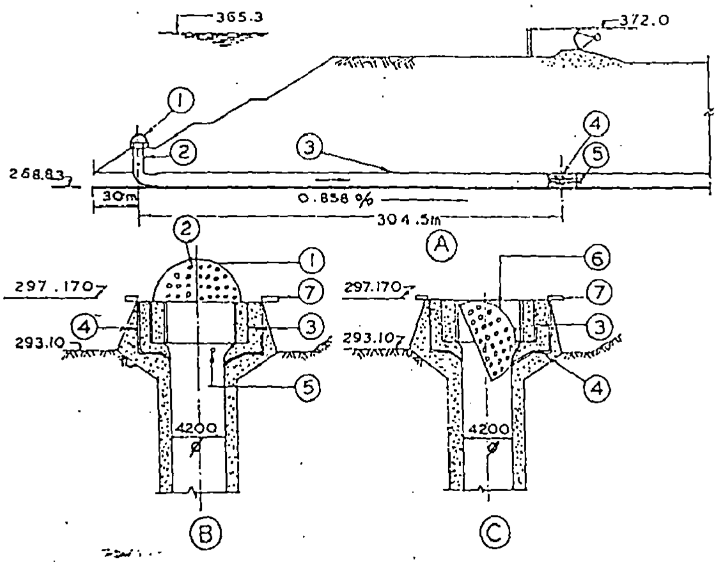


FIG. 5.66

Ramganga project auxiliary outlet.

(A) Layout of intake and outlet.
(1) Hemispherical trash rack.
(2) Intake shaft.
(3) Outlet tunnel.
(4) Butterfly valve.
(5) Howel bunger valve.
(B) Hemispherical trash rack before collapse.
(C) After collapse.
(1) Trash rack before collapse.
(2) Holes 160 mm dia. at 320 mm centres.
(3) Vertical trash racks.
(4) Filling line.
(5) Vent pipe.
(6) Trash rack after collapse.
(7) Valve for the filling line.

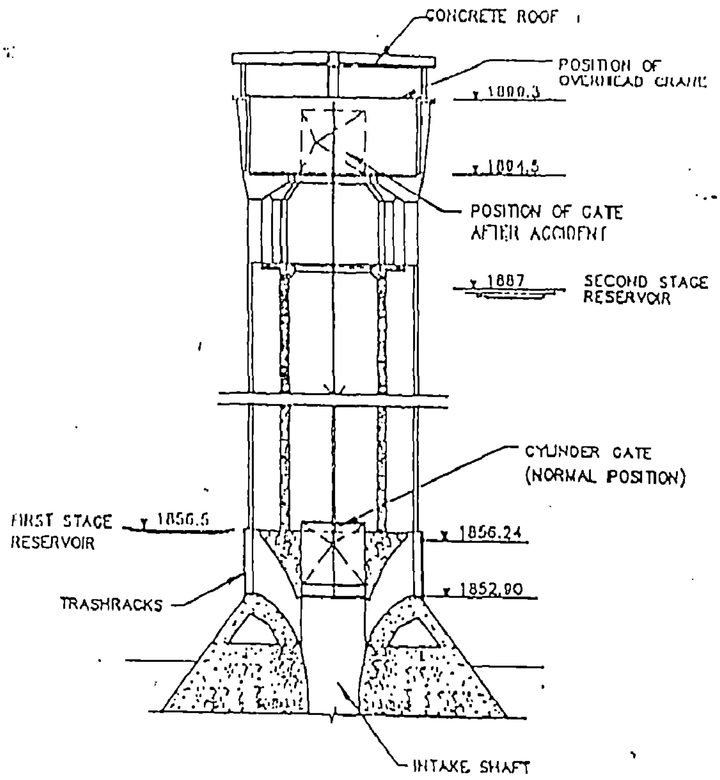
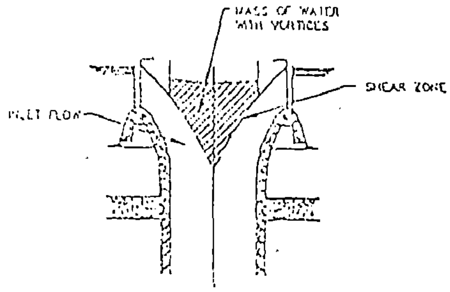
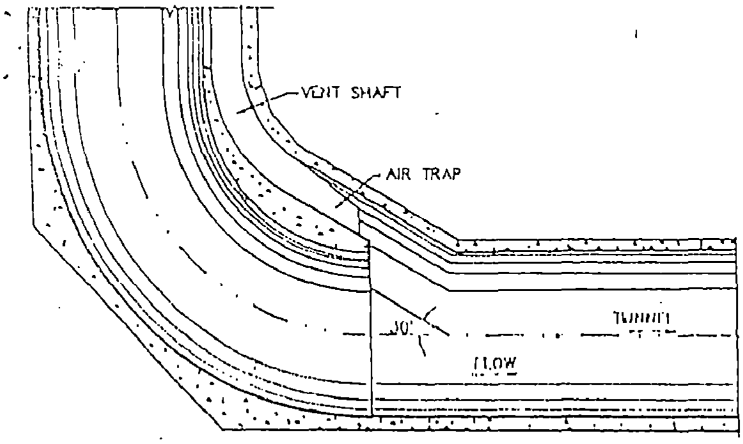


FIG. 5.67(a) Section through intake tower.

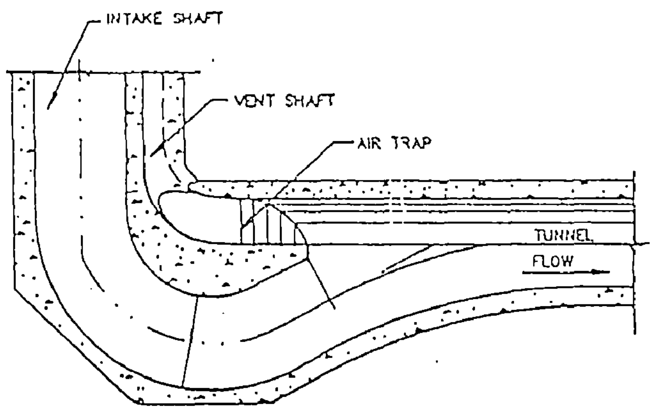


(b) Vortex formation inside tower.



(a)

FIG. 5.68 Alr trap-



(b)

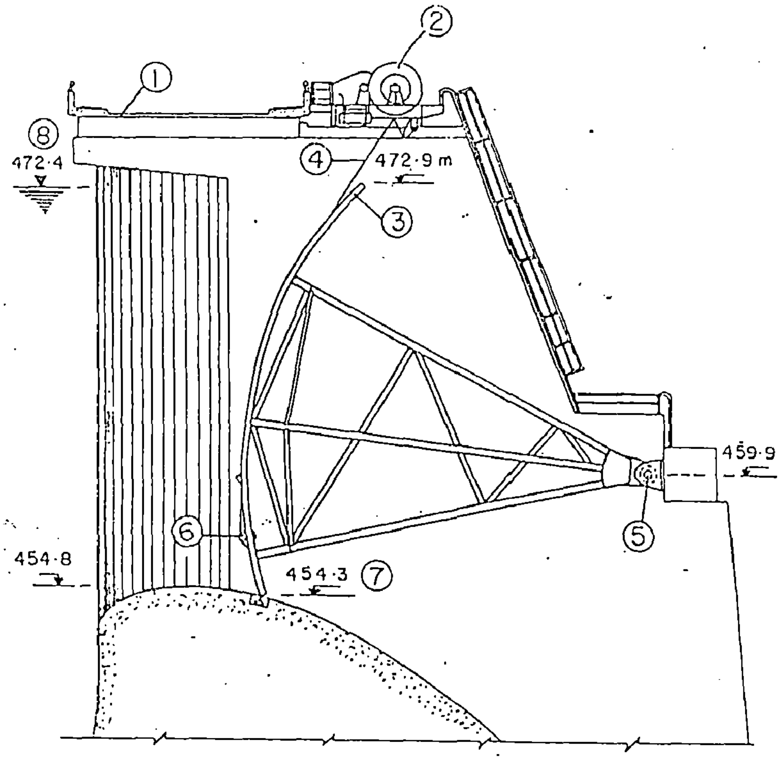


FIG. 5.69

① Spillway bridge
② Hoist drum & gear
③ Gate leaf
④ Wire ropes
⑤ Trunnion
⑥ Wire rope attachment assembly
⑦ Sill beam elevation
⑧ Full reservoir level

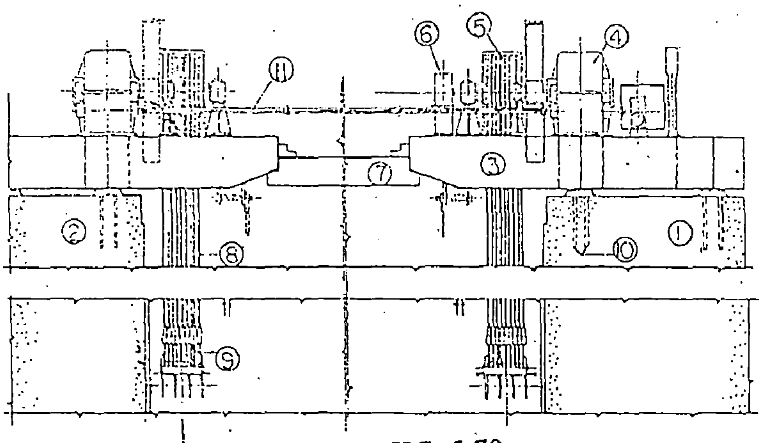


FIG. 5.70

① Abutment
② Pier
③ Hoist platform
④ Speed reducer
⑤ Hoist drum
⑥ Program switch
⑦ Catwalk
⑧ Wire ropes
⑨ Wire rope attachment assembly
⑩ Anchor bolts
⑪ Drive shaft

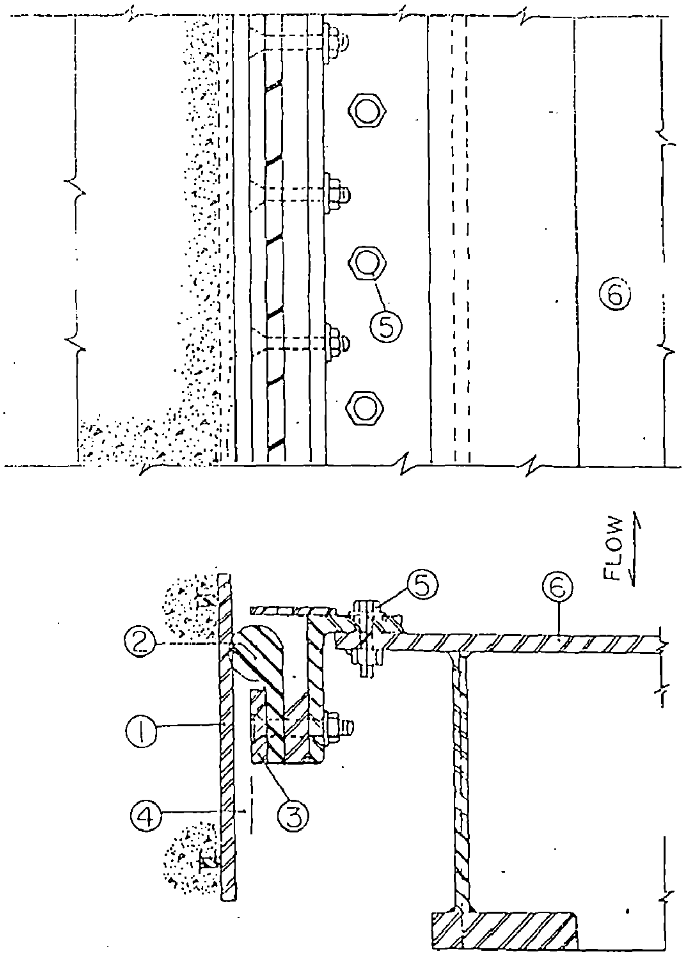
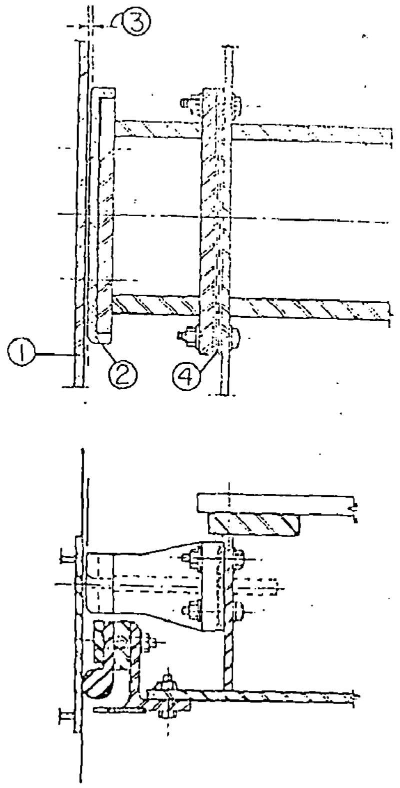


FIG. 5.71

(1) Embedded seal plate
(2) Rubber seal
(3) Clamping bar
(4) Clearance – standard 17 mm
(5) Bolt 16 mm holding side seal holder assembly in 27 mm hole

(6) Skin plate



(1) Embedded seal plate
(2) Buffer plate of bronze copper alloy

(3) Clearance - standard 4 mm
(4) Skins for adjusting clearance

FIG. 5.72

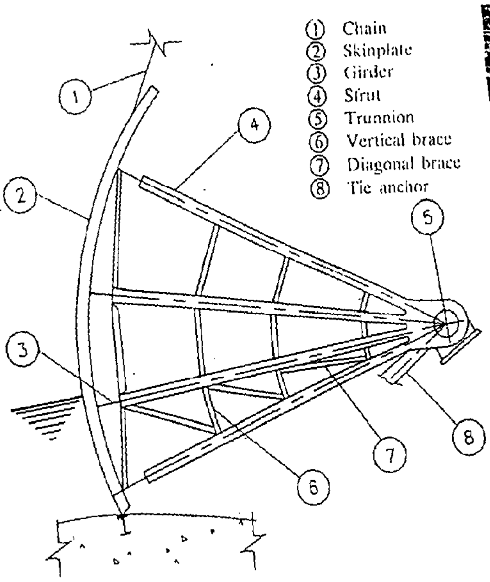


FIG. 5.73

Original gate

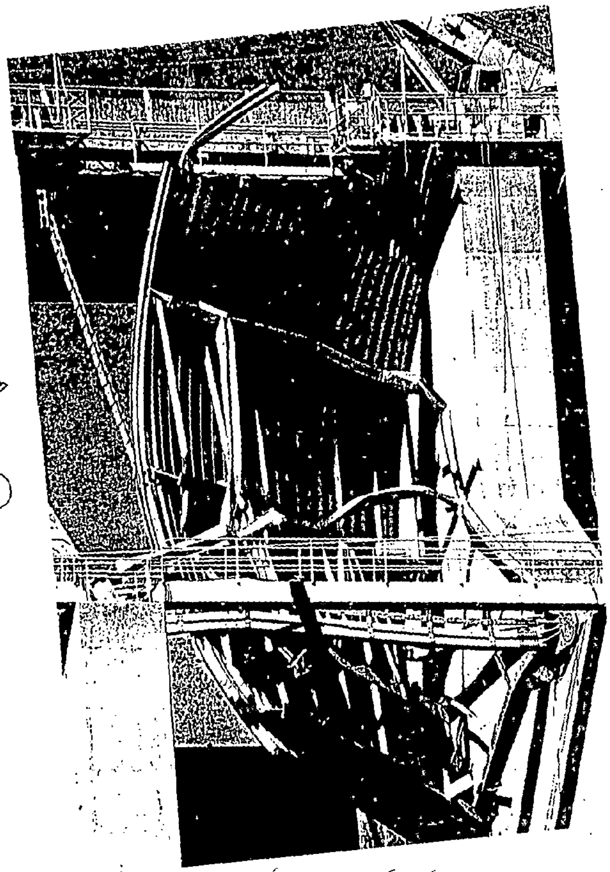


FIG. 5.75

Failed Gate

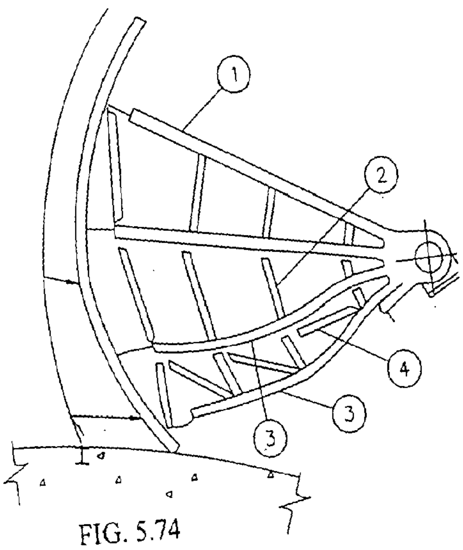


FIG. 5.74

Primary failure mode of gate

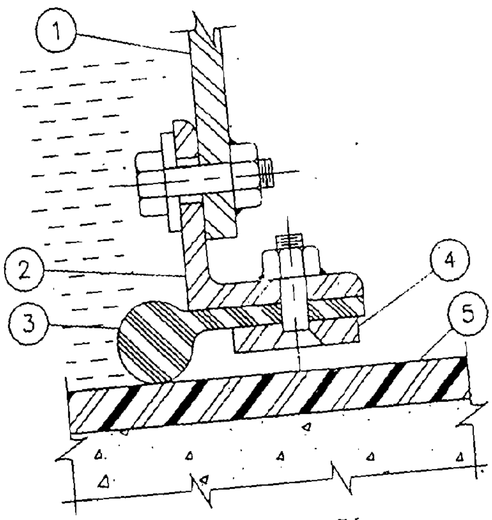


FIG. 5.76

Side Seal

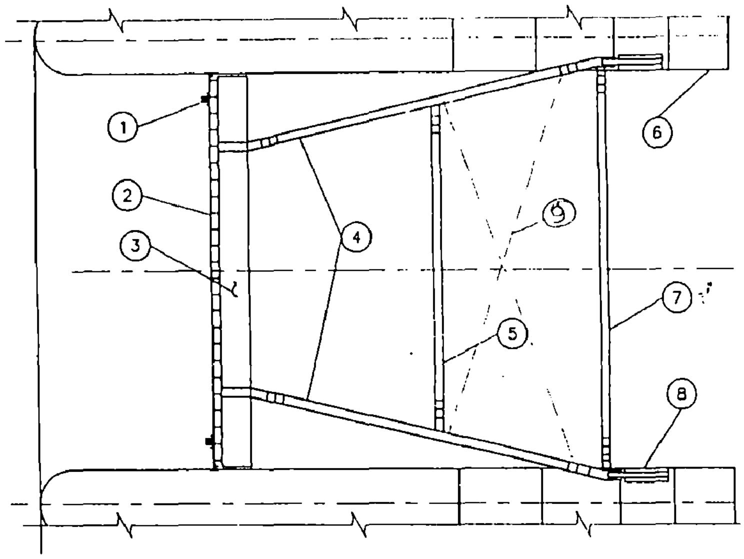


FIG. 5.77

Plan of original gate

1. Chain
2. Skinplate
3. Girder
4. Struts
5. Tie beam
6. Concrete pier
7. Trunnion tie beam
8. Trunnion
9. BRACINGS

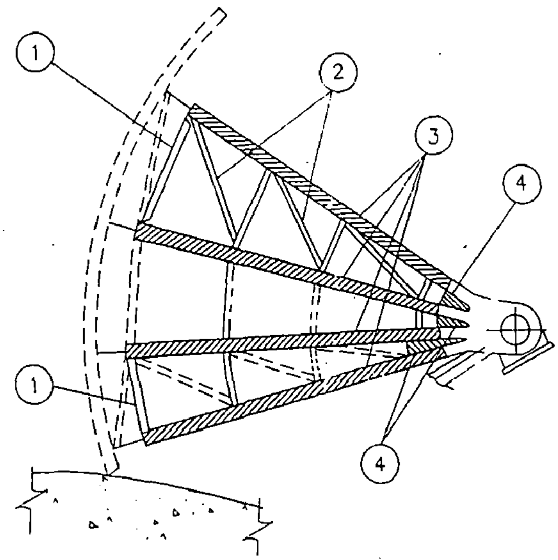


FIG. 5.78

Reinforced gate

1. Vertical brace
2. Diagonal braces
3. Strut reinforcing
4. Stiffening plates

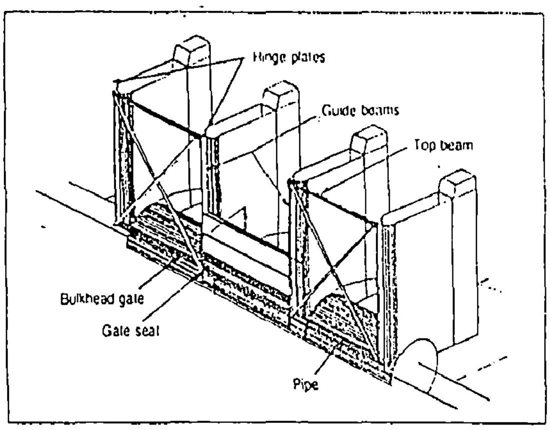


FIG. 5.79 BULKHEAD (STOPLOGS) UNITS & FRAME

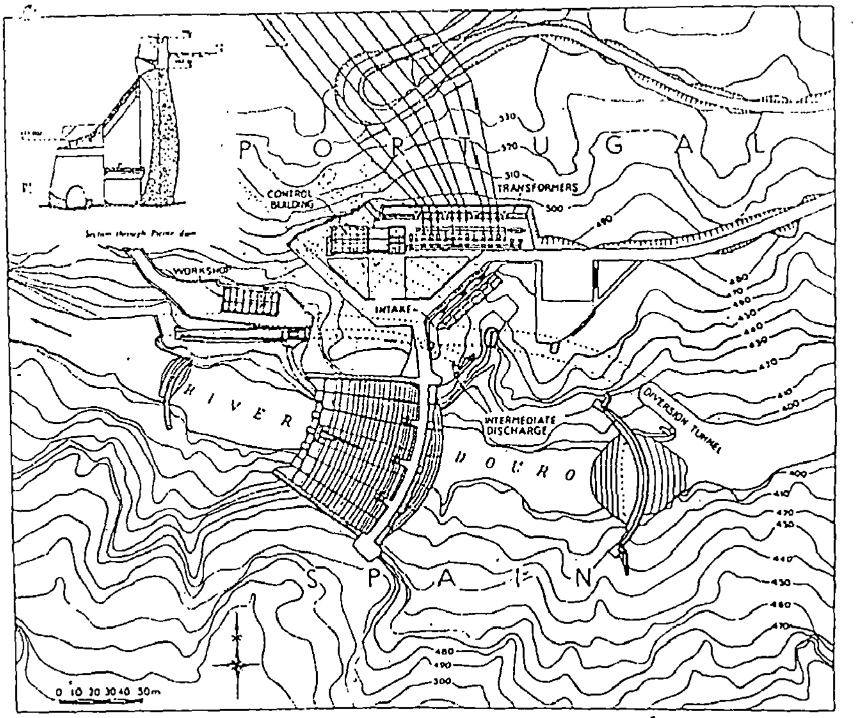


FIG. 5.80

General plan of the Picote dam and power-station.

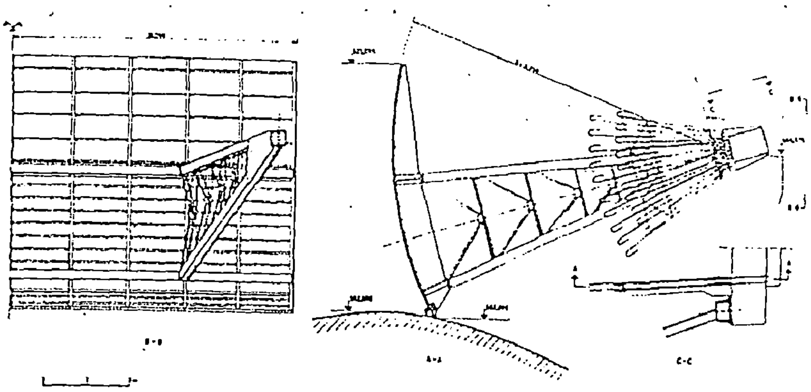


FIG. 5.82

Picote : Radial gate (Anchorage).

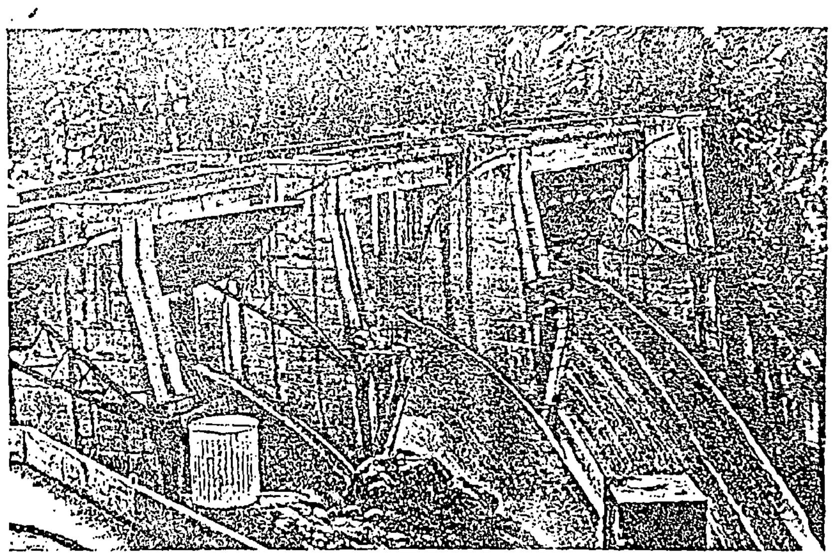


FIG. 5.83

Picote Dam : General view after the accident.

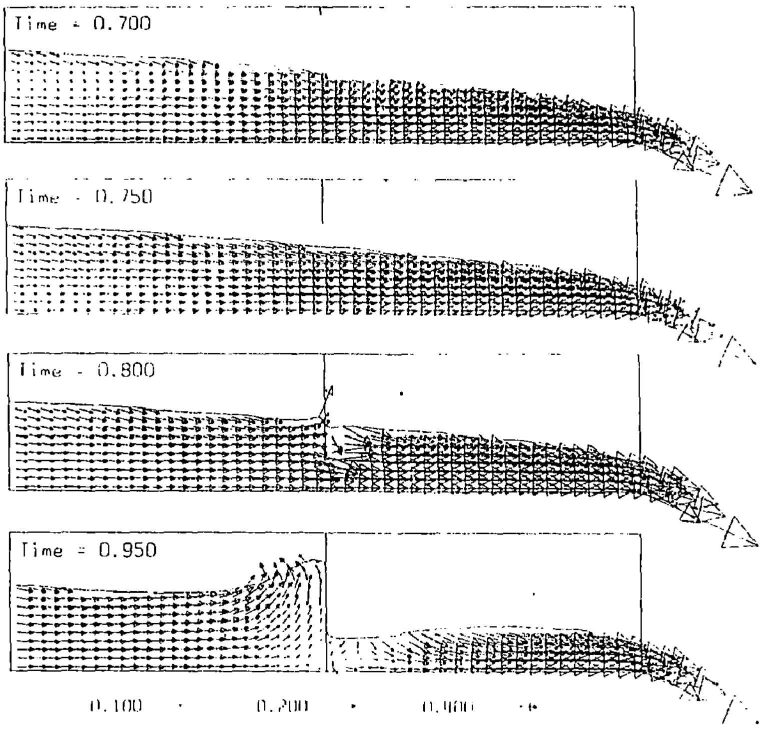


FIG. 5.84
Test 3: velocity (m/s) and free surface configurations

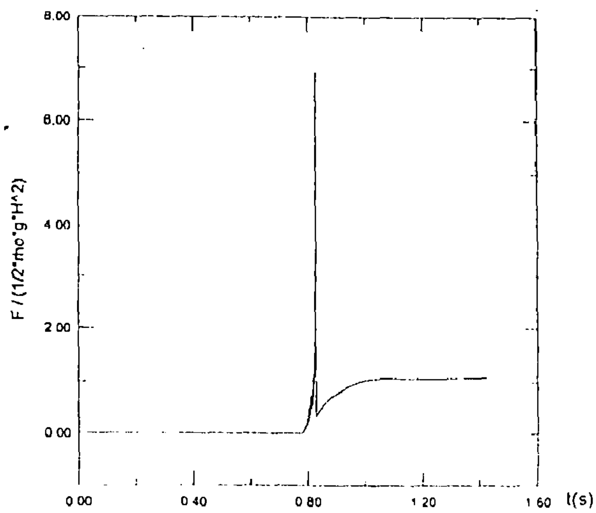


FIG. 5.85
Test 3: time history of the non-dimensional force on the gate

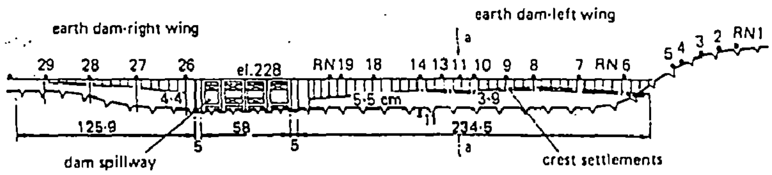


FIG. 5.86 longitudinal section

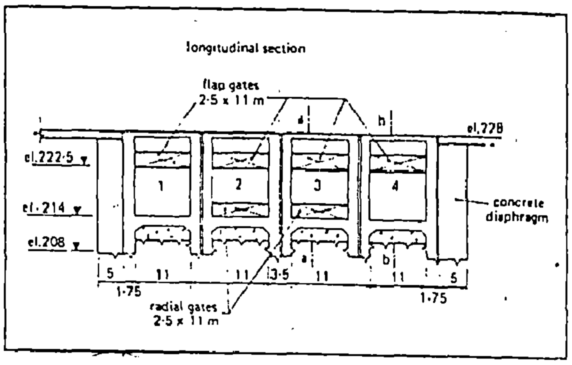


FIG. 5.87 *Characteristic sections of the spillway.*

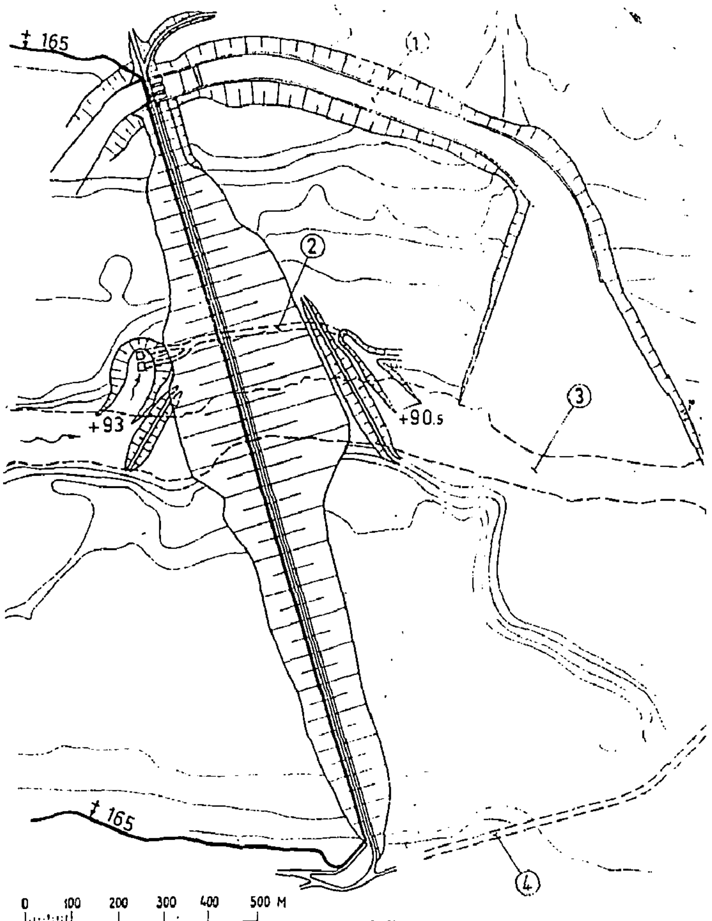


FIG. 5.88

Plan of Messaure dam and diversion tunnel.

1. Spillway channel.
2. Diversion tunnel.
3. River Luleälven.
4. Dicharge tunnel.

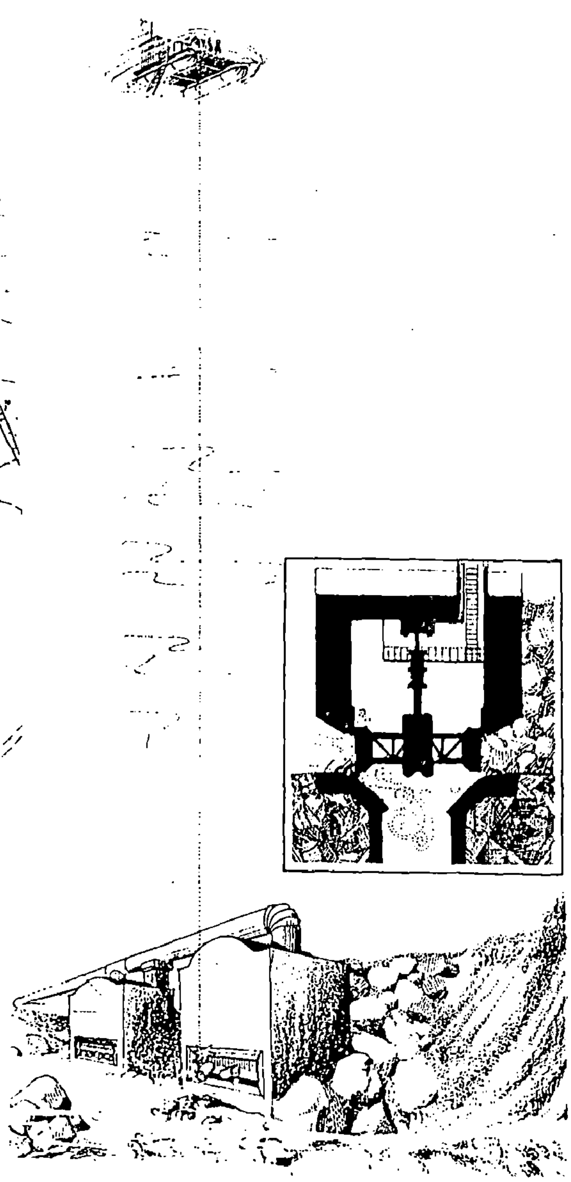
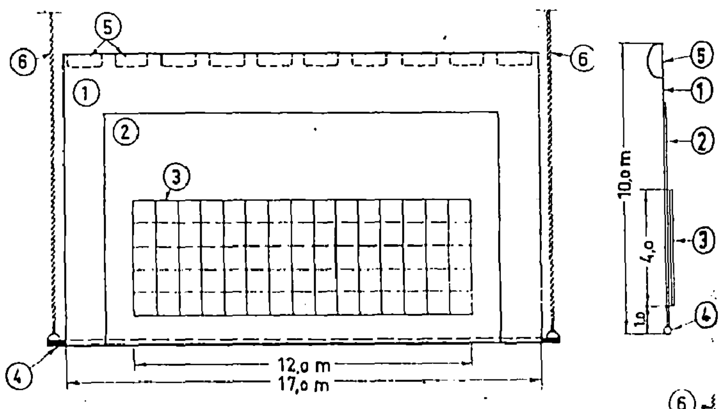


FIG. 5.89

partly blocked gate system and the method used for the first partial closure.



1. Extra strong plastic tarpaulin.
2. Double layers of *ditto*.
3. Two layers of 2 cm thick rubber strips.
4. Steel beam as dead-weight.
5. Floats to keep the curtain stretched in the water.
6. Ropes or wires for the lowering.

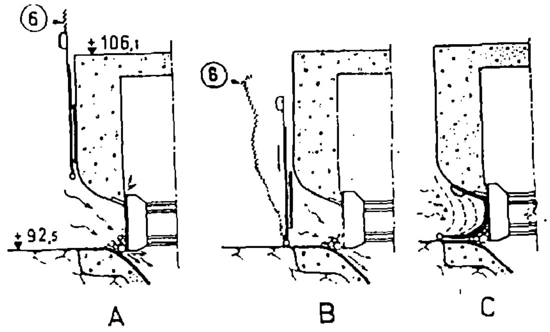
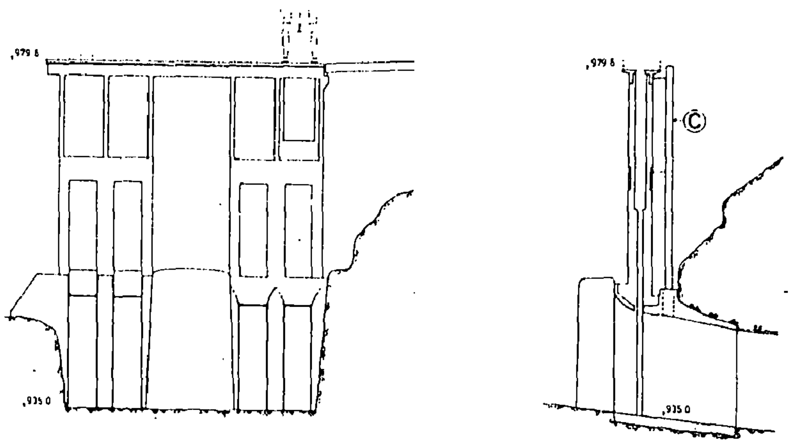
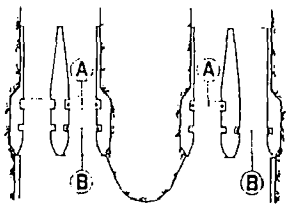


FIG. 5.90

Final closure by use of a reinforced plastic tarpaulin curtain.





KAFUE GORGE -
DIVERSION TUNNEL INTAKES

(A) Concrete stoplog grooves
(B) Bulkhead gate grooves
(C) Vents for right hand intake

FIG. 5.91

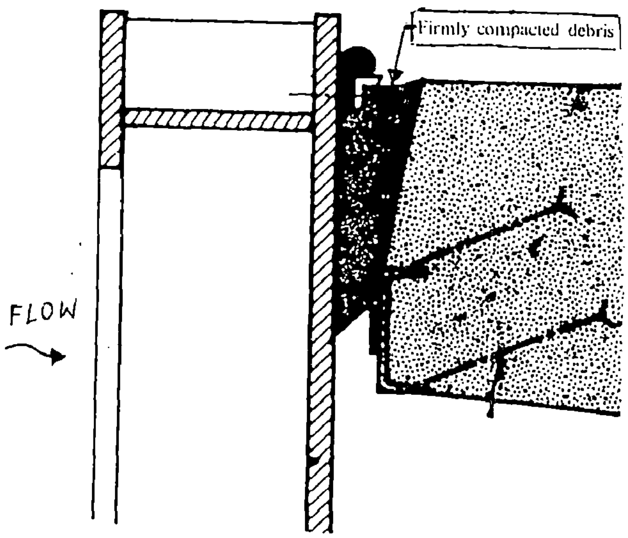
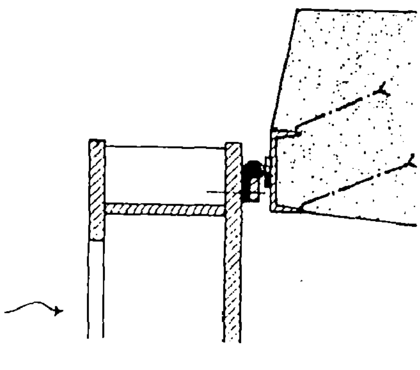
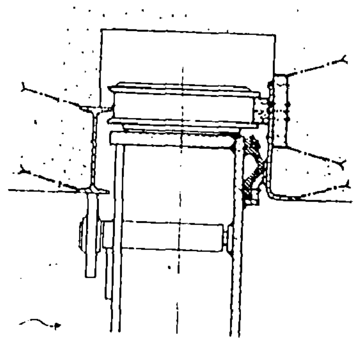


FIG. 5.93
Accumulation of debris at the bulkhead gate top seal

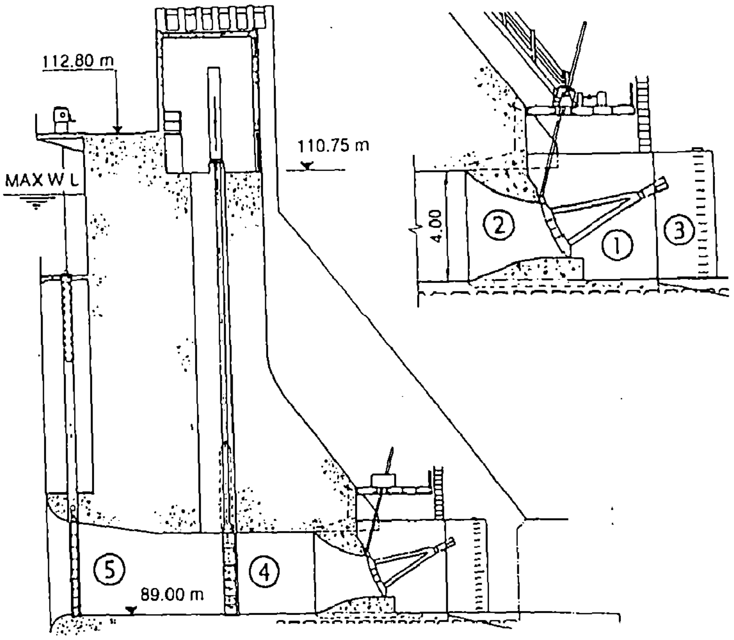


(a)
Bulkhead gate top
seal in closing position



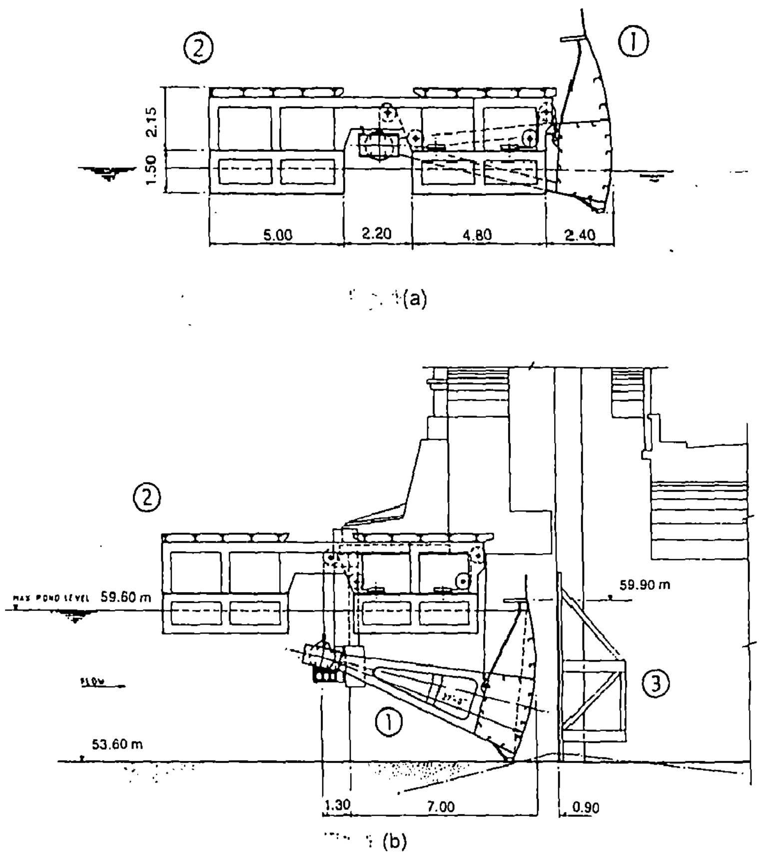
(b)
Bulkhead gate side seal

FIG. 5.92
SEALING ARRANGEMENT



(1) Radial gate
(2) Fairing
(3) Flexible joint
(4) Emergency gate
(5) Bulkhead gate

FIG. 5.95
Koka dam - Section through irrigation outlet



(a) Floating on headpond
(b) In place at structure

(1) Caisson gate
(2) Pontoon
(3) Existing barrage gate

FIG. 5.94 -Sukkur barrage - Caisson gate

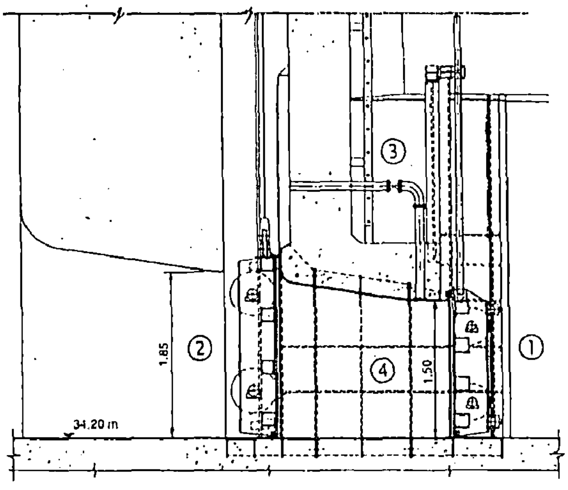


FIG. 5.96
Kelinchi dam - Section through bottom outlet

① Control gate
② Emergency gate
③ By-pass valve
④ Culvert lining

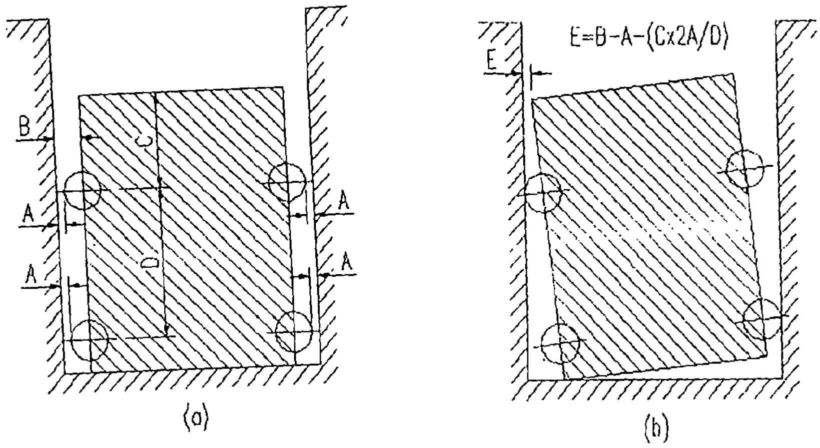


FIG. 5.97
Gate corner clearance at maximum tilt

Fig. 2(a) Gate upright and central
Fig. 2(b) Gate at maximum tilt
(A) Clearance of wheels

(B) Clearance of steel edge

(C) Height of gate above wheels

(D) Height between wheels
(E) Clearance of corner at maximum tilt

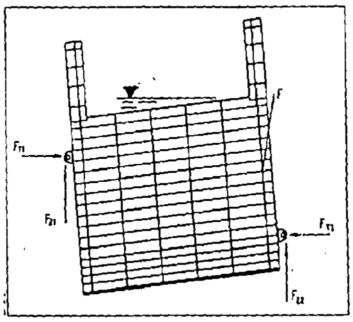


FIG. 5.98 FORCES ON GATE DUE TO TILTING

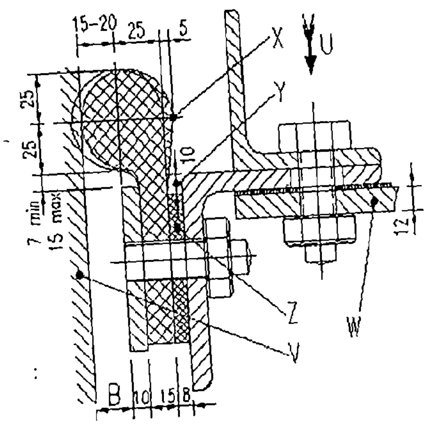


FIG. 5.99
Side seal mounting arrangement

(B) Clearance of steel edge

(U) Direction of flow
(V) Embedded plate
(W) Skinplate of gate
(X) Rubber seal bent 5 mm backwards

(Y) Gap to facilitate backward bending of seal

(Z) Rubber backing strip

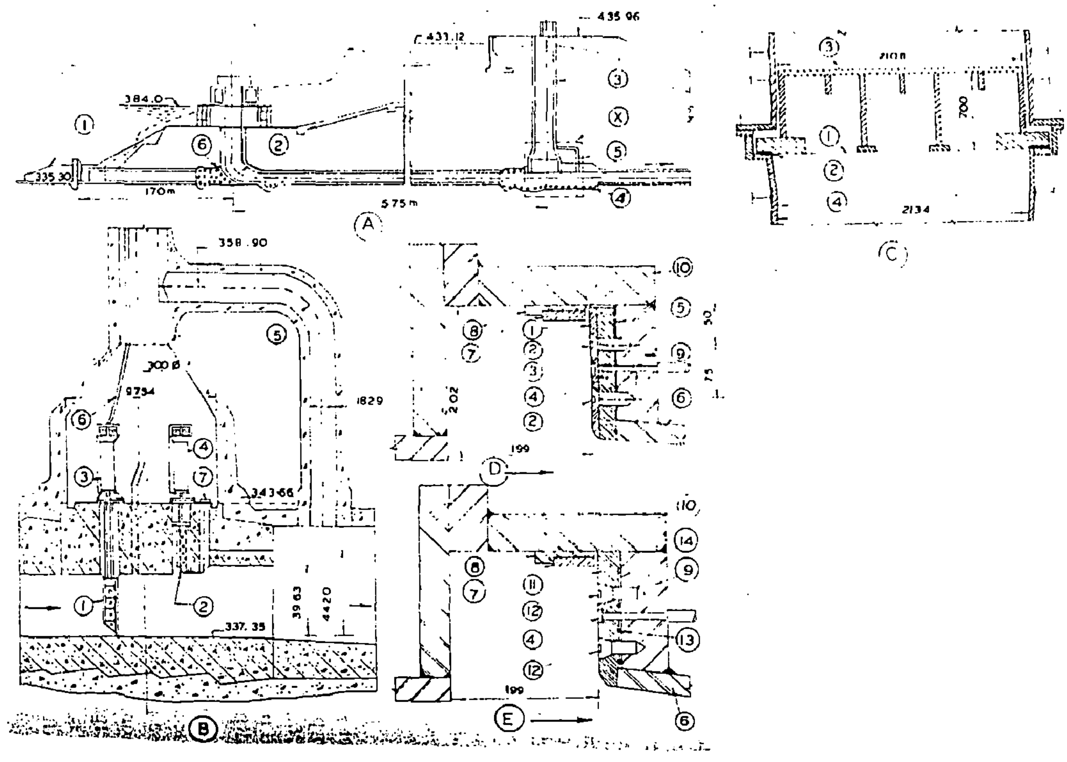


FIG. 5.100

Beas project — Pong dam irrigation tunnel gates.

(A) Layout of T 2 tunnel.
(1) Portal at intake.
(2) Intake shaft.
(3) gate shaft.
(4) T 2 Emergency & service gates.
(5) Air vent.
(6) Concrete plug.
(B) Hoist chamber and gate conduit (détail (X)).
(1) Emergency gate.
(2) Service gate.
(3) Hoist emergency gate.
(4) Hoist service gate.
(5) Air-vent (Service gate).
(6) Air-vent (Emergency gate).
(7) Man hole.
(C) Plan of T 2 gates.
(1) Gate leaf.
(2) Bronze seal.
(3) Liners on upstream.
(4) Liners on downstream.
(D) T 2 Gate slot before failure.
(E) T 2 Gate slot after rectification.

(1) Stainless steel plate.
(2) Slotted counter sunk stainless steel screws.
(3) M.S. plates.
(4) Grease hole.
(5) 3 mm lead packing.

(6) Liner plate.
(7) Stainless steel guide plate.
(8) M.S. plate.
(9) Base plate.
(10) Liner plate.
(11) New stainless steel plate.
(12) New counter sunk stainless steel screws.
(13) O-ring seals.
(14) Grooves for epoxy.

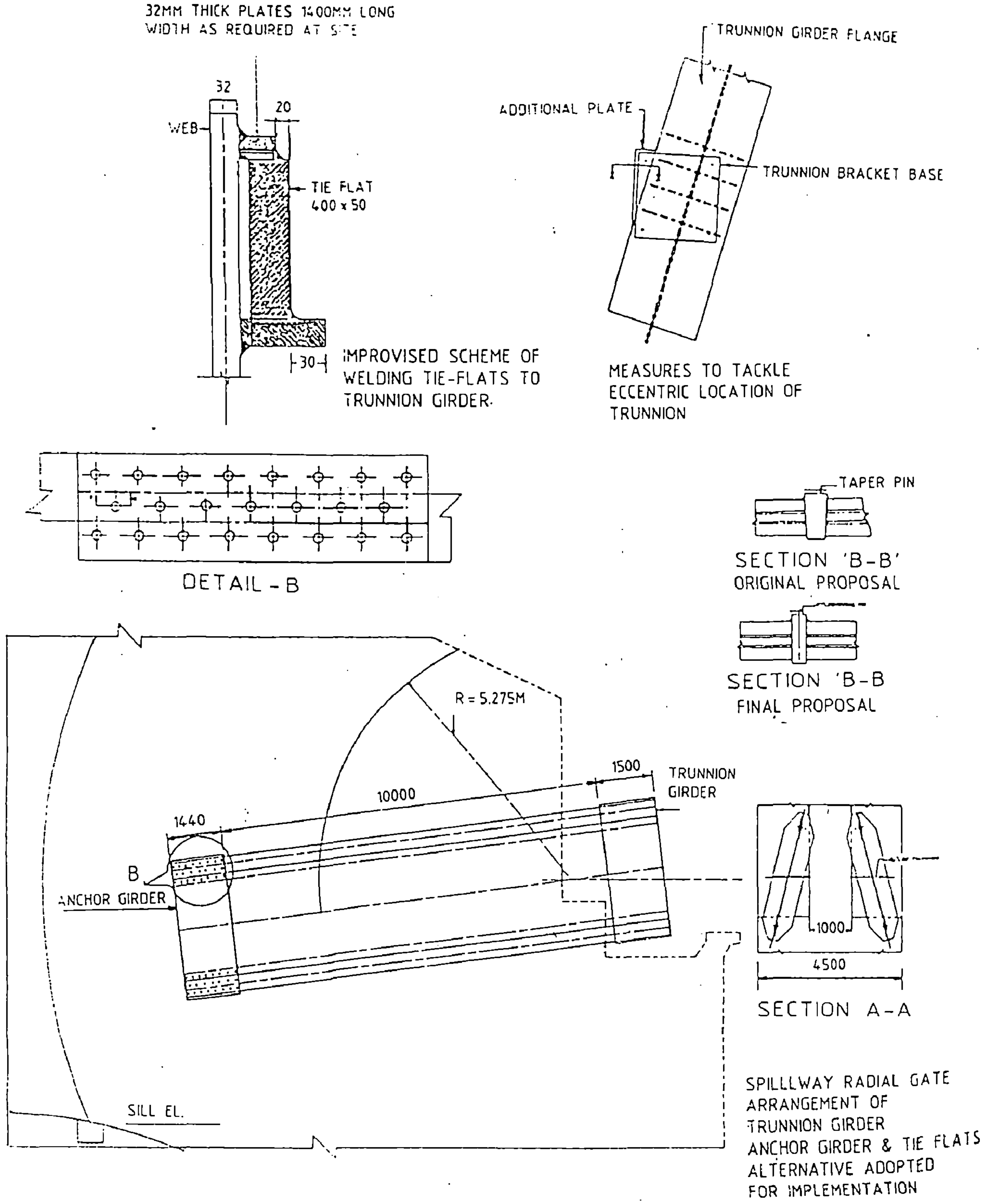


FIG. 5.101 : Failure of radial gate anchorages

FIG. 6.1 **Tainter gate failure caused by increased bearing friction**

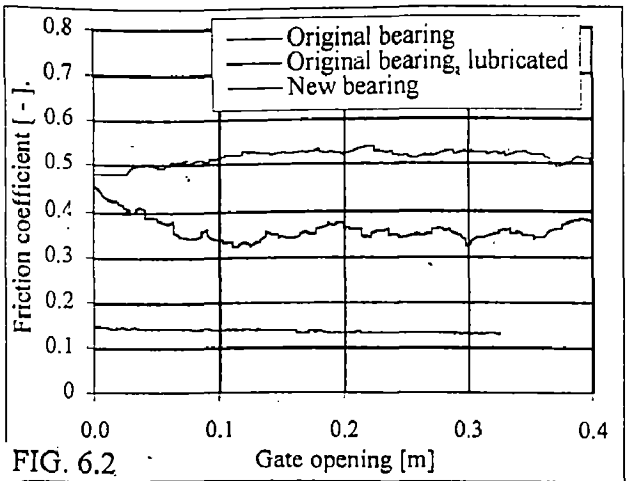


FIG. 6.2

Graph showing the results from three of the measurements of the right bearing on gate No. 1 on Lundevann dam

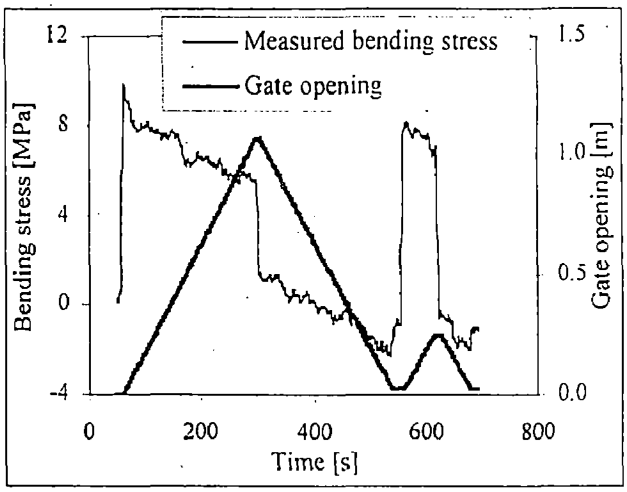


FIG. 6.3 **Graph showing the measured stress in the right gate arm at the Lundevann dam with the original bearing thoroughly lubricated. The gate was opened, almost closed, opened and finally closed. The vertical gate opening was measured simultaneously as shown in the graph**

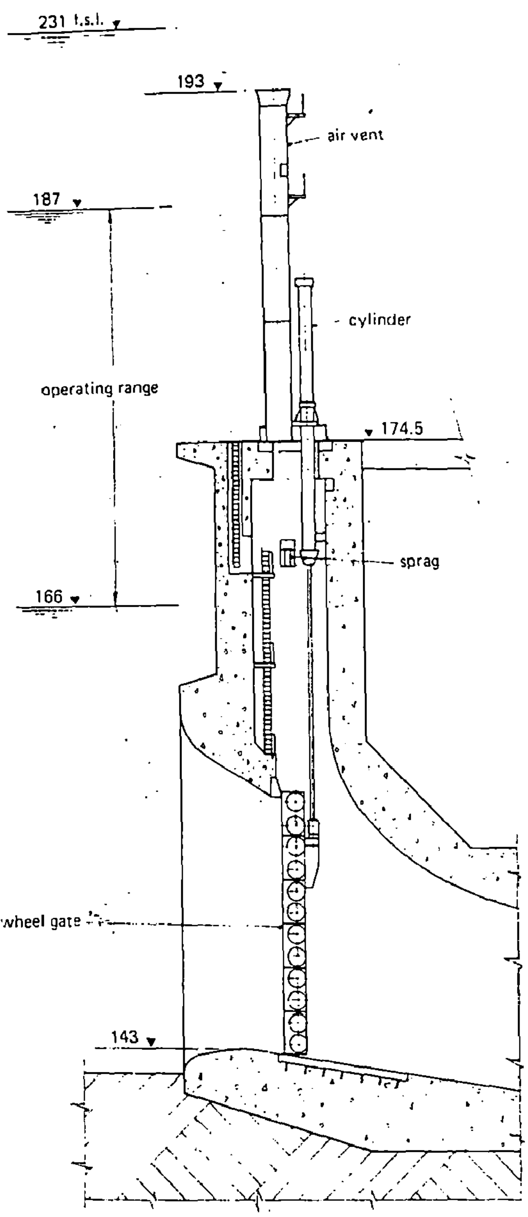


FIG. 6.4 *Section of the diversion intake.*

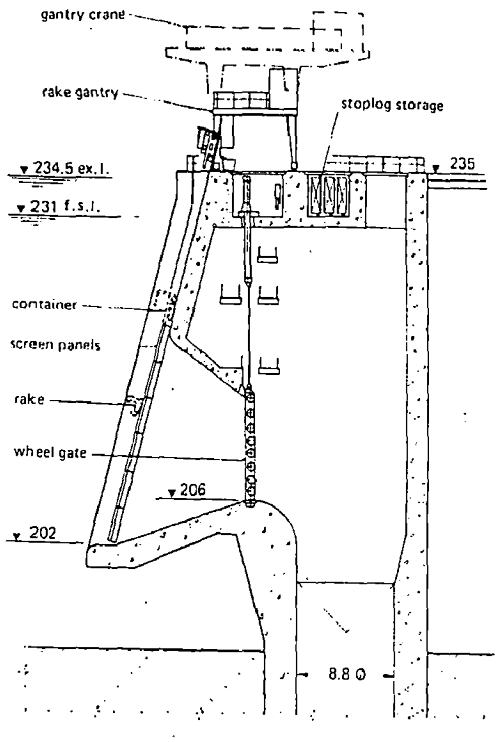


FIG. 6.5 *The power intake.*

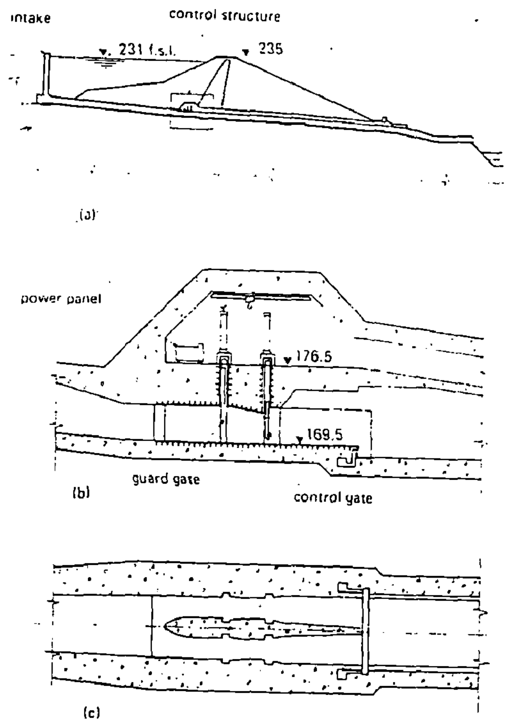


FIG. 6.7 *Sections of (a) drawdown culvert; (b) control structure; and, (c) waterway.*

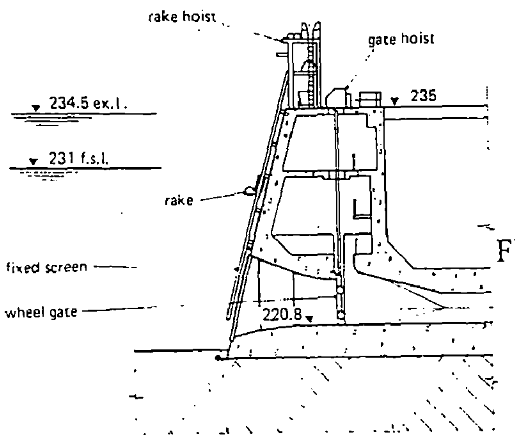


FIG. 6.6 *The irrigation outlet intake.*

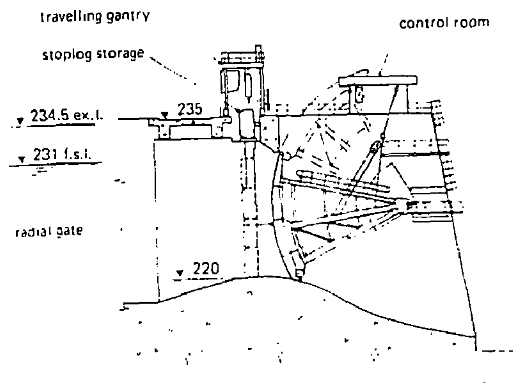
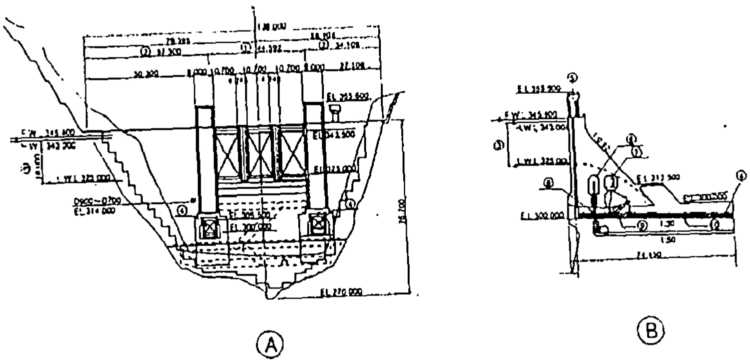


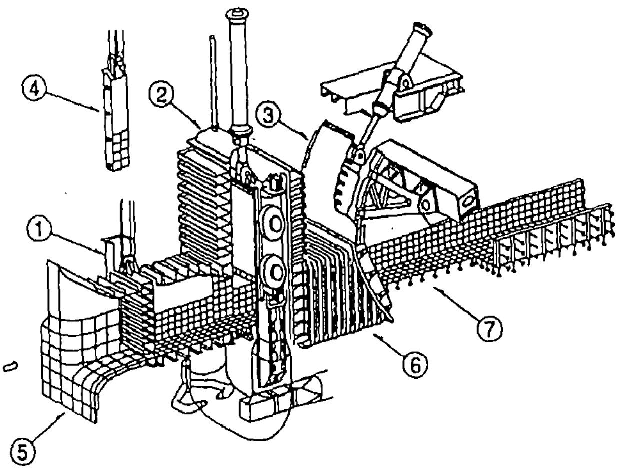
FIG. 6.8 *The spillway*



A Upstream view
B. Cross section
1. Overflow section
2. Non-overflow section
3. Drawdown range
4. Flushing channel
5. Dam axis
6 Intermediate gate chamber
7. Gate on the downstream side chamber
8. Intermediate gate
9. Gate on the downstream side
10 Lining

FIG. 6.9

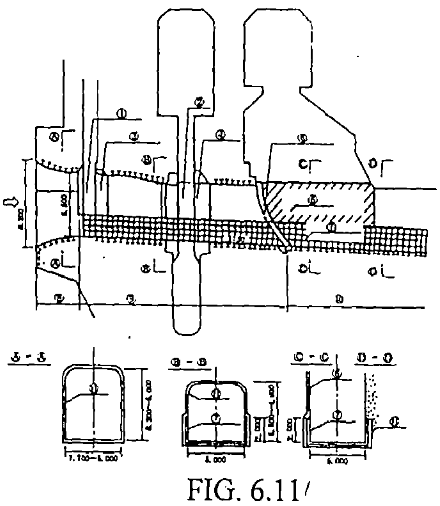
Outline view of the Dashidaira dam



1. Slide gate
2. Roller gate
3. Radial gate
4. Protection frame
5. Flushing channel (inlet)
6. Flushing channel (pressured)
7. Flushing channel (open channel)

FIG. 6.10

Outline view of sediment flushing facility



1. Protection frame
2. Intermediate gate (a roller gate with legs)
3. Gate sheet of the gate on the upstream side
4. Gate sheet of intermediate gate
5. Gate sheet of the gate on the downstream side
6. Current plate
7. Lining
8. Flushing channel (intake)
9. Flushing channel (pressured)
10. Flushing channel (open channel)
11. Plate

FIG. 6.11

Outline view of the sediment flushing channel and lining

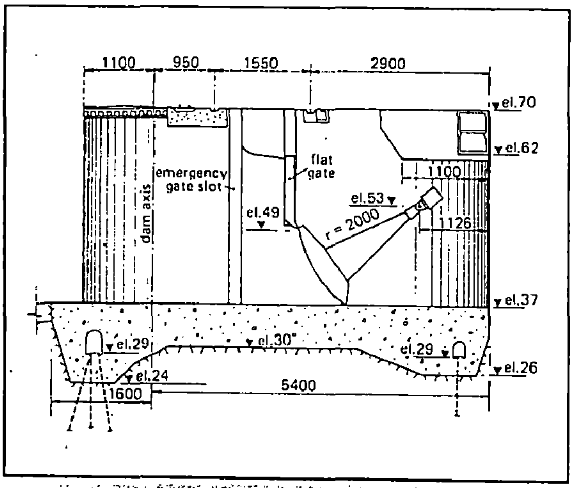


FIG. 6.12

Fig. 1. Split level spillway gates at Gezhouba project, dimensions in centimetres.

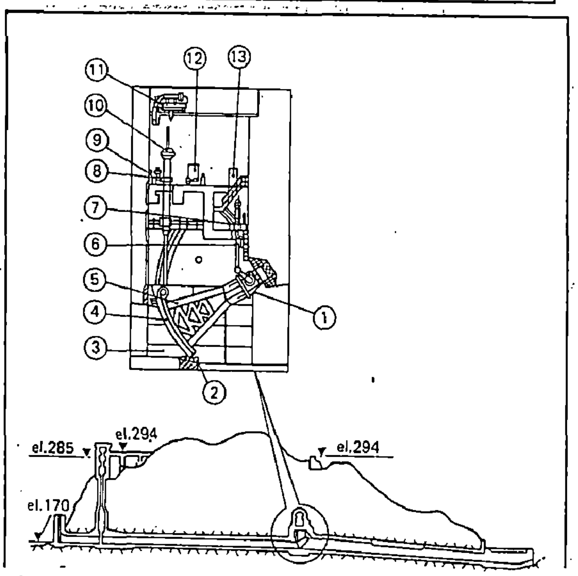


FIG. 6.13

Fig. 2: Layout of eccentric hinge spillway gate at the Dongjiang project, where: 1 = eccentric hinge base; 2 = embedded waterseals; 3 = gate groove protection; 4 = gate surface plate; 5 = gate arm; 6 = rotary locking; 7 = rotary cylinder; 8 = lifting locking; 9 = throttle pump; 10 = lifting cylinder; 11 = bridge crane; 12 = pump station; and; 13 = control board.

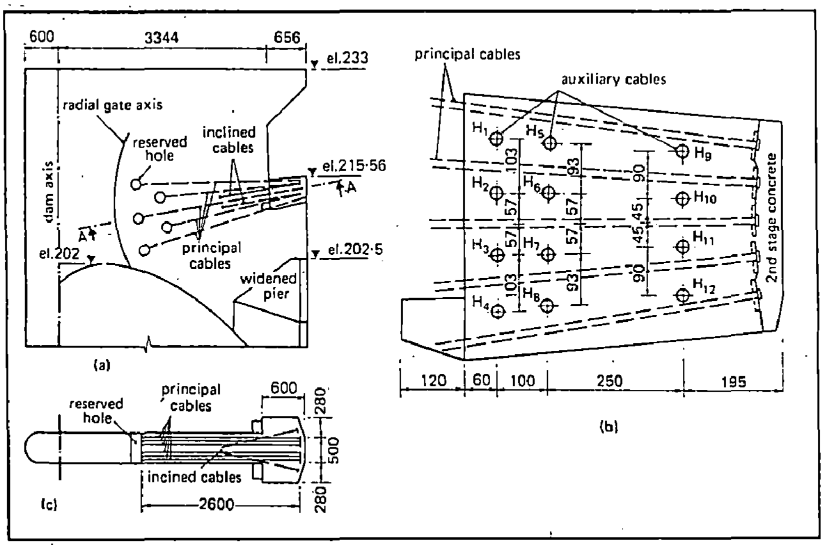


FIG. 6.14 *3. (a) Prestressed gate piers at the Yantan project; (b) A-A cross section; and, (c) detail of the pier anchor blocks (dimensions in cm).*

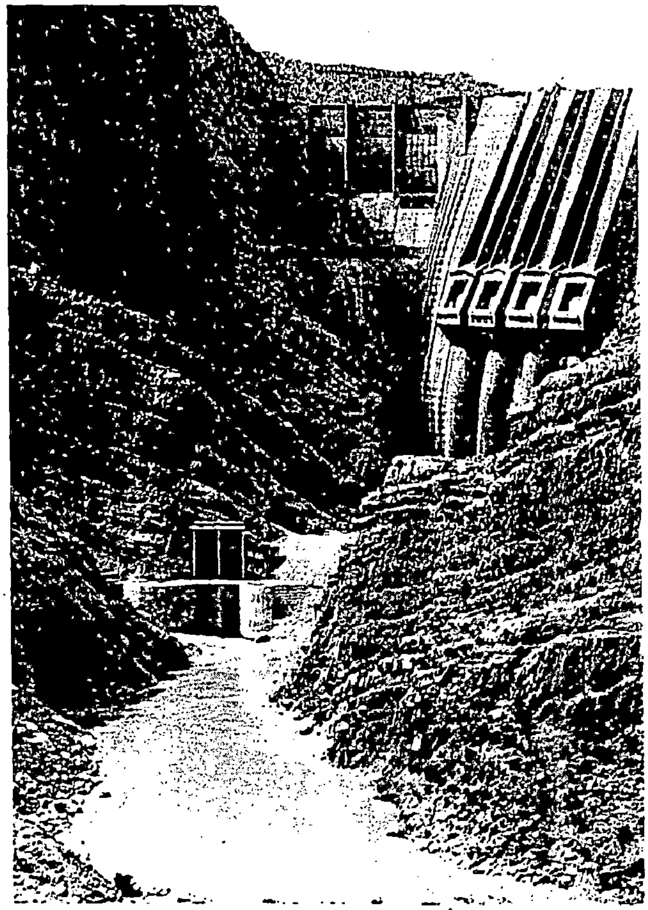
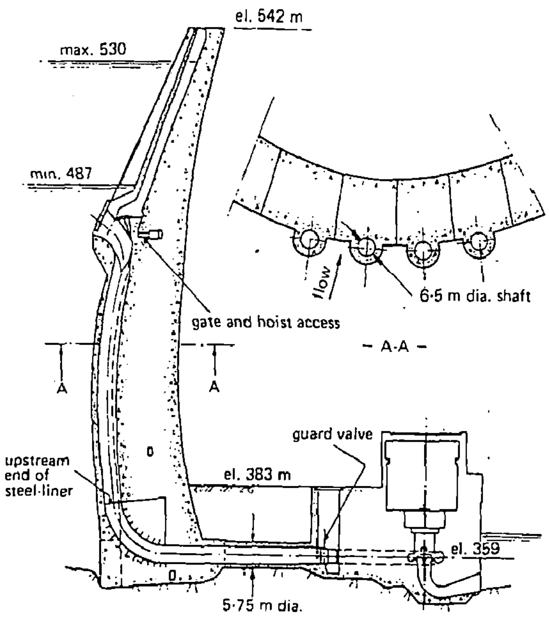


FIG. 6.15 *[illegible] view of the penstocks from the upstream side showing also the diversion tunnel and the spillway gates.*



Section through the intakes and penstocks

FIG. 6.16

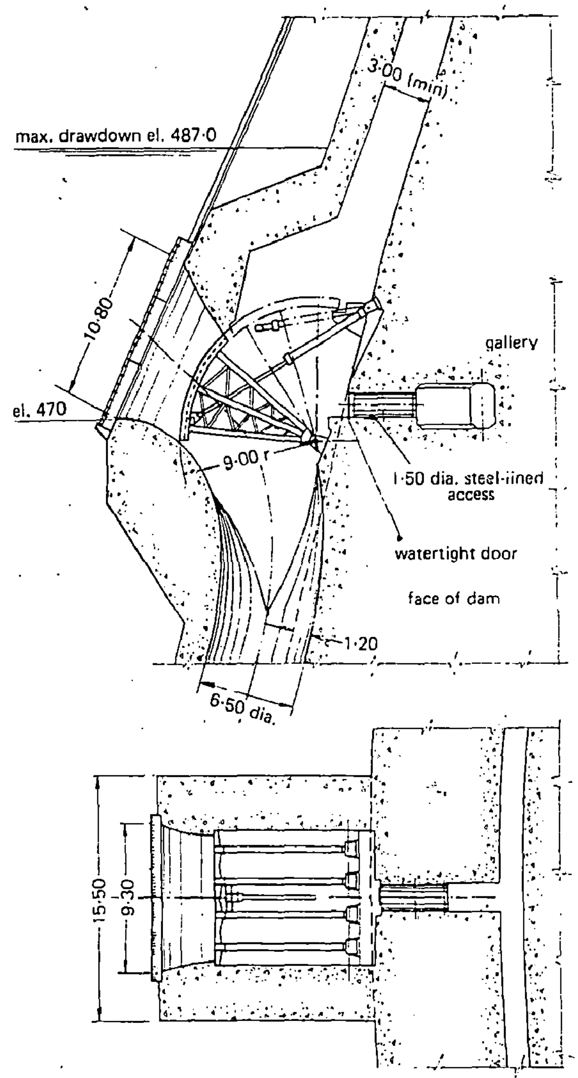


FIG. 6.17 *Intake and gate.*

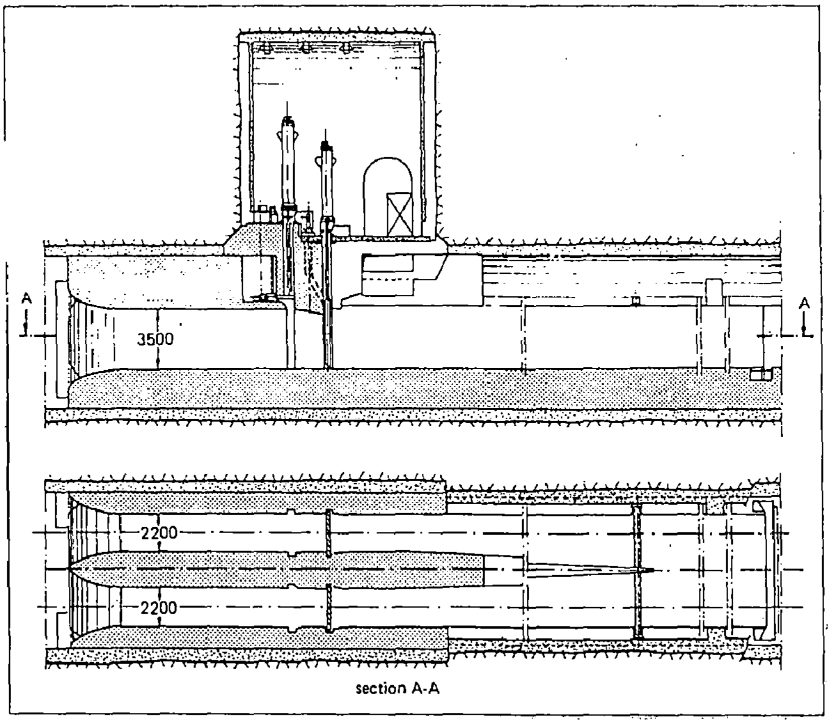


FIG. 6.18 1. Alicura's bottom cutlet structure in plan and section.

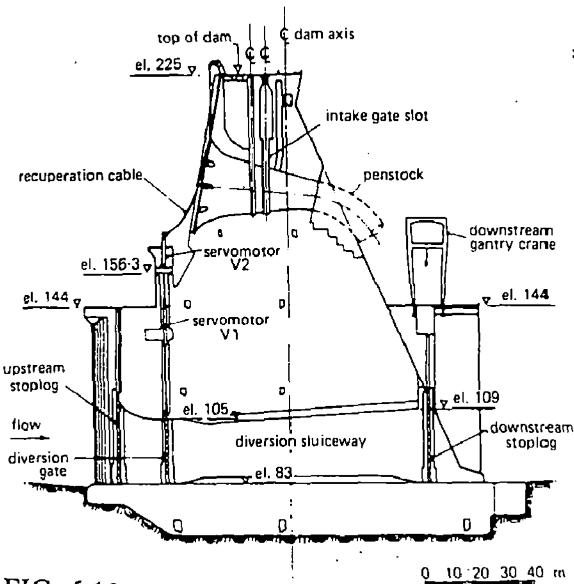
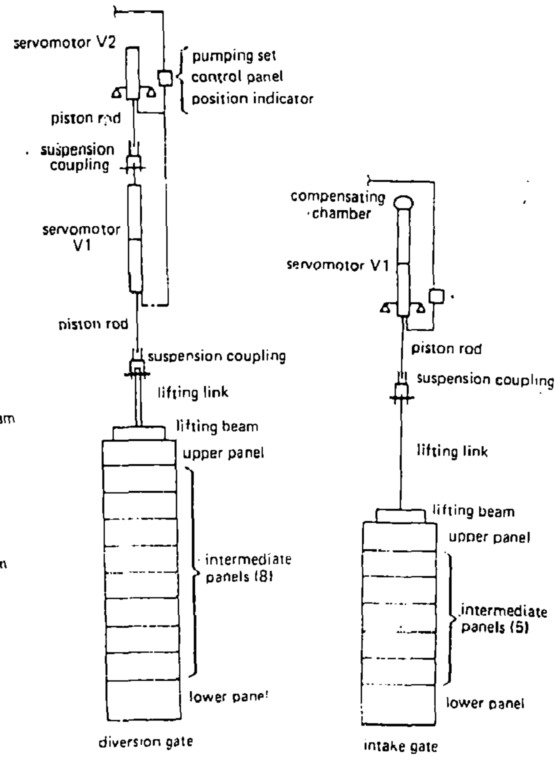


FIG. 6.19
Fig. 4. Cross section of the diversion control structure.



Schematic diagrams of the diversion and power intake gates.

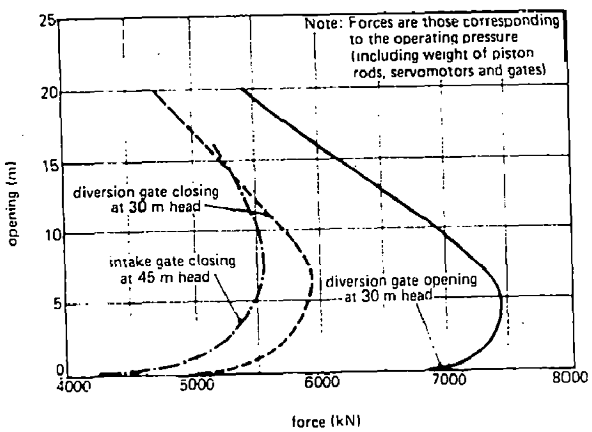


FIG. 6.21 5. *Forces acting on the servomotors*

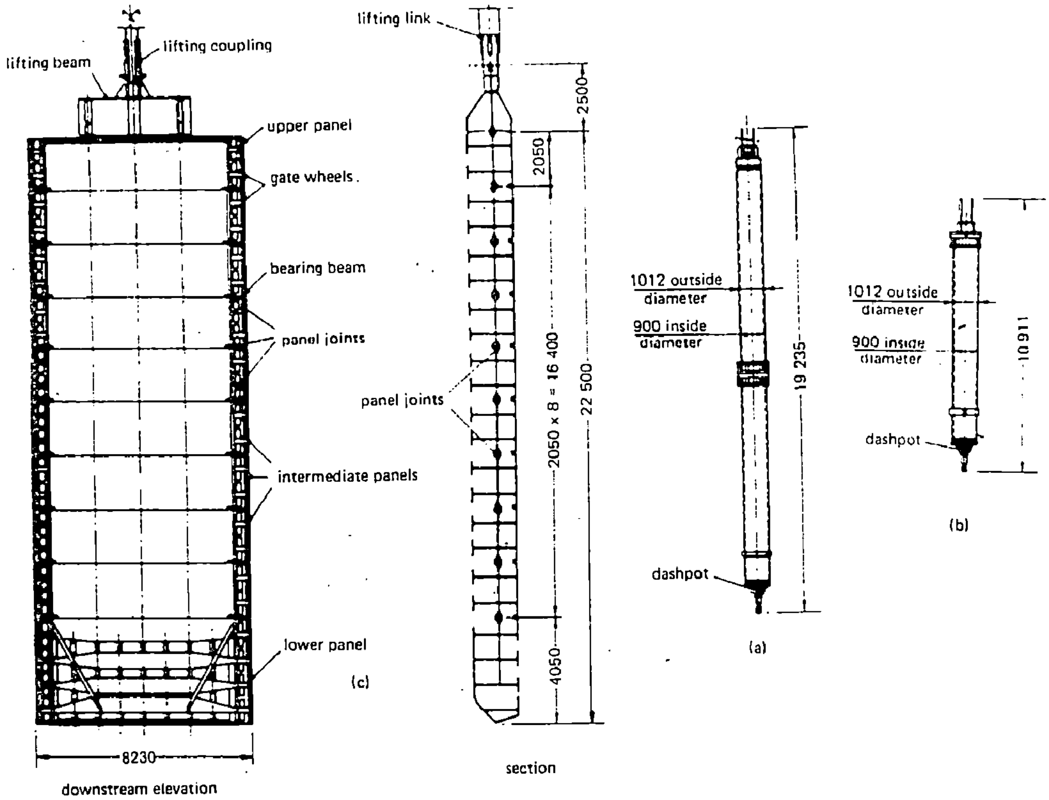


FIG. 6.20 _ '8. *Details of the gate and servomotors, showing: (a) V1 servomotor; (b) V2 servomotor; and (c) diversion gate.*

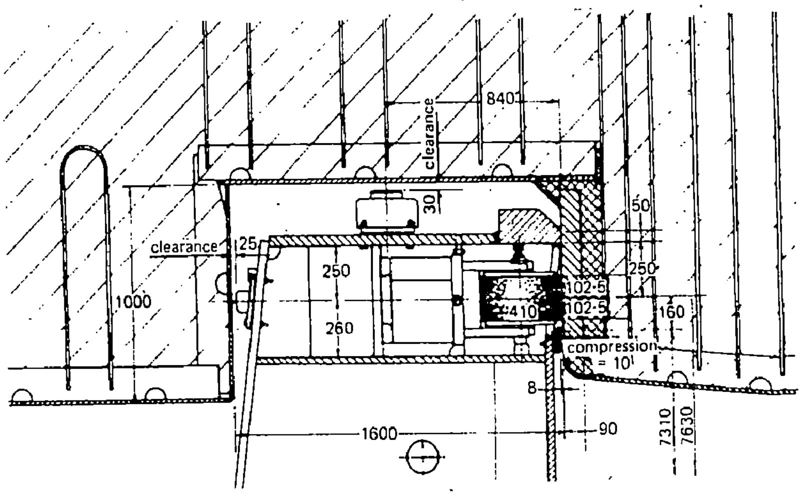
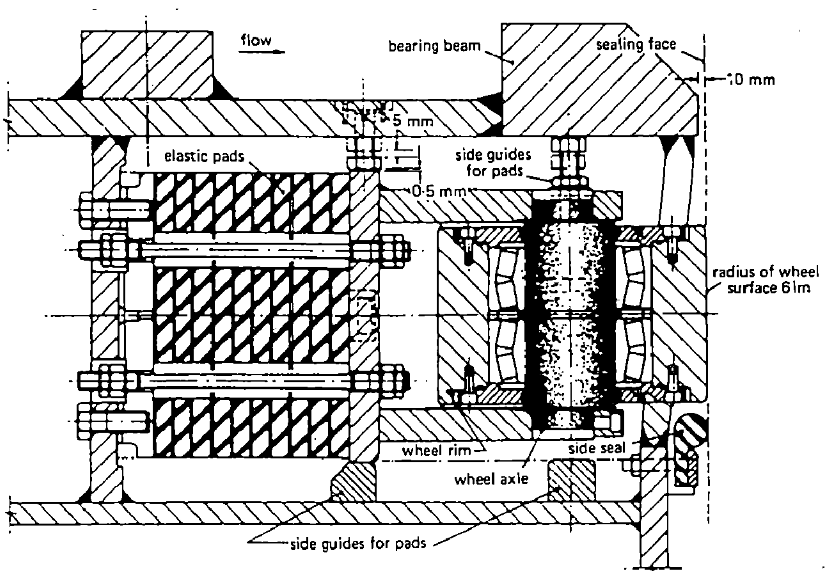


FIG. 6.22 *Cross section of the diversion gate and guides between el. 83 m and el. 105 m.*



wheel assembly.

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