EXPERIMENTAL STUDY OF FLOW PATTERN IN MULTISLOPE STEPPED SPILLWAYS

A DISSERTATION
Submitted in partial fulfillment of the
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(CIVIL)

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled **"Experimental study of flow pattern in multi-slope stepped spillways"** in partial fulfillment of the requirement for the award of the degree of master of technology in Water Resources Developments in civil (WRD Civil) submitted in the Department of Water Resources Developments Training Center (WRDTC), IIT, Roorkee; is an authentic record of my own work carried out during the period from June 30th, 2003 to the date of submission under the supervision of prof.Dr.Nayan Sharma WRDTC,IIT, Roorkee.

I have not submitted the matter embodied in this dissertation for the award of any other degree.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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SYNOPSIS

Stepped Spillways are those types of chute spillways whose face is provided with a series of steps, from near the crest to the toe. The main function of a spillway is to dispose of excess water from a reservoir safely and in addition to it the steps of a stepped spillway dissipate the falling energy of flow and **reduces the size of dissipater generally** provided at the toe of spillways.

Stepped spillways have been used since more than **3000 years.** These are used in different types of dams (masonry dams, concrete dams, earth dams etc). Stepped channel are used for handling flood releases in storm water channels in river training works, water treatment plants etc. Stepped fountains have been constructed in different cities (HongKong, Taipei, Tokyo etc) for the aesthetical applications. Check dams are usually constructed as a succession of drop structures to reduce the steep gradient in mountain areas. It has been used in irrigation and power channels also.

The stepped channels are mainly of three **types:** flat steps, pooled steps and inclined steps channels. Flat stepped are horizontal, pooled steps are those where a sill height is provided at the end of steps. The inclined steps are inclined upward and downwards.

A stepped chute consists of an open channel with a series of steps or drops. The flow over stepped chute can be divided into **three regimes:** nappe flow regime,transition flow regime and skimming flow regime. **In nappe flow regime** the total fall is divided into a number of smaller free falls. The water proceeds in a series of plunges from one step to another. The energy dissipation occurs by jet break-up in air, jet mixing in the step and formation of fully or partially developed hydraulic jump on the step. **In transition flow regimes** the flow is neither nappe nor skimming flow régime. The flow is characterized by significant air entrainment and flow instabilities.**In the skimming flow regime** the water flows down the stepped face as a cushioned by the recirculating fluid trapped in between them. The external edges on the steps form a pseudo-bottom over which the flow passes. Beneath this **recirculating vortices** are developed.

Most of the small dams have single slope stepped spillways. The high dam and hill irrigation channels, where the chute/channel may align through different country slopes, may have multislope spillways channel. Till now the exact design principle solutions have not been found out. So it is still under investigation process.

The aim of the dissertation is to study the flow pattern in multi-slope stepped spillways. The study has been done over a model of multi-slope stepped spillways (scale: 1:15) of Rammam hydel project II, West Bengal electricity board, in River Engg. Lab.of WRDTC, IIT Roorkee.

The main questions that have been directed in the study are: 1. How the different discharges passing over the model behave 2.Whether the flows are nappe, transition or skimming regimes 3.What are the pressures at the bottom of the channel 3. What are the flow depths in the channel 4.What is the velocity of flow 5. How the recirculating vortices are being generated in the skimming flow regimes 6.What is the rate of energy dissipation through the stepped chute 7. What is the residual head at the toe of the spillways, which is to be dissipated in stilling basin 8. What is the position of the cavitations risks of the damages of the spillways etc. **The objectives of the study are**: 1. Study of the flow patterns in multi-slope stepped spillways without placing suppressor plates. 2. Study of the flow patterns in multi-slope stepped spillways with the use of different suppressor plates (circular and elliptical). 3. How the energy is dissipated through the stepped spillways such that the dimensions of the stilling basin can be reduced i.e cost is reduced. 4. After placement of the suppressor plates the flow depths in the spillway channel is reduced i.e. air concentration is also reduced (so we have to study the cavitations risks then).

The flow patterns in multislope stepped spillways were found to be same as in single slope stepped spillways in first spillway channel slope but were found different patterns in junction point and other downstream slopes of the spillways. At the convex junction point where the flatter slope of channel meets the steeper slope of channel, the flows were of sprayed nature with deflecting or jumping of jet. After the placement of **suppressor plate** at the convex flow region the jet deflection phenomenon is arrested.

In the first channel slope $\alpha_1 = 34^0 32'$ of the experimental set up, the flow patterns were same as in single slope (mono slope) stepped spillways and in other channel slopes d/s of it the flow patterns were different from it. The second channel slope $\alpha_2 = 50^0 14'$, which is steeper than first slope, and the third channel slope $\alpha_3 = 38^0 50'$ which is milder than second slope, had displayed different flow patterns: i.e. the convex flow and trajectory flow depths and the concave flow and trajectory flow depths respectively.

At the first junction point of the channel slopes α_1 and α_2 the flow was of convex nature and the flow past it through a trajectory path d/s of the channel with the slope α_2. The flow at the second junction point of the channel of slopes α_2 and α_3 was of concave nature and similarly in slope α_3 the flow past through a trajectory path d/s of the channel with the slope α_3. At the lower unit discharge rates (3 to 4 lps/0.2m i.e. 0.015 to 0.02 m3/s/m) the flow pattern followed transition and skimming flow regimes pattern where as at higher flow rates than these rates (6 to 20 lps/0.2m i.e. 0.03 to 0.10m3/s/m) the flow were all skimming flow regimes with recirculating vortices. At the convex and concave flow regions first-six to first-two steps were having air cavities with bigger sizes at upper ones and decreasing the cavity sizes to d/s steps.

After the placement of suppressor plates at the junction points of slopes the flow followed uniform depth throughout the channel d/s of it. The placement height of the suppressor plate was fixed as the depth of flow at the toe of respective slopes. Hence the suppressor plates were found to be a good key structural element to check the deflecting flow flow depths in the spillways, which help thereby in reducing the sidewall height of the spillways. Among the circular and elliptical suppressor plates used in experiments, the elliptical suppressor plate gave good result in uniformity of flow with smaller flow of depths after placement of it at the junction points. It means after placement of suppressor plate the flow depth decreases and obviously the air entrainment of the flow also decreases.

Multislope stepped spillways with the final or last channel slope steeper than the second last slope dissipated more head or energy compared to spillways channels with the milder slope than the second slope. The rates of energy dissipation in the multislope and single slope stepped spillways were found to be in between 85 to 90%.

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d_c = Critical depth
h = Step height
l = Step length
d_p = Height of water in pool behind the over fall jet
d_1 = prejump depth
d_2 = post jump depth
d_3 = Sill height
L_d = Distance from the drop wall to the position of d1
L_j = length of jump
d_o/d_w = Average water flow depth
q_w = Unit discharge
g = Accelerations due to gravity
Q = Discharge
b = Width of spillways (If not stated)
σ = Surface tension
ρw = Water density
d_{ap} = Air bubble diameter
u_r = Bubble rise velocity
α = Slope of spillways (If not stated)
V' = Turbulent velocity
H_o = Head at crest
$H_{spill} = H_{dam}$ = Height of spillways
L_i = Length of inception point from crest
d_i = Depth of water at inception point
$\lambda = \left(h^2 + l^2\right)^{\frac{1}{2}}$
τo = Average shear friction
K_s = Step roughness height
R = Hydraulic mean radius
$F = F_r = F_b$ =Froude no.
$\Delta H = \Delta E$ = Difference between the maximum head and residual head
C = Air concentration
Y_{90} = Flow depth where C = 90%
f_e = Darcy friction factor = f_{we}
DH = Hydraulic diameter
K_s' = Skin roughness height
f= Friction factor
k = Karman constant
Cr = Fluid friction
Ec (α) =Coriolic coeff. = Kinetic energy correction coefficient
n = mannings roughness coeff.
Z = section factor
η = Factor of safety
y_a = Aerated flow depth = d_a
y = d_w = flow depth
h_d = Height of side wall of spillways

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CHAPTER- 1
INTRODUCTION

Chapter-1

Introduction

1.1 Introduction:

Stepped spillway is a type of chute spillways whose face is provided with a series of steps, from near the crest to the toe. The main function of a spillway is to dispose of excess water from a reservoir safely and in addition to it the steps of a stepped spillways dissipate the falling energy of flow and reduces the size of dissipater generally provided at the toe of the spillways.
A stepped spillway can be economically integrated on the downstream face of an RCC gravity dam and on the embankment dams as emergency spillways to safely pass the maximum flood over the crest of dam. Advantages of stepped spillways include the ease of construction, reduction of cavitations risks potential and reduction of the stilling basin dimensions at the downstream toe of the dam due to continuous energy dissipation along the stepped chute.
Multi-slope stepped spillways are those chute/spillways, which have more than one longitudinal channel slopes with different step geometries in their faces.

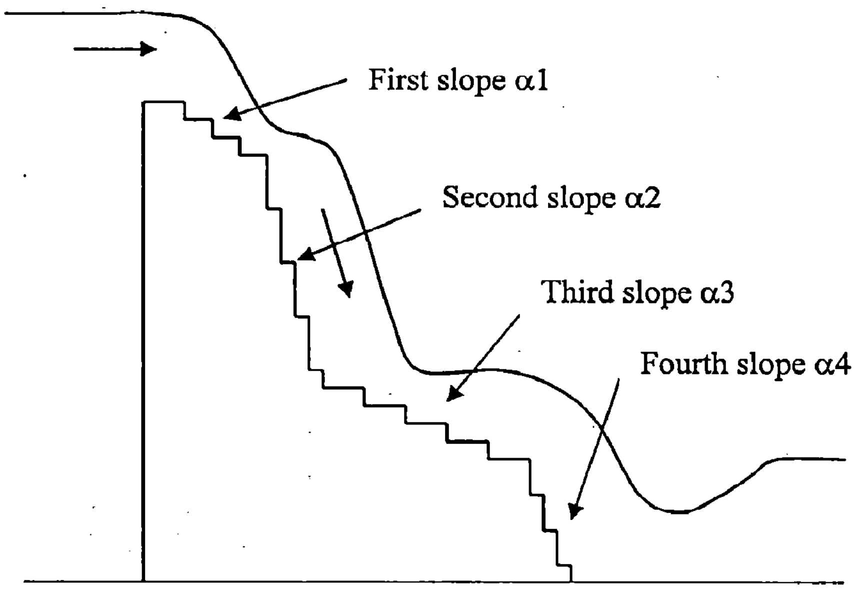


Fig. 1 Multi-slope stepped spillways: With four L-slopes

The aim of the dissertation is to study the flow pattern in multi-slope stepped spillways. The study has been done over a multi-slope stepped model (scale: 1:15) of Rammam hydel project II, West Bengal electricity board, situated at the River Engg. Lab.of WRDTC, IIT Roorkee. The main points to be studied are: 1. How the different discharges passing over the model behave 2.Whether the flows are nappe, transition or skimming regimes 3.What are the pressures at the bottom of the channel 3. What are the flow depths in the channel 4.What is the velocity of flow 5. How the recirculating vortices are being generated in the skimming flow regimes 6.What is the rate of energy dissipation through the stepped chute 7. What is the residual head at the toe of the spillways, which is to be dissipated in stilling basin 8. What is the position of the cavitations risks of the damages of the spillways etc.
The application limits of stepped spillways is up to unit discharge of q =25 to 30 m3/s/m (Minor 2000) which is far below the maximum discharge of q =200 to 280m3/s/m for smooth

chutes (Volkart 1984). This limitation comes from the fact that the inception point of air entrainment moves downstream with increasing unit discharge, leaving a longer spillways stretch without air bubbles counteracting cavitations damage at the concrete surface (Boes 2000). Appropriate placement of aerators should be designed to check cavitations risk in the stepped spillways. That's why the investigation over exact design solution of stepped spillways with mono/multiple slopes have to be undertaken

1.2 Present study and the objectives of the study:

The main questions to be addressed are: 1. How the different discharges passing over the model behave 2.Whether the flows are nappe, transition or skimming regimes 3.What are the pressures at the bottom of the channel 3. What are the flow depths in the channel 4.What is the velocity of flow 5. How the recirculating vortices are being generated in the skimming flow regimes 6.What is the rate of energy dissipation through the stepped chute 7. What is the residual head at the toe of the spillways, which is to be dissipated in stilling basin 8. What is the position of the cavitations risks of the damages of the spillways etc

The objectives of the study are: 1. Study of the flow patterns in multi-slope stepped spillways without placing suppressor plates. 2. Study of the flow patterns in multi-slope stepped spillways with the use of different suppressor plates (circular and elliptical). 3. How the energy is dissipated through the stepped spillways such that the dimensions of the stilling basin can be reduced i.e cost is reduced. 4. After placement of the suppressor plates the flow depths in the spillway channel is reduced i.e. air concentration is also reduced (so we have to study the cavitations risks then).

1.3 Scope and limitation of the study:

The study of flow pattern in multi-slope stepped spillways provides the knowledge of:

Scope of the study:

1) Water flow depth: – so that we can design the sidewall of the spillways accordingly.
2) Velocity of flows and pressure at the bottom of the steps: – so that we can check the cavitations risks of damage of the channel.
3) Water pressure exerted on the underneath of the suppressor plate placed above the water surface at convex or concave regions of the spillways:- so that we can design the thickness of the suppressor plate (designed as a beam).
4) The recirculating vortices generated between the pseudobottom and the niches of the steps helps in reducing the velocity of flow thereby reducing the falling energy of the spillways.
5) The inception of air in the flow reduces the risks of cavitations damages to the channel and spillways and the stilling basin provided at the bottom of the spillways.
6) Studies of the flow patterns after the placement of different types of suppressor plates (circular and elliptical) have been done so that which of the suppressor plate gives minimum water flow depth in the spillway channel without cavitations risks.

Limitations of the study:

1) The study is done over a multi-slope stepped spillways model (scale 1:15) of Rammam hydel Project II, west Bengal electricity board, situated at the River Engg. Laboratory of WRDTC, IIT Roorkee.
2) The height and width of the spillway model are 2m and 0.20m respectively.
3) The longitudinal slopes of the spillways channel are $34^o32'$, $52^o14'$ and 38^o $50'$.
4) The discharges allowed passing over the spillways for experiment is from 4 lps to 20 lps.

1.4 Methodology used in the studies:

1) Computation of discharges passing through the spillways by venturimeter measurement of flow.
2) The flow allowed passing through the spillways ranged from 4 lps to 20 lps.
3) Depth of flow was measured perpendicular to pseudobottom.
4) Rate of energy dissipations were computed by Chanson (1994) and Tatewar & Ingle (1996) and Knight & McDonold (1979) methods.
5) Then residual head at the end of spillways were computed.
6) The graphs of flow patterns and their AutoCAD drawings and the experimental photographs have also been prepared and presented in Annexes-B & C.
7) The distance x verses d_{90} graphs, H_{res}/H_{max} verses H_{spill}/d_c graphs, Velocity V_w verses d_{90} graphs, and rate of flow q_w verses d_{90} graphs for different slopes have been prepared and presented in Annex-B.
8) The AutoCAD drawings of flow patterns of different discharges with the use of circular/elliptical or without suppressor plate have also been prepared and presented in Annex-C

1.5 Organization of the dissertation:

Chapter-1: Chapter 1 deals with the introduction, which includes objectives, scopes, limitations, methodology, organizations and the findings of the study.
Chapter-2: Chapter 2 deals with the review of literature.
Chapter-3: Chapter 3 deals with the experimental study of flow pattern in multi-slope stepped spillways/Mono-slope stepped spillways which includes:
(Model laws, Suppressor plates, Experimental procedures, Experimental data, Analysis of results, Rate of energy dissipations, and Study of cavitations risks).
Chapter-4: Chapter 4 deals with the discussions of results and conclusions.
References.
Appendix A: It deals with the hydraulic design of stepped spillways by different methods.
Appendix B: Table of calculation of d_{90} vs x , d_{90}/h vs Fr , H_{res}/H_{max} vs H_{spill}/d_c graphs with or without circular suppressor plate and Table of calculation of d_w vs V_w and q_w graphs
Appendix C: Drawings and photographs of flow patterns in multi and mono-slope stepped spillways

1.6 Experimental Problems of the study:

(1) Lack of smooth transition at the entrance of the experimental stepped spillways model the flows showed irregularities in water depths d/s of it.
(2) The improper positioning of the suppressor plate may also create the problems in the flow patterns.
(3) The tips of nut and bolts projected from the suppressor plate also hindered the flow patterns in the channel.

1.7 Findings of the study:

The flow patterns of the multi-slope/mono-slope stepped spillways with or without suppressor plates are given in section 3.6.2.7 tables, 3.7,in graphs (Annex-B), in AutoCAD drawings & photographs (Annex-C) and energy dissipation rates by Tatewar & Ingle (1996) and Knight & McDonold (1979) in the multi-slope and mono-slope stepped spillways were found to be 87.4% and 89.9% respectively for the flow rate of 20 lps (or unit flow rate q =

0.10 m3/s/s). And similarly by Chanson (1994) the rate of energy dissipation were found to be 85.3% and 85.85% respectively for the same flow rate.

Among the circular and elliptical suppressor plates used in experiments, the elliptical suppressor plate (P=135mm) gave good result in uniformity of flow with smaller flow of depths after placement of it at the junction points. It means after placement of suppressor plate the flow depth decreases and obviously the concentration of air in the flow also decreases.

Multi-slope stepped spillways with the final or last channel slope steeper than the second last slope dissipated more head or energy compared to spillways channels with the milder slope than the second slope.

CHAPTER- 2
REVEW OF LITERATURE

Chapter-2

Review of literature

2.1 Multi-slope stepped spillways:

Stepped spillway is a type of chute spillways whose face is provided with a series of steps, from near the crest to the toe. The main function of a spillway is to dispose of excess water from a reservoir safely and in addition to it the steps of a stepped spillways dissipate the falling energy of flow and reduces the size of dissipater generally provided at the toe of the spillways.

Multislope stepped spillways are those chute/spillways, which have more than one longitudinal channel slopes with different step geometries in their faces.

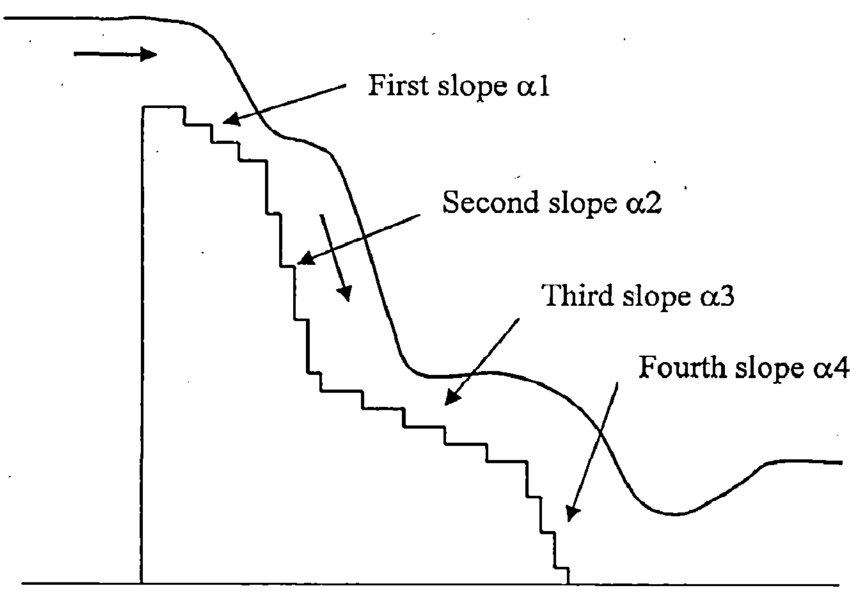


Fig. 2 Multislope stepped spillways: With four L-slopes

2.2 Applications:

Stepped channels have been used since more than 3000 years. These are used for handling flood releases in storm water channels for river training works. Stepped cascades are utilized in water treatment plants (along or besides of rivers and streams to re-oxygenate waters with low dissolved oxygen contents). Stepped fountains have been constructed in different world cities for the aesthetical applications. Check dams are usually constructed as a succession of drop structures to reduce the steep gradient in mountain areas. It has also been used in Irrigation and power channels.

Stepped spillways are being used in different types of dams or weirs such as in masonry dam, concrete dam, gabion dam, debris dam, timber and crib dam, diversion weirs, tunnel spillways, unlined rock spillways etc in different countries (USA, UK, Brazil, South Africa, Norway, Australia, Canada etc).

Multi-slope stepped spillways are used in earthen dams, masonry dams etc and irrigation canal falls where there may be of different side of dam and country slopes.

2.3 Type of stepped channels:

(A) According to geometry:

1. Flat type steps
2. Pooled steps
3. Inclined steps

Flat steps are horizontal steps. **Pooled steps** are those where a raised sill is provided at the end of steps to make a pool for the flowing jet to impinge over it. **The inclined** steps are made inclined downstream or upstream according to requirements.

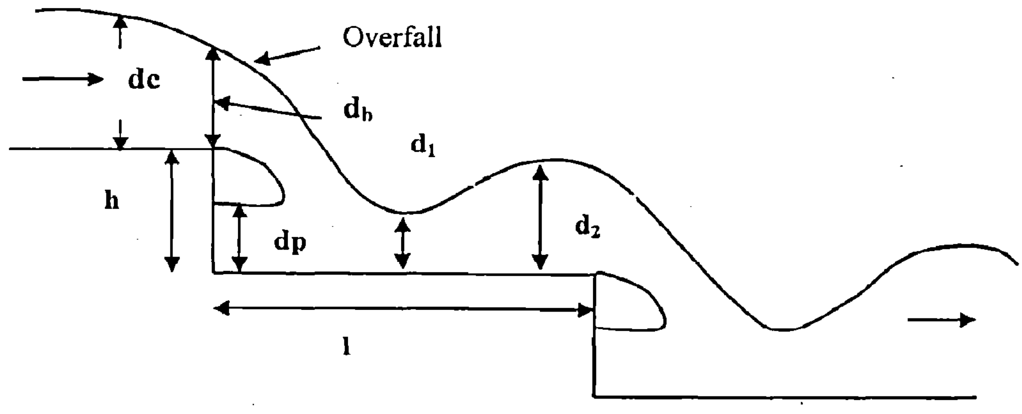


Fig.3.Nappe flow with flat slope

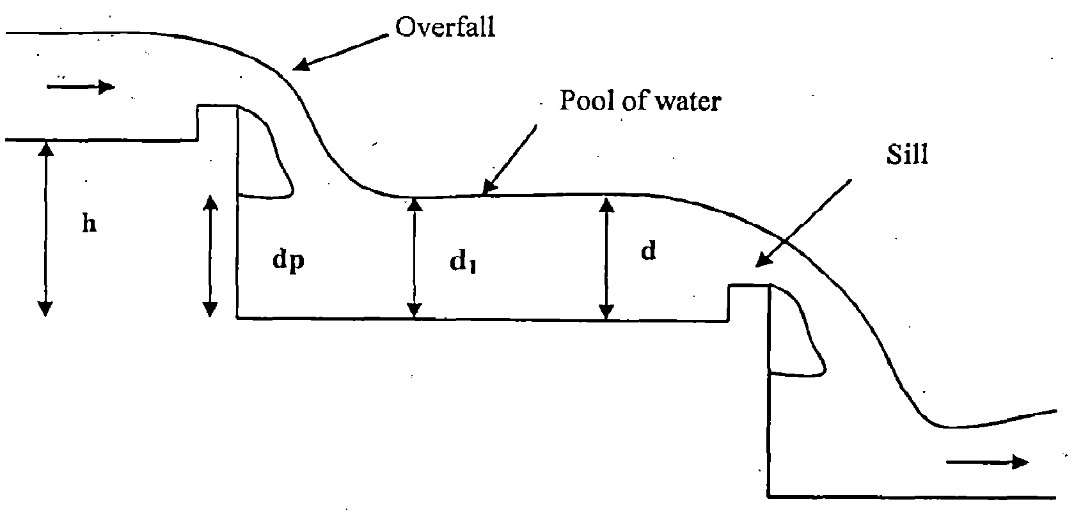


Fig.4.Nappe flow with pooled steps

(B) According to construction materials:

1. Concrete stepped spillways
2. Gabion stepped spillways
3. Earth dam spillways with pre-cast concrete blocks
4. Stone block stepped spillways

Concrete stepped spillways are made to assist energy dissipation and help to reduce the size of downstream stilling basin. The step should be of high strength to withstand the impinging forces of flowing jets. Nowadays Roller Compacted Concrete (RCC) stepped spillways are being used because of easy to construct and economic in construction.
Gabion stepped spillways are extensively used in different weirs and channel linings. Their porosity, flexibility, low cost and stability and easiness for construction are the characteristics of popularity. They are made of local stones.
Earth dam spillways with pre-cast concrete blocks have been in use for its capacity to pass the design flows without failure. They are made of pre-cast concrete blocks of different geometry and configurations. The blocks are laid on a filter to protect the dam from erosion.
Stone block stepped spillways are made of local stones. These are used to decrease the cost of the structures as a whole. These chutes release the seepage pressure and make the structure stsble. These are easy to construct and maintain.

2.4 Flow regimes:

A stepped chute consists of an open channel with a series of steps or drops. The flow over stepped chute can be divided into **three regimes:** nappe, transition and skimming flow regimes.

2.4.1 Nappe (Jet) flow Regimes

2.4.1.1 Introduction:

The nappe flow regime is defined as a succession of free falling nappies. The flowing waters bounce from one step to the next as a series of small falls. Along a chute with horizontal steps, a typical nappe flow situation consists of a series of free fall jets impinging on the next step and followed by a hydraulic jump. The flow energy is dissipated by jet breakups in air, by jet impact and mixing, on the step and by the formation of a hydraulic jump on the step. Stepped channels with nappe flows can be analyzed as a succession of drop structures.
There are three types of nappe flows occurring:
1.nappe flow with fully developed hydraulic jump for low flow rate and small flow depth.
2.nappe flow with partially developed hydraulic jump.
3.nappe flow without hydraulic jump.

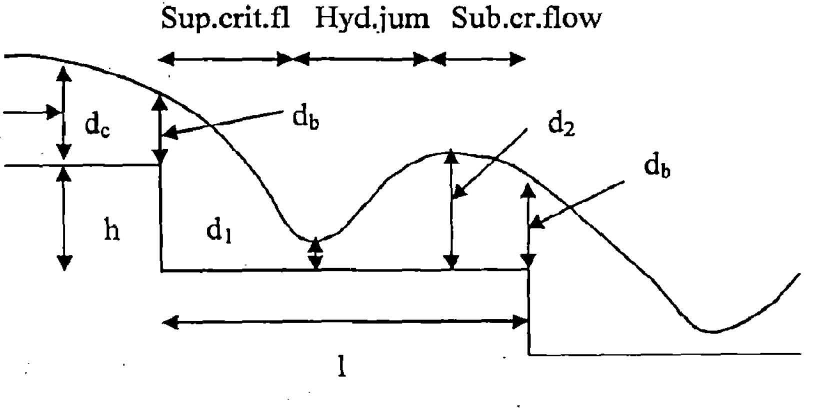


Fig. 5. Nappe flow regime with fully developed hydr.jump

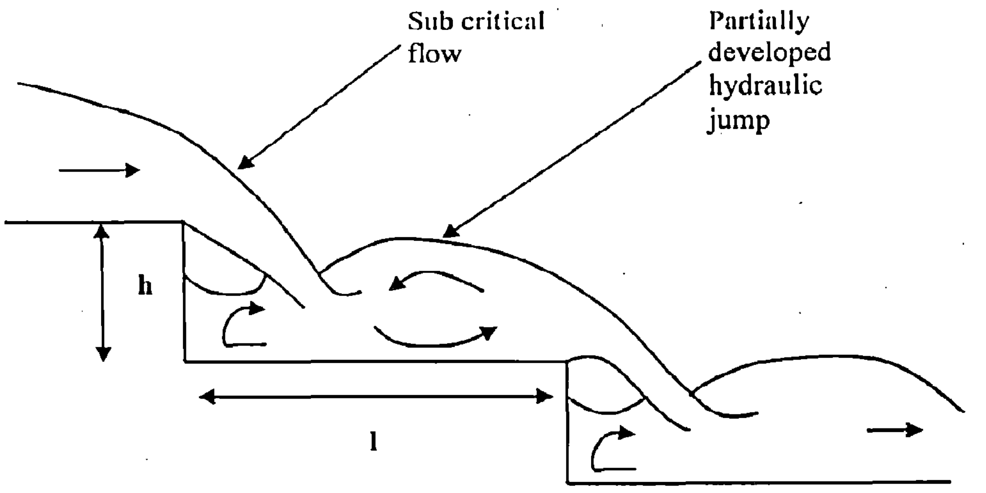


Fig.6.Nappe flow with partially developed hydraulic jump

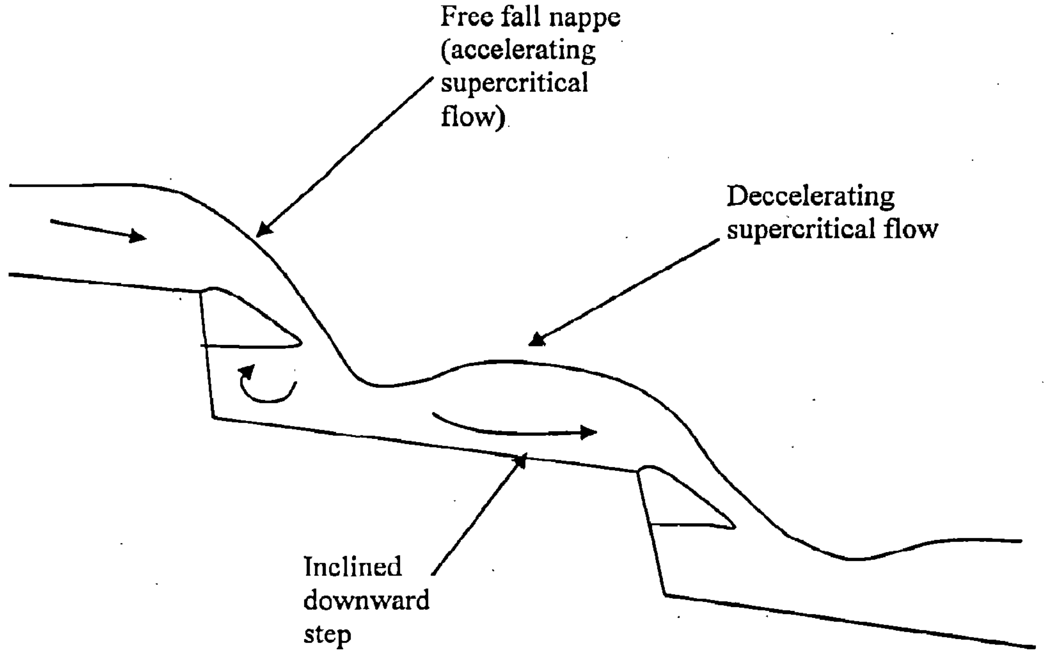


Fig.7 Nappe flow without hydraulic jump

A nappe flow without hydraulic jump might occur for relatively large discharges, before the starting of skimming flow.

2.4.1.2 Hydraulic characteristics of nappe flow:

The flow depth at the brink of step d_b (Rouse 1936) is: $d_b = 0.715\, d_c$ (1)
where d_c is critical depth of flow.
Application of the momentum equation to the base of the over fall leads to (White 1943):

$$\frac{d_1}{d_c} = \frac{2^{\frac{1}{2}}}{\frac{3}{2^{\frac{3}{2}}} + \sqrt{\frac{3}{2} + \frac{h}{d_c}}} \qquad (2)$$

where d1 is the pre jump depth.
The total head H_1 at section 1 can be expressed non-dimensionally as:

$$\frac{H_1}{d_c} = \frac{d_1}{d_c} + \frac{1}{2}\left(\frac{d_c}{d_1}\right)^2 \qquad (3)$$

The flow depth and total head at the section 2 are given by the classical hydraulic jump equations:

$$\frac{d_2}{d_1} = \frac{1}{2}\left(\sqrt{1 + 8F_{r1}^2} - 1\right) \qquad (4)$$

where d_2 is post jump and $F_{r1} = \frac{qw}{\sqrt{g d_1^3}}$.

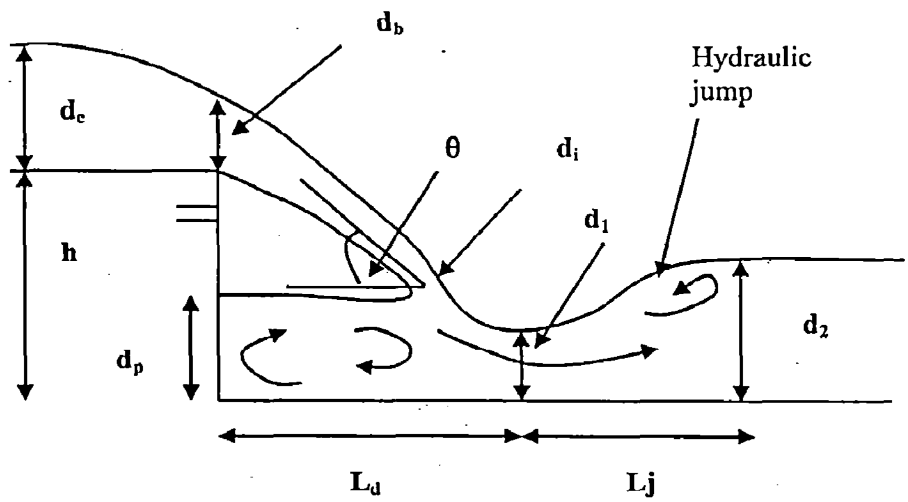


Fig.8 Flow at a drop structure

Rand (1955) reanalyzed several experiments and developed the following correlations:

$$\frac{d_1}{h} = 0.54\left(\frac{d_c}{h}\right)^{1.275} \qquad (5)$$

$$\frac{d_2}{h} = 1.66\left(\frac{d_c}{h}\right)^{0.81} \qquad (6)$$

$$\frac{d_p}{h} = \left(\frac{d_c}{h}\right)^{0.66} \qquad (7)$$

$$\frac{L_d}{h} = 4.3\left(\frac{d_c}{h}\right)^{0.81} \qquad (8)$$

where d_p= height of water in pool behind the over fall jet
L_d= distance from the drop wall to the position of the depth d1

Using equations (1) and (7) the nappe thickness di, the nappe velocity V_i and the angle θ of the nappe with the horizontal can be correlated by:

$$\frac{d_i}{h} = 0.687\left(\frac{d_c}{h}\right)^{1.483} \qquad (9)$$

$$\frac{V_i}{V_c} = 1.455\left(\frac{d_c}{h}\right)^{-0.483} \qquad (10)$$

$$\tan\theta = 0.838\left(\frac{d_c}{h}\right)^{-0.586} \qquad (11)$$

$$\frac{L_j}{d_i} = 8\left[\left(\frac{d_c}{d_i}\right)^{\frac{3}{2}} - 1.5\right] \qquad (12)$$ (Hager et al 1990)

Combining equations (8)& (12) a condition of nappe flow regime with fully developed hydraulic jump is deduced. A nappe flow regime with fully developed hydraulic jump occurs for discharges smaller than a critical value defined as:

$$\left(\frac{dc}{h}\right)char = 0.0916\left(\frac{h}{l}\right)^{-1.276} \qquad (13)$$

where for nappe situation with fully developed hydraulic jump occurs for dc/h < (dc/h)char. Equation (13) was obtained for: 0.2 < h/l < 6. For steep slopes (h/l > 0.5) the fully developed hydraulic jump nappe flow can occur only for low flow rates.
For supercritical over falls (i.e. nappe flow without hyd.jump) fig.14, the application of the momentum equation at the base of the over fall, using same method as White (1943) leads to the result:

$$\frac{d_i}{d_c} = \frac{2F_r^{-\frac{2}{3}}}{1 + \frac{2}{F_r^2} + \sqrt{1 + \frac{2}{F_r^2}\left(1 + \frac{h}{d_c}F_r^{\frac{2}{3}}\right)}} \qquad (14)$$

where F_r is the Froude no of the supercritical flow upstream of the over fall brink.

2.4.1.3 Design of chute with nappe flow regime:

Stephenson (1991) suggested that the most suitable conditions for nappe flow situations are:

$$\tan\alpha = \frac{h}{l} < 0.20 \qquad (1) \text{ and}$$

$$\frac{dc}{h} < \frac{1}{3} \qquad (2)$$

where α is the slope of channel.
The two equations satisfy the equation,

$$\left(\frac{dc}{h}\right)char = 0.0916\left(\frac{h}{l}\right)^{-1.276} \qquad (3)$$

i.e. the flow situation satisfying both equations (1)&(2) is a nappe flow regime with fully developed hydraulic jump.
These recommendations imply relatively large steps and flat slopes. This situation is not often practical, but it may apply to relatively flat spillways, natural etreams, creeks, and river training and storm waterways. For step channels or small step heights, a skimming flow regime is more desirable and will achieve large rate energy dissipation.

(A) Chamani and Rajaratnam (1994) have presented a technical note of a method to estimate the energy loss on stepped spillways for the jet flow regime, which occurs when the ratio of the critical depth, dc to the height of the step,h is less than approximately 0.8.It introduces the concept of α the proportional energy loss per step and using the extensive experimental results of Horner α was evaluated .It was found that α is a function of dc/h and h/l, where l is the length of step and an equation has been developed that describes this variation. It was also found that the energy loss on a stepped spillway with a large number of steps could be very significant in the jet flow regimes. It also appears that for skimming flow, which occurs for dc/h larger than about 0.8,the average energy loss per step would be less than that of jet flow.
The relative energy loss $\Delta E / Eo$ with dc/h for a stepped spillway with several steps, where ΔE is the energy loss and Eo is the total energy at the base of the drop, assuming no energy loss is:

$$\Delta E/Eo = 1- \frac{\{(1-\alpha)^N[1+1.5(dc/h)]+\sum_{i=1}^{N-1}(1-\alpha)^i\}}{N+1.5(dc/h)} \qquad (1)$$

Where α = proportional energy loss per step
N = total no.of steps of spillways of height H_{spill}
d_c = critical depth

Using the experimental results of Horner (1969) for stepped spillways and Moore (1943) for a single step it is evaluated that α decreases continuously as dc/h increased. It was also found that the variation of α with h/l was described well by the equation;

$$\alpha = a - b \log (d_c/h) \qquad (2)$$

Where, the coefficients a = 0.30-0.35 h/l & b = 0.54 + 0.27 h/l

Equation (1) explains that for relatively smaller value of dc/h, α is large and $(1-\alpha)^N$.
Becomes negligible when the no. of steps N is large. Under such condition the energy loss ΔE/Eo approaches to unity. This approach is supported by observations of Horner (1969) where in case of 30 steps d_c/h =0.3 and relative energy loss is about 0.97.
It appears that for skimming flow, which occurs for dc/h larger than about 0.8, an analysis of observations of Sorensen (1985) as well as equation (2) indicate that the average energy loss per step would be less than for jet flow.

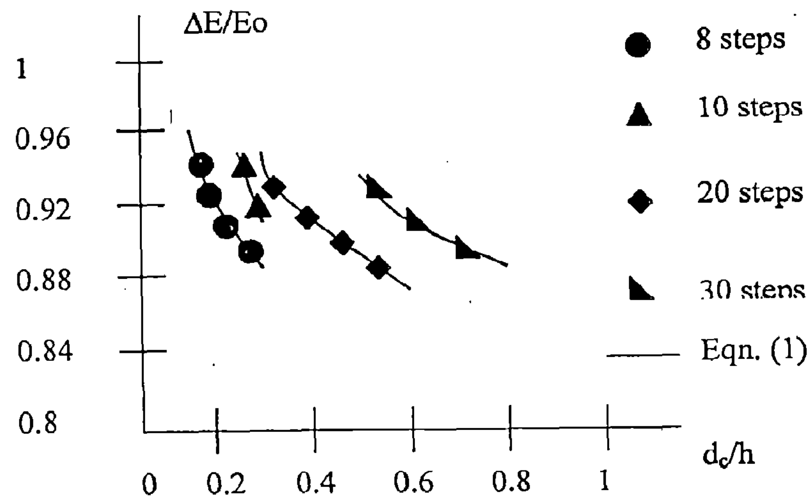


Fig 9. Variation of relative energy loss over several steps for h/l =0.421

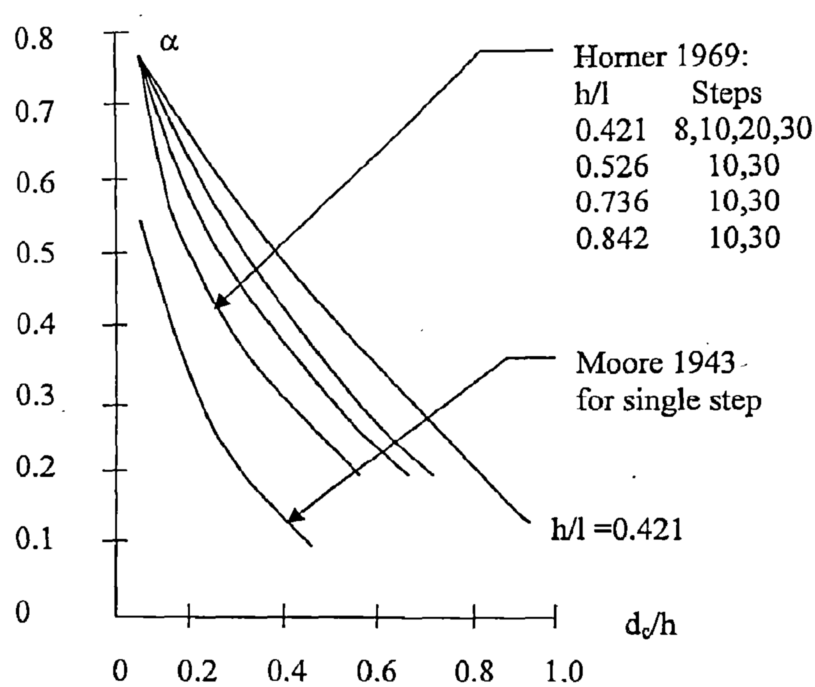


Fig.10 Consolidated results of variation of a with d_c/h for Horner and Moore

(B) Yasuda & Ohtsu (1999) presented a technical paper to define the upper limit of rnappe flow regime and lower limit for skimming flow regime. According to them the equation to define the flows are:

$$d_c/h = \frac{(1.4 - h/l)^{0.26}}{1.4} \qquad \text{(1) for upper limit of nappe flow regime}$$

$d_c/h = 0.862\ (h / l)^{-0.165}$ (2) for lower limit of skimming flow regime

and these equations appear to be effective for the chute inclination lower than 53 °.

(C) Detlef Aigner (2000) German presented a technical paper on the hydraulic design of pooled step cascades. If the steps of the cascades are designed as small stilling basins to dissipate the energy, they are called pooled cascades. The hydraulic design are as follows:

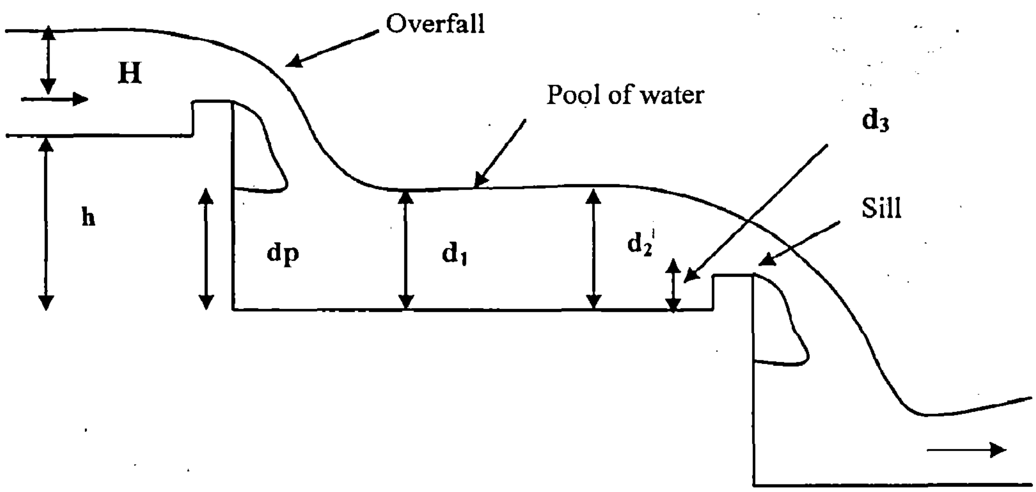


Fig.11.Nappe flow with pooled steps

If α is the slope of the step;

$$\tan\alpha = h/l \qquad (1)$$

and dc is the critical depth;

$$d_c = \sqrt[3]{\frac{q^2}{g}} \qquad (2)$$

specific discharge;

$$q = \frac{2}{3} Cd \sqrt{2g} H^{\frac{3}{2}} \qquad (3)$$

The discharge coeff. C_d (sharp crested weir, Bollrich 2000) should include the coef. of approach velocity.

$$C_d = 0.615\ (1 + \frac{1}{1000H + 1.6})\{1 + 0.5(\frac{H}{H + d3})^2\} \qquad (4)$$

The velocity V_1 at the downstream end of the jet is calculated from the enegy equation without loss of energy as:

$$V_1 = \sqrt{\{d3 + h + H - d_1 + \frac{dc^3}{2(d3 + H)^2}\}} \qquad (5)$$

$$d_1 = \frac{q}{V_1} \qquad (6)$$

The hydraulic jump is assumed to be developed fully and calculated with the conjugate depth equation (Bollrich 2000):

$$\frac{d_2}{d_1} = \frac{1}{2}\left(\sqrt{1 + 8\left(\frac{d_c}{d_1}\right)^3} - 1\right) \quad (7)$$

Height of the weir d_3 plus a 5% safety margin for d_2 amounts to:

$$d_3 = 1.05d_2 - H \quad (8)$$

Length of floor L;

$$L = L_d + L_j \quad (9)$$

Where L_d = length of drop & L_j =Length of jump.
Length of drop L_d ,

$$L_d = 1512\left(\frac{d_3 + h}{H}\right)^{0.556} H \quad (10)$$

Length of jump L_j,

$$L_j = 6d_2 \quad (11)$$

The above-described equations allow to design pooled step cascades with full hydraulic jump.

(D) Chanson (1994) has presented a report for the energy dissipation in nappe flow regime. He has written that in nappe flow regimes of chute the total head loss along the chute ΔH equals the difference between the maximum head available H_{max} and the residual head at the downstream end of the channel H_1 ie

$$\frac{H_1}{d_c} = \frac{d_1}{d_c} + \frac{1}{2}\left(\frac{d_c}{d_1}\right)^2 \quad (1)$$

In dimensionless form the head loss yields:

$$\frac{\Delta H}{H_{max}} = 1 - \left\{\frac{\frac{d_1}{d_c} + \frac{1}{2}\left(\frac{d_c}{d_1}\right)^2}{\frac{3}{2} + \frac{H_{max}}{d_c}}\right\} \quad \text{(2) For ungated chute}$$

$$\frac{\Delta H}{H_{max}} = 1 - \left\{\frac{\frac{d_1}{d_c} + \frac{1}{2}\left(\frac{d_c}{d_1}\right)^2}{\frac{H_{dam} + H_o}{d_c}}\right\} \quad \text{(3) for gated chute}$$

Where H_{dam}= dam crest head above downstream toe
H_o=reservoir free surface elevation above chute crest
For an ungated chute, the maximum head available and the dam height are related by:
$H_{max} = H_{dam} + 1.5d_c$

For a gated channel,

$H_{max} = H_{dam} + H_o$

The residual head or energy is dissipated at the toe of the chute by a hydraulic jump in the dissipation basin. We have also,

$$\frac{d_1}{h} = 0.54\left(\frac{d_c}{h}\right)^{1.275} \qquad (4)$$

Combining equations (4)&(2), the total energy loss becomes:

$$\frac{\Delta H}{H_{max}} = 1 - \left[\frac{0.54\left(\frac{d_c}{h}\right)^{0.275} + \frac{3.43}{2}\left(\frac{d_c}{h}\right)^{-0.55}}{\frac{3}{2} + \frac{H_{dam}}{d_c}}\right] \qquad \text{(5) for ungated chute}$$

$$\frac{\Delta H}{H_{max}} = 1 - \left[\frac{0.54\left(\frac{d_c}{h}\right)^{0.275} + \frac{3.43}{2}\left(\frac{d_c}{h}\right)^{-0.55}}{\frac{H_{dam} + H_o}{d_c}}\right] \qquad \text{(6) for gated chute}$$

from the fig.26, given below, it indicates that most of energy is dissipated on the step channel for large numbers of step and for a given dam height the rate of energy dissipation decreases when the discharge increases.

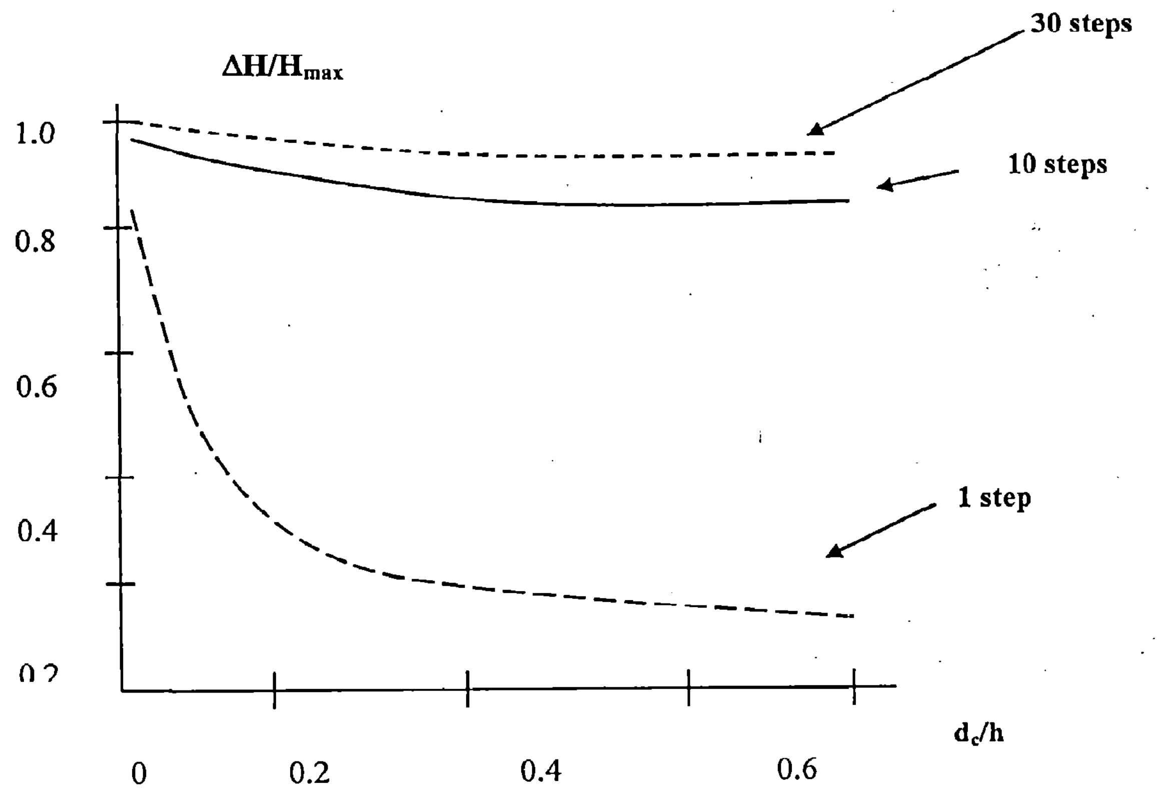


Fig.12 Energy dissipation in nappe flow regime-comparision betwwen equations (for ungated & gated chute) by CHANSON and experimental data (MOORE 1943,RAND 1955,HORNER 1969,STEPHENSON 1979a).

Equations (5),(6) may be applied with a reasonable accuracy to most nappe flow situations on horizontal step chutes& are for fully developed hydraulic jumps.

Chanson has also written that a nappe flow regime with fully developed hydraulic jump occurs for a discharge smaller than a critical value defined as;

$$(\frac{d_c}{h})char = 0.0916(\frac{h}{l})^{-1.276} \qquad (7)$$

Where l is the length of step. Nappe flow situations with fully developed hydraulic jump occur for $\frac{d_c}{h} < (\frac{d_c}{h})char$.

Equation (7) was obtained for: $0.2 < h/l < 6$.

(E) Schoklitch (1937) has presented a note for the designing the steps and estimating energy dissipations in nappe flow regime, which are as flows:

$$\frac{h}{l} = \tan\alpha = [3 + 4.3(\frac{d_c}{h})^{0.81}]^{-1} \qquad (1)$$

$$\frac{\Delta E}{E} = 1 - [\frac{\frac{d_1}{d_c} + \frac{1}{2}(\frac{d_c}{d_1})^2}{\frac{3}{2} + \frac{H_{spill}}{d_c}}] \qquad (2)$$

$$\frac{d_1}{h} = 0.54(\frac{d_c}{h})^{1.275} \qquad (3)$$

(F) Stephenson (1991) has presented a note for fully developed hydraulic jump in a nappe flow regime, which are as;

$$\tan\alpha < 0.2 \qquad (1)$$

$$\frac{d_c}{h} < \frac{1}{3} \qquad (2)$$

2.4.2 Transition flow regimes:

Chanson (2002) has presented a technical note for the method of predicting the flow characteristics of transition flow regime on stepped spillways. He writes that the type of flow regime (ie, nappe, transition & skimming flow) is a function of the discharge and step geometry. The low flows behave as a succession of free jets (nappe flow) while large discharges skim over pseudo-bottom formed by the step edges. For a range of intermediate flow rates, a transition flow regimes take place. The dominant feature is stagnation on the horizontal step face associated with significant splashing and a chaotic appearance. Transition flows are then characterized by significant air entrainment and flow instabilities.

The upper limit of nappe flow regime may be approximated as:

$$\frac{d_c}{h} = 0.89 - 0.4(\frac{h}{l}) \qquad (1)\ (NA\text{-}TRA)$$

The lower limit of skimming flow regime may be estimated as:

$$\frac{d_c}{h} = 1.2 - 0.325(\frac{h}{l}) \qquad (2)\ (TRA\text{-}SK)$$

Where dc is critical depth, h is the step height and l is the step length; NA is nappe flow, TRA is transition and SK is skimming flow regime. These equations (1) and (2) were deduced for flat horizontal steps with $0.05 < h/l < 1.7$; there is no information on their validity outside this range. These equations (1)&(2) characterize a change in flow regime for uniform or quasi-uniform flows only; for rapidly varied flows, the results are in accurate.

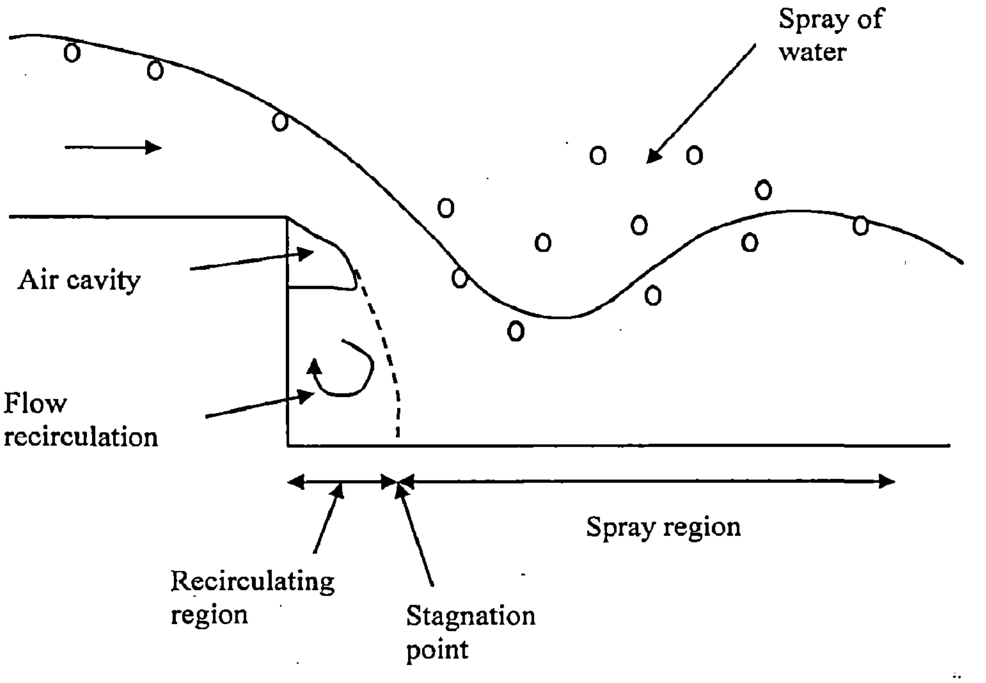


Fig.13.Transition flow regime on steep slope

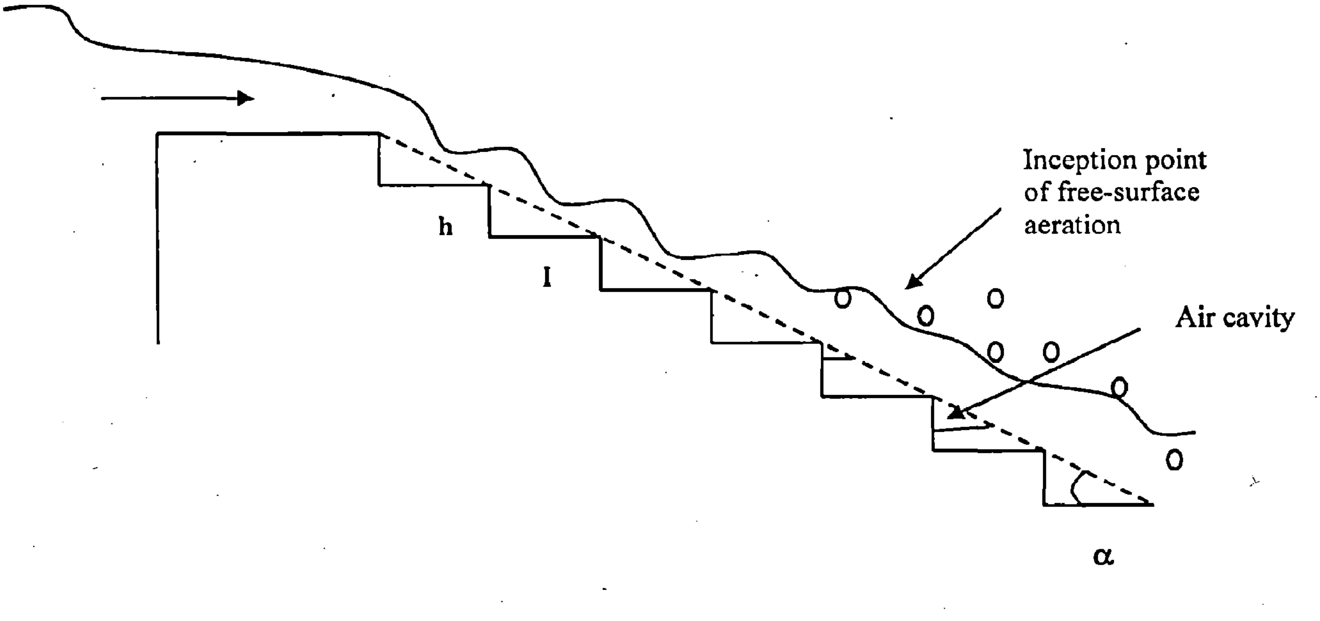


Fig.14 Transition flow on steep slope

2.4.3 Skimming Flow Regimes

2.4.3.1 Introduction:

Depending on the discharge value, for a given step height and channel slope, two different hydrodynamic behaviors can be observed in stepped channels. In particular, for low discharges and large steps, a nappe flow occurs and for higher discharges and smaller steps the water flow down a stepped channel as a coherent stream, skimming over the steps. In the skimming flow, the external edges of steps form a pseudo-bottom over which the water skims. Beneath the pseudo-bottom, recirculating vortices develop, filling the zone between the main flow and steps. The vortices are maintained through the transmission of shear stress from the fluid flowing past the edges of the steps. In addition small-scale vorticity is generated continuously at the corner of the step bottom. Most of the flow energy is dissipated to maintain the circulation of the recirculation vortices.

On stepped chutes with skimming flow regime, the flow is highly turbulent and the condition of free-surface aeration is satisfied. [illegible]. Large quantities of air are entrained along the channel. The free surface aerated flow region where the flow over the chute is smooth and glassy. Next to the boundary, turbulence is generated and the boundary layer grows until the outer edge of the boundary layer reaches the free surface. When the outer edge of the boundary layer reaches the free surface, the turbulence initiates natural free surface aeration. The location of the start of air entrainment is called the point of inception.

Downstream the inception point, a layer containing a mixture of both air and water extends gradually through the fluid. Far downstream, the flow will become uniform and for a given discharge, any measure of flow depth, air concentration and velocity distribution will not vary along the chutes. This region is defined as the uniform equilibrium flow region.

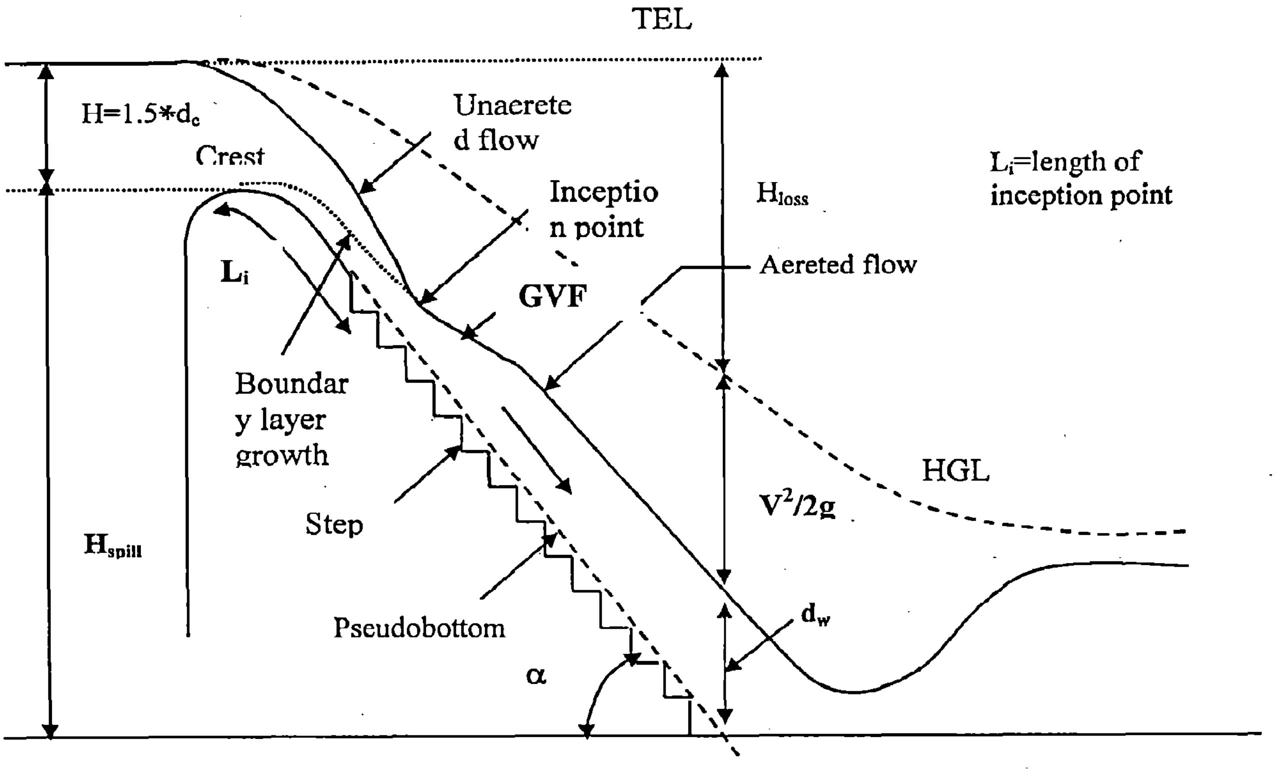


Fig.15. Section of stepped spillways showing flow patterns in skimming flow regime

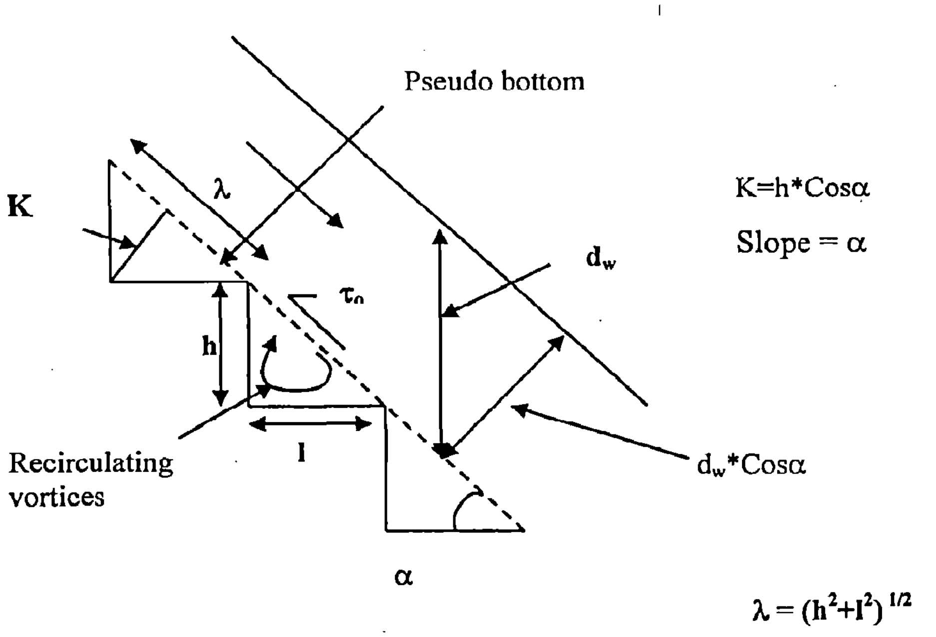


Fig.16.Skimming flow with stable cavity recirculation

2.4.3.2 Onset of skimming flow:

For small discharges and flat slopes, in the stepped chutes, the water flows as a nappe flow regime and an increase of discharge or of the slope of channel might induce the apparition if skimming flow regime.
The onset of skimming flow is defined by the disappearance of cavity beneath the free falling nappes, the waters flowing as a quasi-homogeneous stream. The phenomenon presents some similarities with the cavity filling or submergence of aeration devices and ventilated cavities.
Two different ways to define the onset of skimming flow were proposed by **Chanson (1994).** In particular, a first relation (Chanson 1994) was obtained by means of a fitting procedure of the experimental data:

$$\frac{(dc)onset}{h} = 1.057 - 0.465\frac{h}{l} \qquad (1)$$

and it is valid for dc > (dc)onset & for slopes between 0.2 1.25.
The second relation (Chanson 1996) was derived by imposing that, at the onset of skimming flow, the air cavities beneath the falling nappe disappear and by using simplified jet trajectory calculations.

$$\frac{(dc)onset}{h} = \frac{Fb^{\frac{2}{3}}\sqrt{1+\frac{1}{Fb^2}}}{\sqrt{1+2Fb^2(1+\frac{1}{Fb^2})^{\frac{3}{2}}(1-\frac{\cos\theta b}{\sqrt{1+\frac{1}{Fb^2}}})}} \qquad (2)$$

in which Fb is the Froude no at the step edge and θb is the angle of streamline falling from the step that at the onset of skimming flow should be equal to the channel slope.

According to **Boes (2000)** skimming flow sets in for ratios larger than,

$$\frac{dc}{h} = 0.91 - 0.14\tan\alpha \qquad (3)$$

where α is channel slope.

Chamani and Rajaratnam (1999 Sept) proposed two equations for the onset of skimming flow, which are as under:
The upper limit of the nappe flow domain is,

$$\frac{h}{l} = 0.405(\frac{dc}{h})^{-0.62} \qquad (4)$$

While the onset of skimming flow for steeply sloped structures (h/l > 1) is given by:

$$\frac{h}{l} = \sqrt{0.89[(\frac{dc}{h})^{-1} - (\frac{dc}{h})^{-0.34} + 1.5] - 1} \qquad (5)$$

Equations (4) & (5) have been derived through some empirical relationships **(Chamani & Rajaratnam 1995 and 1955).** Equation (4) has been obtained by imposing that the length (in other words, the inner side of jet coincides with the tip of the step) and equation (5) has been obtained by observing that, in incipient skimming flow, the jet becomes parallel to the spillways slope.
However, the authors observed that equation (4) under estimates the experimental data and hence its applicability appears to be limited, while equation (5) provides a rather good fitting

of their data. This observation points out that the application range of this methodology is too narrow and probably is strongly related to their experimental data.
From the previously recalled studies, it appears that the hydraulic behavior of stepped spillways is not clearly understood and that the available experimental data are very difficult to compare with each other.

Rajaratnam (1990) has presented a technical note for the method of predicting the characteristics of skimming flow on stepped spillways. For a stepped spillway with a slope of 1V:0.78(H), the fluid friction coefficient, C_f was evaluated using the experimental results of Sorenson and found to be 0.18. An estimate has also been made of energy loss on stepped spillways for skimming flow.
The characteristics or onset of skimming flow and estimate of energy loss has been given below as:

Onset of skimming flow:

At the onset of skimming flow, the range of h/l from 0.4 to 0.9, dc/h was approximately equal to 0.8.This means that for dc/h greater than 0.8, the skimming flow occurs. And for d_c/h less than 0.8, one would expect to get nappe flow. After experimental observations the nappe flow occurred for dc/h less than 0.33.

Energy loss:

An estimate of energy loss for skimming flow in stepped spillway is as follows:

$$E = y_0 + \frac{Vo^2}{2g} \qquad (1)$$

Average Reynolds's shear stress: $\tau = yo\gamma \sin\alpha$ (2)

And again, $\tau = C_f\rho \frac{Vo^2}{2}$ (3)

Where C_f=coeff.of fluid friction (C_f=f/4,f=Darcy friction factor); Vo=constant mean velocity; ρ=mass density of fluid; yo=normal depth; α=slope of stepped spillways.
From equation (2)&(3),

$$Cf = \frac{2yo^3 g \sin\alpha}{q^2} \qquad (4)$$

Where q = discharge per unit width of spillways.
From equations (1)&(4),

$$E = \left(\frac{Cfq^2}{2g\sin\alpha}\right)^{\frac{1}{3}} + \left(\frac{q\sin\alpha}{Cf\sqrt{2g}}\right)^{\frac{2}{3}} \qquad (5)$$

If yo' and Vo' =corresponding depth and velocity at the toe of a smooth spillways without steps,

$$E' = yo' + \frac{Vo^2}{2g} \qquad (6)$$

and one can write an equation similar to (5) with Cf' replacing Cf, where Cf'= the coeff.of skin friction for the smooth spillways. Sorenson's test (B series) on a smooth spillway give a value of 0.0065 for Cf'. If ΔE is defined as:

ΔE=E'-E (7)

ΔE gives the energy loss caused by the steps over that caused by the smooth spillways face. If the relative energy loss is defined as ΔE/E, it can be shown that,

$$\frac{\Delta E}{E'} = \frac{(1-A) + \frac{Fo^2}{2}\frac{(A^2-1)}{A^2}}{1 + \frac{Fo'^2}{2}} \qquad (8)$$

Where $A=(\frac{Cf}{Cf'})^{\frac{1}{3}}$; and Fo'= the Froude no. at the toe of the smooth spillways. Taking C_f = 0.18 and Cf' =0.0065 then A = 3 and for relatively large of Fo', ΔE/E is approximately equal to $\frac{A^2-1}{A^2}$, which further reduces to 8/9 i.e. 88.88%. This indicates the considerable amount of energy loss that can be produced by steps, as found by Sorenson.

Ohtsu and Yasuda (1997) proposed a different approach to the problem by introducing a transition regime that appears to fit the available experimental data, even if some uncertainties remain.
Recently, their analysis has been improved, producing two equations that can be used to define the upper limit for nappe flow regime and the lower limit for the skimming flow regime (Yasuda and Ohtsu (1999)). The proposed equations are:

$$\frac{dc}{h}=\frac{(1.4-\frac{h}{l})^{0.26}}{1.4} \qquad (1)$$

$$\frac{dc}{l}=0.862(\frac{h}{l})^{-0.165} \qquad (2)$$

and they appear to be effective for chute inclination angles lower than 55 °.

2.4.3.3 Transition from nappe to skimming flows:

Boes and Minor (2000) & Boes and Hager (2003):
The transition from nappe to skimming flow can be expressed by the ratio of critical flow depth, dc and step height h. According to Boes(2000), skimming flow sets in the ratios larger than,

$$\frac{dc}{h}=0.91-0.14\tan\alpha \qquad (1)$$

where α is the spillway channel slope. It is an approximate agreement with the transition functions given by Rajaratnam(1990),Stephenson(1991),Yasuda&Ohtsu(1999),Chanson(1996),Tatewar&Ingle(1999) and Matos(2001) and is applicable for chute inclim=nation angles of approximately $25^\circ < \alpha < 55^\circ$.
A certain risk of acoustic noise due to vibrations of the falling jets exists in the nappe flow regime, especially for wide spillways where the cavity below the nappe is not aerated over the entire width. The nappe aeration at the free surface is rather large due to the high degree of turbulence caused by the macro roughness of the steps, so that the excessive sub pressures beneath the falling nappe are likely to occur. Further studies on the pressure distribution for the transition between nappe and skimming flows are recommended.

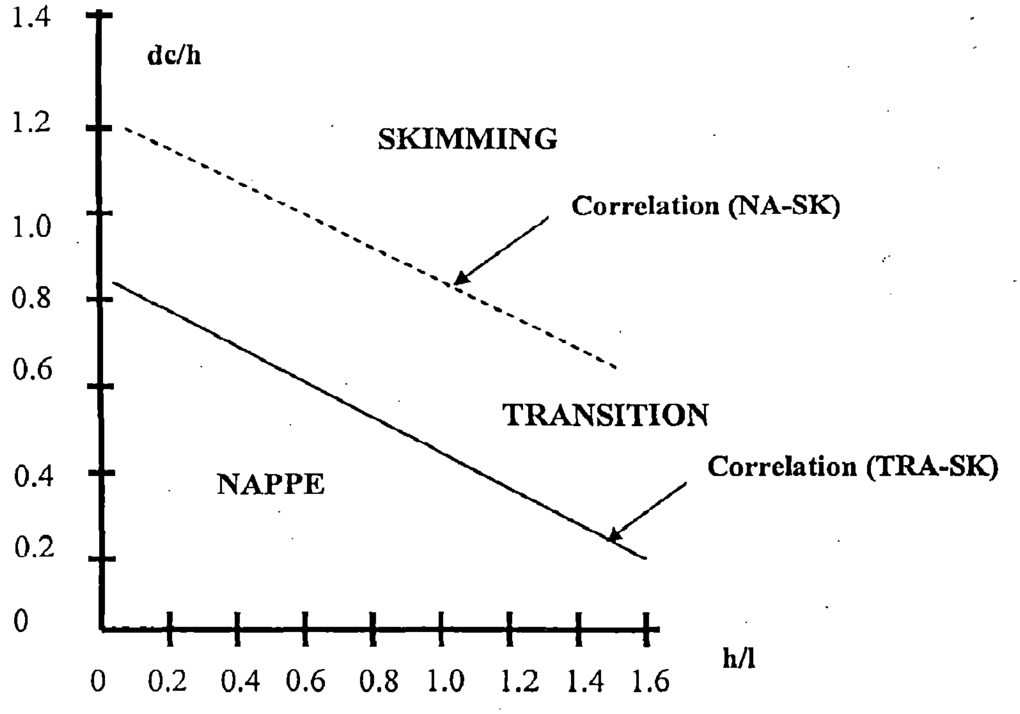


Fig.17 Flow conditions for the transition from nappe to skimming flow-Summary of experimental data (after CHANSON 2001)

2.5 Boundary layer growth:

(a) **Chanson (1994):** From the crest of the chute or from the upstream gate, a bottom turbulent boundary layer develops. The location where its outer edge reaches the free surface is called the inception point of air entrainment. Downstream of that location, the turbulence next to the free surface become large enough to initiate natural free surface aeration. The characteristics at the inception point are Li and di: Li = the distance from the start of the growth of boundary layer and di = the depth of flow at the point of inception.
On stepped spillways, the position of the point of inception is primarily the function of the discharge and chute roughness (Keller & Rastogi 1977), suggested for smooth spillway:

$$\frac{Li}{Ks'} = 13.6(\sin\alpha)^{0.0796} Fr^{0.713} \qquad (1)$$

$$\frac{di}{Ks'} = \frac{0.223}{(\sin\alpha)^{0.04}} Fr^{0.643} \qquad (2)$$

where Froude no.F = $\frac{qw}{\sqrt{g\sin\alpha (Ks')^3}}$ and Ks' is skin roughness height and

$$\frac{di}{Li} = 0.0212(\sin\alpha)^{0.11}(\frac{Li}{Ks'})^{-0.10} \quad (3)$$

Chanson reanalyzed the flow properties at the point of inception of model experiment of stepped spillways and found the equations (1), (2), (3) for stepped spillways as:

$$\frac{Li}{Ks} = 9.719(\sin\alpha)^{0.0796} Fr^{0.713} \quad (4)$$

$$\frac{di}{Ks} = \frac{0.4024}{(\sin\alpha)^{0.04}} Fr^{0.592} \quad (5)$$

where Froude no.F = $\frac{qw}{\sqrt{g\sin\alpha(Ks)^3}}$ and Ks = h cos α and

$$\frac{di}{Li} = 0.06106(\sin\alpha)^{0.133}(\frac{Li}{Ks'})^{-0.17} \quad (6)$$

Indeed the rate of boundary layer growth on stepped chute (eqn. (6)) is approximately 2.8 times larger than on smooth channels (eqn. (3)).
For a given channel geometry, equation (4) implies that the location of the inception point moves downstream with increasing discharge.
The results of equation (4) and (5) after the experimental model test by Chanson can be shown in the following figs. as:

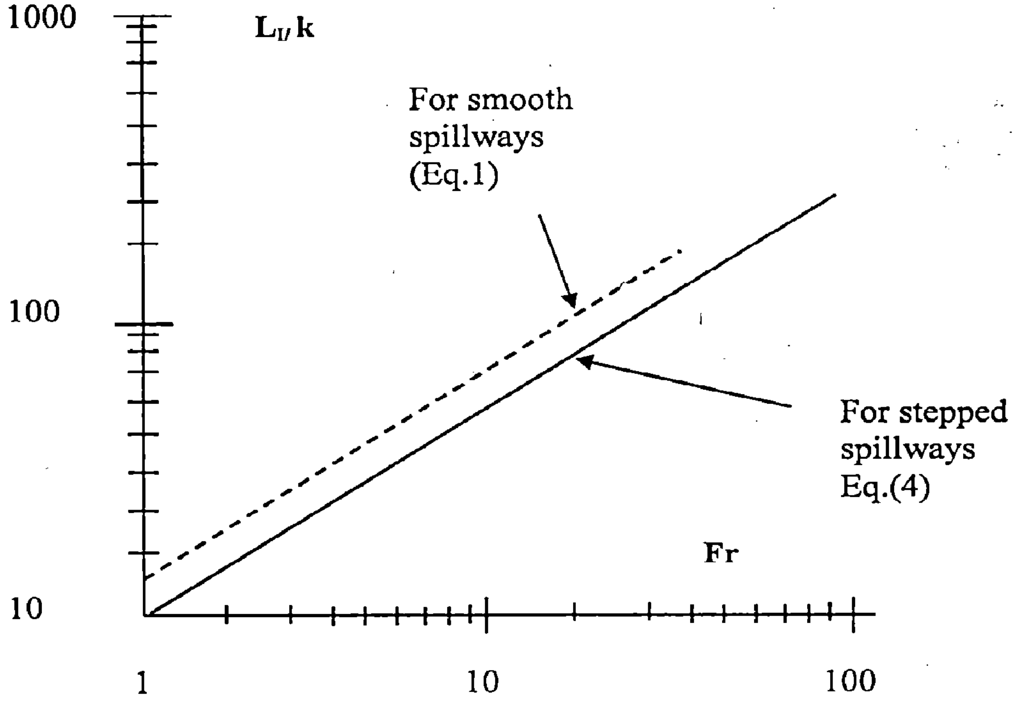


Fig.18. Characteristics of the inception point of air entrainment (based on experiments by BEITZ&LAWLESS 1992,BINDO et al 1993,FRIZEL&MEFFORD 1991,SORENSON 1985,TOZZI 1992) and equation by CHANSON 1994.

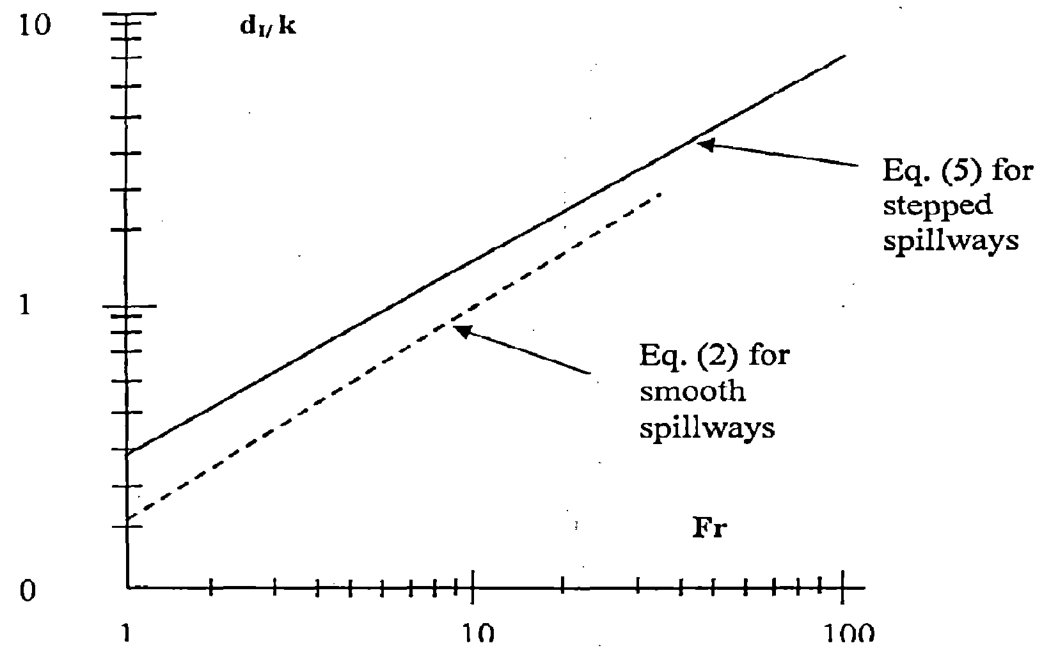


Fig.19 Characteristics of the inception point of air entrainment (based on experiments by BINDO et al 1993,FRIZEL&MEFFORD 1991,SORENSON 1985,TOZZI 1992) and equation by CHANSON 1994.

Definition of the roughness height Ks for skimming flow regime (equation and fig. are given below):

$$K_s = h \cos\alpha \qquad (7)$$

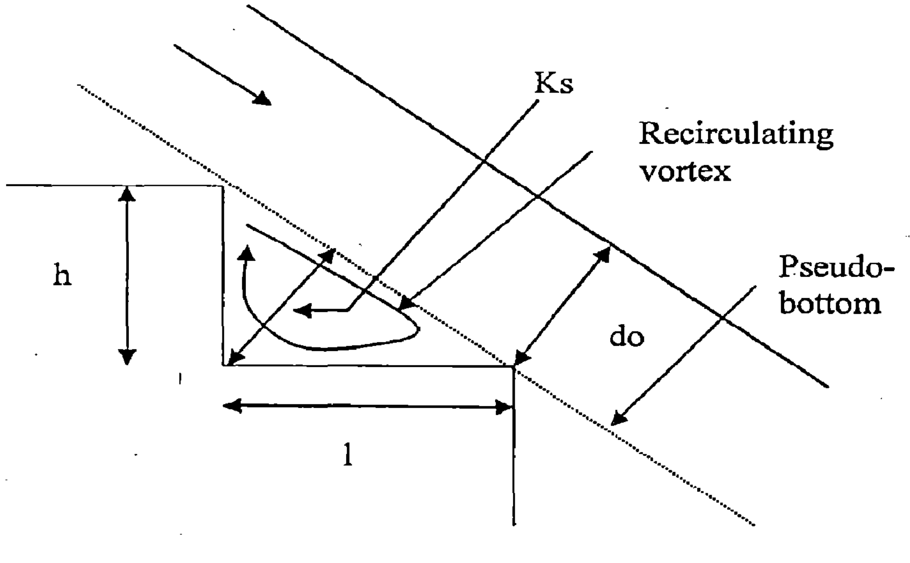


Fig. 20 Definition sketch of roughness height K_s

(b) Boes and Minor (2000):

Air entrainment: Where the turbulent boundary layer reaches the free surface, the degree of turbulencê is large enough to entrain air into the water flow at the so called inception point of air entrainment. For the designer of the stepped chute knowing the location of inception point is important to have an idea of unaerated spillways zone, which is potentially prone to cavitations damage due to large sub pressures. According to Boes (2000), the unaerated or black water length Li from the spillway crest to inception point can be described by:

$$\frac{Li}{Ks} = 9.72(Fr)^{0.86} \qquad (1)$$

where K_s=h $\cos\alpha$ denotes the roughness height perpendicular to pseudo-bottom

$Fr = \frac{qw}{\sqrt{g \sin\alpha h^3}}$ is a roughness Froude no. containing the relevant parameters of stepped spillway flow such as unit discharge qw, step height h and chute inclination angle α and g is the acceleration due to gravity. The above equation can be written as in dimensional form:

$$Li = 9.72 \frac{qw^{0.86} \cos\alpha}{g^{0.43} (\sin\alpha)^{0.43} h^{0.29}} \qquad (2)$$

The small influence of step height becomes obvious, where as it can be seen that the unit discharge predominantly determines the location of the inception point.

If in the case of high velocities the hydrodynamic pressures on the step surfaces or at the step corners fall below the vapor pressure, cavitations might cause severe damage to the spillway concrete. The placement of an aerator to artificially entrain air is therefore of interest in the black water region of stepped spillways. This can also be achieved by bridge-supporting piles downstream of the spillway crest. Further research on the hydrodynamic pressure fluctuations should shed more light on the cavitations risk potential of stepped spillways, particularly of unaerated spillways zone.

2.6 Uniform flow conditions:

If the chutes are long enough, uniform flow conditions are reached before the end of inclined chute (Smooth or Stepped).

The local air concentration, C is defined as the volume of air per unit volume of air and water. The characteristic water flow depth dw is defined as:

$$dw = \int_0^{y90} (1 - C) dy \qquad (1)$$

where y is measured perpendicular to the channel surface and y90 is the depth where the local air concentration is 90%. The characteristic depth dw is defined from 0 to y90: above 90% of air concentration, air concentration and velocity measurement are not accurate (Chanson 1992a) & the integration of the air concentration above y90 becomes meaningless.

The depth averaged mean air concentration Cmean is defined as:

$$Cmean = \frac{1}{y90} \int_0^{y90} C dy \qquad (2)$$

and combining with equation (1), this yields:

$$Cmean = 1 - \frac{dw}{y90} \qquad (3)$$

The mean flow velocity is defined as:

$$Uw = \frac{qw}{dw} \qquad (4)$$

where qw is the water discharge per unit width. The characteristic velocity V90 is defined as that at y90.

2.7 Flow aeration:

(a) Chanson (1994):

The amount of air entrained within the flow is defined usually in terms of the depth averaged mean air concentration (Cmean):

$$\frac{qair}{qw} = \frac{Cmean}{(1 - Cmean)} \qquad (1)$$

The mean equilibrium air concentration Ce is a function of slope only (not of discharge, flow depth, and roughness (Wood 1983, Chanson 1993a)). For slopes flatter than 50 °, the average air concentration may be estimated as:

$Ce = 0.90 \sin\alpha$ (2)

The quantity of air entrained on rock fill channels was found to be related as:

$Ce = 1.44 \sin\alpha - 0.08$ (3)

which is similar to equation (2).

The plotting eqn 2 as Ce vs channel slope (From model data of Straub & Anderson 1958, prototype data (Aivazyan 1986) and rock fill channel (Knauss 1979) is given below in fig.23.

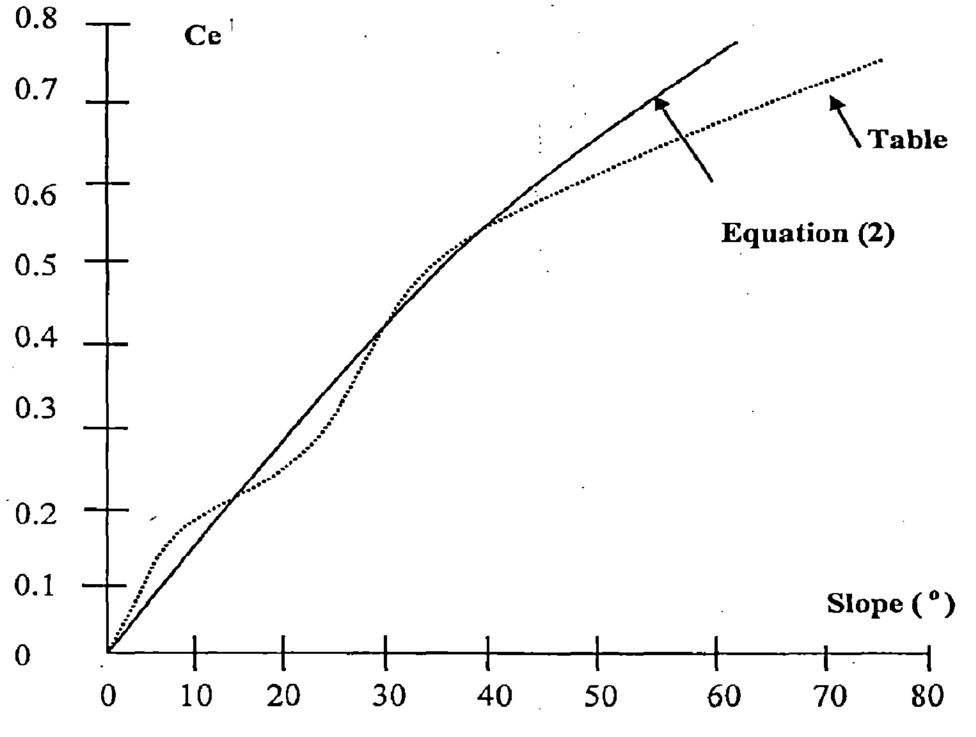


Fig 21 Uniform equilibrium air concentration Ce as a fn. Of chute slope α -Model data (STRAUB &ANDERSON 1958), prototype data (AIVAZYAN 1986) and equation Ce=0.9*sinα and Table of average air concentration in uniform self aerated flows

(b) Hager (1991):

Mean air concentration Cmean,

$$Cmean = 0.75(\sin\alpha)^{0.75} \qquad (1)$$

To check the validity of this equation for stepped spillways, the writer calculated the aerated flow depth and comparedwith the experimental data of Sorenson 1985, and Diea-Cascon et al 1991. The aggrement was found to be good.

(c) Chanson (2001):

Void fraction or air concentration, C

$$C = 1 - \tanh^2(K' - \frac{y}{2D'y90}) \qquad (1)$$

where C=void fraction or air concentration

tanh=hyperbolic tangent function

y =distance normal to the pseudo-bottom formed by the step edges

y90 =distance where C=90%

D' =dimensionless turbulent diffusibility

K'=integration constant

D' and K' are the functions of mean air content Cmean only (table below) where Cmean is the depth averaged air content defined in terms of y90:

$$Cmean = \frac{1}{y90}\int_0^{y90} C\,dy \qquad (2)$$

The uniform equilibrium mean air content Ce is a function of the slope α only. For slope less than 50°, it may be estimated Ce as:

$$Ce = 0.9\sin\alpha \qquad (3)$$

Table:

SN	Cmean	D'	K'
1	0.01	0.0073	68.7045
2	0.05	0.0366	14.0029
3	0.1	0.0731	7.1652
4	0.15	0.1097	4.8852
5	0.2	0.1465	3.7400
6	0.3	0.2232	2.5670
7	0.4	0.3110	1.9340
8	0.5	0.4230	1.5100
9	0.6	0.5870	1.1780
10	0.7	0.8780	0.8970

2.8 Flow properties:

Assuming a long stepped channel and if the uniform flow conditions are reached before the end of the channel, the uniform flow depth is deduced from the momentum equations, i.e. the weight component in the flow direction equals the bottom friction. It yields:

$$\tau o Pw = \rho w g A w \sin\alpha \qquad (1)$$

where Pw is the wetted perimeter, τo is the average shear stress between the skimming flow and the recirculating fluid underneath i.e. the men shear stress along the pseudo-bottom, ρw is the water density, g is the gravity constant, Aw is water flow cross section area.
The average shear stress τo is defined as for open channel flow (Henderson 1966, Streeter & Wylie 1981):

$$\tau o = \frac{fe}{8} \rho w (Uw)o^2 \qquad (2)$$

where fe is the Darcy friction factor of the air water flow and (Uw)o is the uniform velocity of flow.
Combining eqns. (1),(2),

$$(Uw)o = \sqrt{\frac{8g}{fe}} \sqrt{\frac{D_H \sin\alpha}{4}} \qquad (3)$$

where D_H is hydraulic diameter: $D_H = 4Aw/Pw$

For a wide channel, the uniform flow velocity(Uw)o and normal depth do are deduced from the continuity and momentum equations. In dimensionless form, it yields;

$$\frac{(Uw)o}{Vc} = \sqrt[3]{\frac{8\sin\alpha}{fe}} \qquad (4)$$

$$\frac{do}{dc} = \sqrt[3]{\frac{fe}{8\sin\alpha}} \qquad (5)$$

where Vc is critical flow velocity. Combining eqn.(3) of section 5.4 and eqn.(5) the characteristic depth (Y90)o for uniform flow becomes:

$$\frac{(Y90)o}{dc} = \sqrt[3]{\frac{fe}{8(1-Ce)^3 \sin\alpha}} \qquad (6)$$

where Ce is mean equilibrium air concentration and the recorded values corresponding to channel slope is given below (By Straub & Anderson & equations):

Table:

Slope α (degree)	Ce	Y90/do	fe/f	h/l
0	0	1	1	0
7.5	0.1608	1.192	0.964	0.132
15.5	0.2411	1.312	0.867	0.268
22.5	0.31	1.449	0.768	0.414
30	0.4104	1.696	0.632	0.577
37.5	0.5693	2.322	0.43	0.767
45	0.6222	2.647	0.36	1
60	0.6799	3.124	0.277	1.732
75	0.7209	3.583	0.215	3.732

2.8.1 Rapidly varied flow at inception point (Chanson 2001):

Visual observations and detailed point measurements indicate that the flow properties are rapidly varied next to and immediately downstream of the inception point of air entrainment. Side view observations suggest that some air is entrapped in the step cavity i.e upstream of free surface aeration.

Immediately upstream the flow is extremely turbulent and the free surface appears to be subjected to a flapping mechanism. See fig.24.

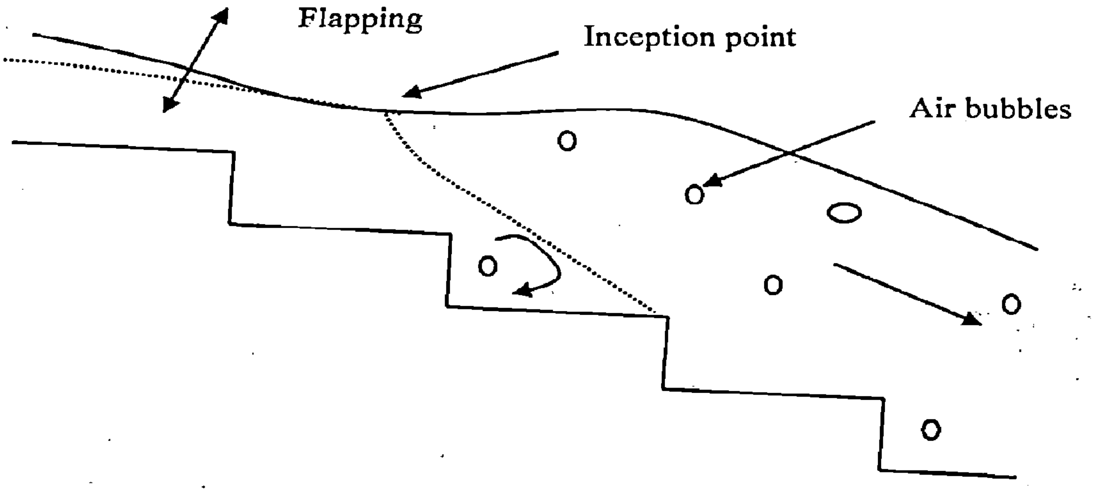


Fig.22.Rapidly varied flow region at the inception point of free surface aeration

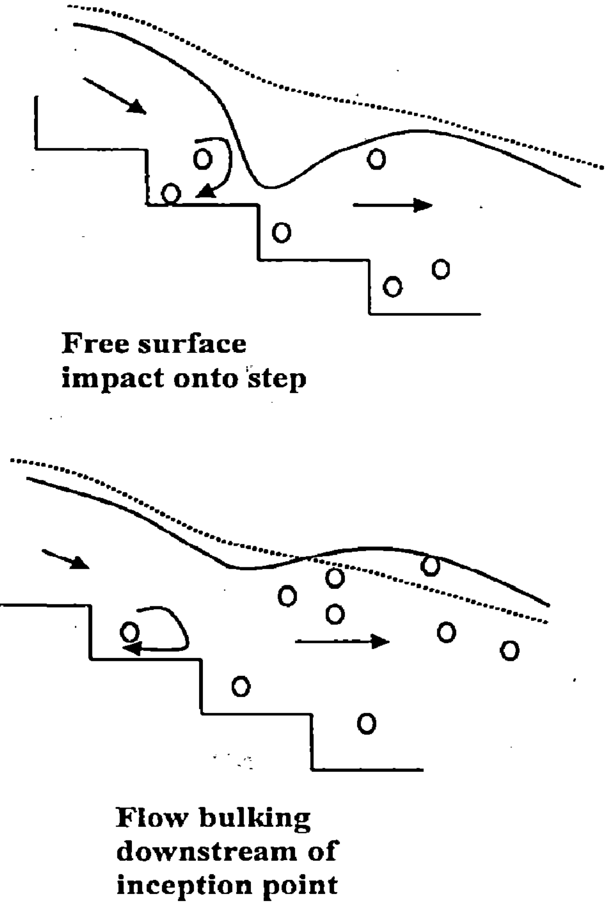


Fig.23 Rapidly varied flow region at the inception point of free surface aeration: Flow mechanisms next to the inception point

2.8.2 Gradually varied flow properties (Chanson 2001):

Downstream of the inception point, the flow is fully developed and the flow properties tend gradually to uniform equilibrium (i.e. normal flow conditions) while the flow resistance on smooth invert chutes is primarily skin friction, skimming flow over stepped chute are characterized by significant form losses.

The water skims over stepped edges with formation of recirculating vortices between the main stream and the step corner. Form drag is predominant. The reanalysis of over 650 laboratories and prototype data showed that the dimensionless friction coefficient f (or Darcy's friction factor) is about 0.1-0.3, with an analytical development implying f = 0.20. The results are independent of step height within limits (1< dc/h < 10).

On smooth invert chutes, the gradually varied flow properties are deduced from the differential form of the energy equation or back water equation:

$$\frac{\partial H}{\partial S} = -Sf \qquad (1)$$

where H= total head, Sf =friction slope, S =longitudinal coordinate in the flow direction.

It is believed that two basic assumptions of the back water calculations are violated in skimming flows. These are:

a. the flow must be gradually varied
b. the flow resistance must be the same as for a uniform flow

The form drag and associated cavity recirculations are very energetic processes and the flow properties in the mixing layer are rapidly varied. A number of researchers showed drastic differences between void fraction and velocity data measured at the step edge and above the cavity at one step, as well as from one step to the adjacent ones. The concept of gradual variation of the flow resistance is inappropriate in a form drag-dominated skimming flow. (Indeed the above equation assumes a one dimensional flow motion that is untrue).

2.9 Flow resistance:

(a) Chanson (1994):

The flow resistance is the sum of the skin resistance and the form resistance of the steps. For a stepped chute geometry of the step is characterized by the depth normal to the streamlines (i.e. Ks=h $\cos\alpha$) and the channel slope ($\tan\alpha = \frac{h}{l}$).

Dimensional analysis suggests that the friction factor is a function of the surface (skin) roughness height Ks', the Reynold's no., the step roughness height Ks, the channel slope and the quantity of air entrained:

$$fe = f\left(\frac{Ks'}{D_H}; \mathrm{Re}; \frac{Ks}{D_H}; \alpha; Cmean\right) \qquad (1)$$

where Reynold's no. $\mathrm{Re} = \frac{\rho_w U_w D_H}{\mu_w}$, μ_w is the dynamic viscosity of water.

But after a detailed analysis of experimental data it has been found that the friction factor is independent of surface roughness Ks' and Re. And then the above equation (1) becomes:

$$f = f(\frac{Ks}{D_H};\alpha) \qquad (2)$$

i.e dependent of $\frac{Ks}{D_H}$ and slope α.

This equation (2) can be correlated by:

$$\frac{1}{\sqrt{f}} = 1.42\ln(\frac{D_H}{Ks}) - 1.25 \qquad (3)$$

for flat slopes and it can be used for $0.02 < Ks/D_H < 0.3$.
The present investigation (by Chanson) recommends to use f=1.0 as an order of magnitude of friction factor for skimming flow on steep slopes (50 to 55°).

(a) Boes and Minor (2000):

The friction factor f varies only slightly with the relative roughness Ks/D_H, where $D_H = 4\ R_h$ denote the hydraulic diameter, $R_h = bh_w/(b+2h_w)$ is the hydraulic ratio and b the spillway width. The uniform equivalent clear water depth can be calculated with the equation;

$$\frac{hw}{dc} = 0.23(\sin\alpha)^{\frac{-1}{3}} \qquad (1)$$

The friction factors:

$$\frac{1}{\sqrt{fw}} = 2.69 - 1.38\log(\frac{ks}{wD_H}) \qquad (2) \text{ for } \alpha = 30^\circ$$

$$\frac{1}{\sqrt{fw}} = 4.25 + 0.58\log(\frac{ks}{wD_H}) \qquad (3) \text{ for } \alpha = 50^\circ$$

where the form coefficient w:

$$w = 0.9 - 0.38\exp(\frac{-5h}{b}) \qquad (4) \text{ for } h/b > 0.04$$

$$w = 0.60 \qquad (5) \text{ foe } h/b < 0.04$$

For $\alpha = 30^\circ$; the friction factor increases with increasing relative roughness, whereas the converse is observed for $\alpha = 50^\circ$.

For preliminary design processes, the friction factor f = 0.09 and 0.07 for $\alpha = 30^\circ$; and 50° respectively are suggested.

2.10 Flow patterns:

For very flat slopes: The flow is characterized by the impact of the wake on the next step, a 3-dimensional unstable recirculation in the wake and some skin friction drag on the step downstream of the wake impact. The flow pattern is called “wake-step interference” sub regime.

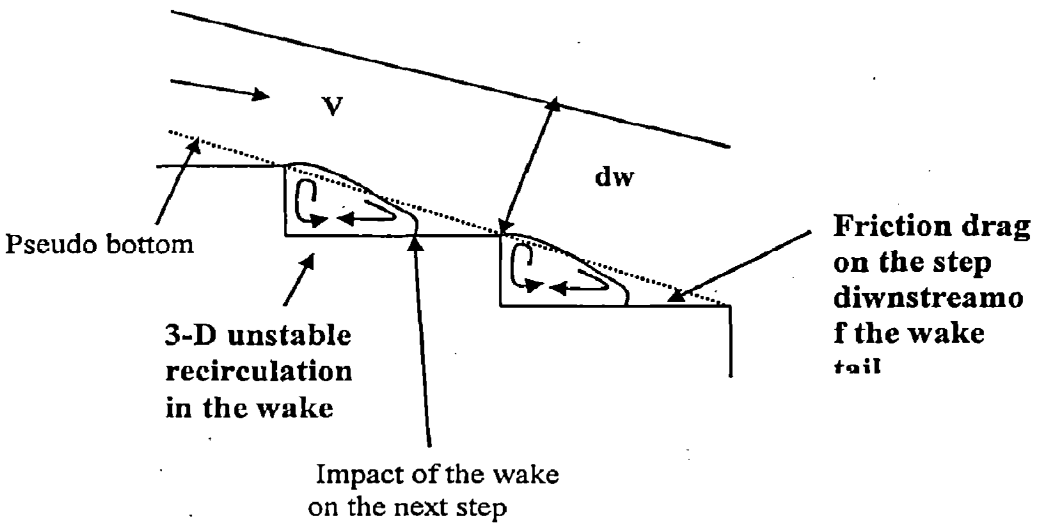


Fig.24. Flow pattern in the cavity between adjascent steps: Wake step interference sub regime in flat slopes

For larger slopes: The wake interferes with the next wake and there is no skin friction drag component. This pattern is called "wake-wake interference" sub regime.

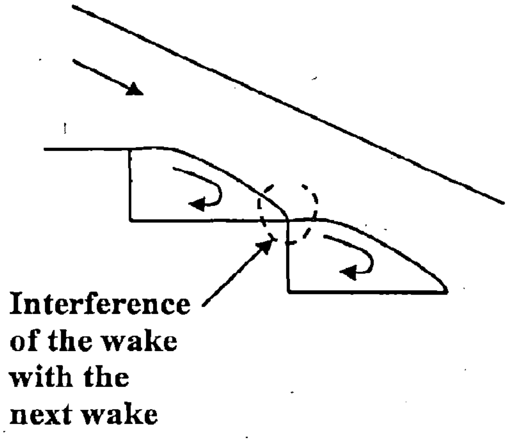


Fig.25 Flow pattern in the cavity between adjascent steps: Wake-wake interference sub regime in slope about 27 degrees

For steep slopes: The energy dissipation and the flow resistance are functions of the energy required to maintain the circulation of the large-scale vortices. The flow pattern is called a "recirculating cavity flow" sub regime.

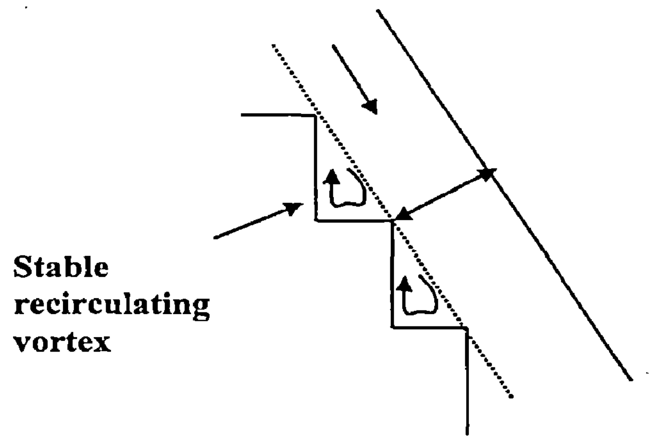


Fig.26 Flow pattern in the cavity between adjascent steps: Recirculating cavity flow sub regime in steep slope

2.11 Velocity distribution:

The velocity distribution in the gradually varied flow region of the stepped spillways with the slopes 27° to 53° has been found to follow the power law (Frezill 1992, Tozzi 1992):

$$\frac{V}{V\max} = \left(\frac{Y}{d}\right)^{\frac{1}{N}} \qquad (1)$$

where Vmax is the velocity near free surface. The exponent of this velocity distribution is about: N =3.5 and 4.
In uniform non aerated flows above smooth chute (Chen 1990):

$$N = K\sqrt{\frac{8}{f}} \qquad (2)$$

Where K= von karman constant=0.4, f= 0.10.

For free surface aerated flows on smooth chutes (Chanson 1993a):

$$\frac{V}{V_{90}} = \left(\frac{Y}{y90}\right)^{\frac{1}{N}} \qquad (3)$$

where V90 is the characteristic velocity at Y90. This applies to both uniform and gradually varied flows, and the exponent N is independent of mean air concentration Cmean.

On stepped chutes, self-aerated skimming flows are expected to behave as free surface aerated flows on smooth spillways. For smooth chute N=6.0 & for stepped chute N=3.5 to 4.
For known air concentration distributions, the characteristic velocity V90 may be deduced from the continuity equation (Chanson 1989):

$$\frac{V90}{Uw} = \frac{1}{(1-Cmean)}[\int_0^1 (1-C)y^{\frac{1}{N}}dy]^{-1} \qquad (4)$$

Chanson described the mean velocity:

$Uw = \sqrt{\frac{8g}{fe}}\sqrt{\frac{D_H \sin\alpha}{4}}$ where D_H =4Aw/Pw and for wide channel he prescribed as:

$\frac{V}{Vc} = \sqrt[3]{\frac{8\sin\alpha}{fe}}$ where fe can be calculated by tables given in section 5.4.

Sorenson's method:

$V = (\frac{2}{Cr})^{\frac{1}{2}}(gSoy)^{\frac{1}{2}}$ where Cr (fluid friction) = 0.18; y = $0.23(\frac{l^4 q^6}{hg^3})^{\frac{1}{12}}$; h =step height, l =step length, So =slope of spillway.

2.12 Energy dissipation:

In a skimming flow regime, the water flow exhibits large friction losses over the stepped bottom. Most of energy is dissipated in maintaining recirculation vortices in the cavities beneath the pseudo-bottom formed by the step edges. Figs 5nos. If the uniform flow conditions are reached before the end of chute, analytical calculations of the energy dissipation can be developed.

Residual energy: The residual energy is the energy of the flow at the end of channel. Usually the residual energy is dissipated in a dissipation basin at the downstream end of chute. The residual head at the bottom of chute is:

$$\frac{\Delta H}{H\max} = [(\frac{fe}{8\sin\alpha})^{\frac{1}{3}}\cos\alpha + \frac{Ec}{2}(\frac{fe}{8\sin\alpha})^{\frac{-2}{3}}] \qquad (1)$$

The aeration of the flow reduces the flow resistance and increases the kinetic energy of the flow. As a result, the residual energy increases with the amount of entrained air. The relative increase of residual energy caused by the aeration of the flow is:

$$\frac{\Delta(Hres)}{Hres} = (\frac{fe}{f})^{\frac{1}{3}}(\frac{1+4\frac{Ec\tan\alpha}{f}(\frac{f}{fe})}{1+4\frac{Ec\tan\alpha}{f}}) - 1 \qquad (2)$$

where $\frac{fe}{f} = 0.5[1+\tanh(0.628\frac{0.514-Ce}{Ce(1-Ce)})]$ where tanh(x) $=\frac{(e^x - e^{-x})}{(e^x + e^{-x})}$

for smooth chutes.

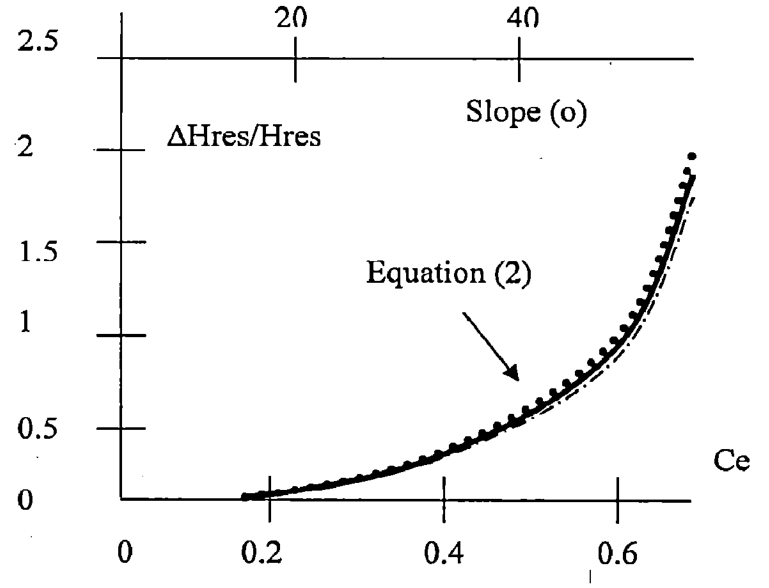


Fig. 27. ΔHres/Hres as a function of the mean air concentration Ce and the channel slope α

Tatewar&Ingle (1996) and Knight&Mc Donold (1979):

Computation of energy dissipation: Knowing the data of a stepped spillway regarding unit discharge, q slope of downstream face, S step size and geometry and the parameters λ, K, and l can be determined as in fig.30 below. Tatewar and Ingle (1996) proposed a method for computation of flow depth at the toe of spillways for skimming flow regime. The toe depth can be determined using Manning's equation as:

$$V = \left(\frac{1}{n}\right) R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad (1)$$

where V=q/y =velocity of flow.

Therefore y = $\left(\frac{qn}{\sqrt{S}}\right)^{0.6}$ (2) where n =manning's roughness coeff.; R =hydraulic mean radius = y for wide channel; S =Sinα=slope of downstream spillway face.

Equating the values of velocity given by eqn(1) and eqn. given by Knight&McDonold1979 for the velocity over large roughness elements, the following equation can be obtained:

$$\frac{Z^{0.1}}{n\sqrt{g}} = 0.25 + 19\log\left(\frac{\lambda}{l}\right) + 5.75\log\left(\frac{Z^{0.6}}{K}\right) \qquad (3)$$

where Z=$\left(\frac{qn}{\sqrt{S}}\right)$=section factor for computation of uniform flow.

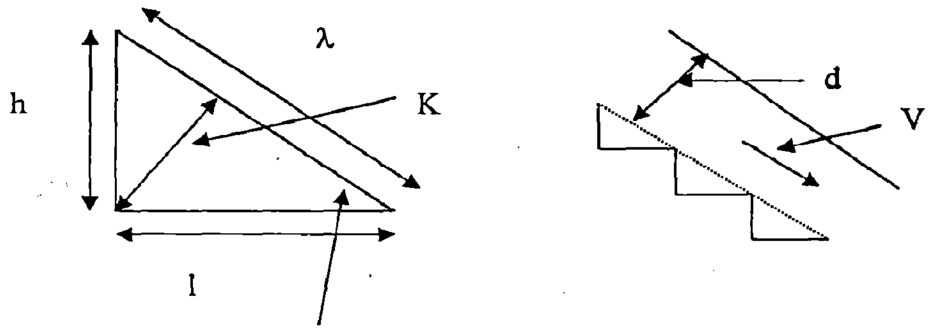


Fig 28 Step geometries

For a known discharge and downstream slope of spillway the value of Manninng's n can be determined from equation (3). With this value of n the toe depth (y) and toe velocity (V) can be computed from equation (2) and equation (1). The energy dissipation over the surface of spillway is given as:

$$\Delta E = Ec - Et \qquad (4)$$

where Ec is energy or head at crest of spillway =H+1.5dc; Et is energy at the toe of the spillway = $y+V^2/2g$; H =height of spillway; dc =critical depth of flow.

Hager and Boes (2000):

Residual energy: If uniform aerated flow is attained i.e. Hdam > 15 dc and 35 dc for α=30o and 50o respectively, the relative residual energy head Hres/Hdam at the toe of ungated stepped spillways can be calculated from equation proposed by Chanson (1994b) for uniform flow:

$$\frac{Hres}{H\max} = \frac{(\frac{fwu}{8\sin\alpha})^{\frac{1}{3}}\cos\alpha + \frac{E}{2}(\frac{fwu}{8\sin\alpha})^{\frac{-2}{3}}}{\frac{Hdam}{dc} + \frac{3}{2}} \qquad (1)$$

where Hmax denotes the reservoir head, fwu is the friction factor for uniform equivalent clear water flow and E is the kinetic energy correction coeff.(=1.21 on an average) i.e. 1.2 < E < 1.26.

If uniform flow is not attained i.e. Hdam < 15dc and 35dc for α = 30o and 50o respectively, the energy head at the spillway toe should be computed as:

$$Hres = Z' + hw\cos\alpha + E\frac{q^2}{2gh_w^2} \qquad (2)$$

where Z' is the elevation above a reference level usually the stilling basin bottom, the equivalent clear water depth hw along a stepped chute is expressed by (Hager&Boes 2000):

$$hw(x) = \frac{hwu}{1-(1-\frac{hwu}{dc})\exp(-\frac{10}{3}\frac{hwu^2\sin\alpha}{dc^3}x)} \qquad (3)$$

$$\text{But, } \frac{hwu}{dc} = 0.23(\sin\alpha)^{\frac{-1}{3}} \qquad (4)$$

So combining these two equations:

$$hw(x) = \frac{0.23\left(\frac{q^2}{g\sin\alpha}\right)^{\frac{1}{3}}}{1-\left(1-\frac{0.23}{(\sin\alpha)^{\frac{1}{3}}}\right)\exp\left(-0.176\left(\frac{g\sin\alpha}{q^2}\right)^{\frac{1}{3}}x\right)} \qquad (5)$$

2.13 Selection of step height:

For Roller Compacted Concrete (RCC) dams, the step height is usually one to four times the thickness of a compacted lift of typically 0.3m i.e. between 0.3m and 1.2m. Two main aspects have to be considered when selecting the step height are: 1. cavitations risk potential and 2. energy dissipation rate of a cascade.

To avoid cavitations damage to concrete faces a minimum value of a local air concentration of about 5 to 8% is accepted today by design engineers.

The step height selected should be such that for a given discharge, the required length of stilling basin should be a minimum. The Froude no. at the toe of the spillway governs the type of stilling basin.

It is recommended that optimum value of Fraude no. Fr at the toe of spillway should be 5.3, which gives the minimum length of stilling basin & which is adequate for all the discharges lower than the design discharge. The step height required for the downstream slope resulting in a Froude no of 5.3 are computed and are given below:

Table:

Slopes (h/l)	Step height (h)	Froude no. (Fr)
1V: 0.6H	h = dc/1.557	5.3
1V:0. 7H	h = dc/2.622	5.3
1V:0. 8 H	h =dc/4.01	5.3

Other approximation of step height is to assume trial step sizes as per fluid condition, which should be less than 1.25 dc for establishment of skimming flow (Rajaratnam 1990).

2.14 Selection of training wall height of stepped spillways:

For a stepped spillway, the considerable aeration leads to bulking of the flow, which has to be taken into account in the design of, stepped spillway-training walls (Side walls). The characteristic mixture flow depth d90 with a surface air concentration of 90% serves as a guide for the design in the aerated or white water region.

Hager and Boes (2000): Starting from the inception point of air entrainment, the air water mixture is described by a super critical backwater curve. Inserting the approximation of the uniform mixture flow depth:

$$\frac{d90}{dc} = 0.55(Frs)^{\frac{-1}{6}} \qquad (1)$$

with Froude no $Frs = \frac{q}{[g(\frac{S}{\sin\alpha})^3]^{\frac{1}{2}}}$ at the step, into the approximation of the differential equation of back water curve (Hager & Boes 2000) yields:

$$d90(x) = 0.55(\frac{q^2 h}{g\sin\alpha})^{\frac{1}{4}} \tanh(\frac{gh\sin\alpha(x-Li)}{3q}) + 0.42(\frac{q^{10}h^3}{(g\sin\alpha)^5})^{\frac{1}{18}} \quad (2)$$

where Li is the length of inception point from crest:

$$Li = 9.72\frac{q^{0.86}\cos\alpha}{g^{0.43}(\sin\alpha)^{0.43}h^{0.29}} \quad (3)$$

The designed training wall height, h_d:

$$h_d = \eta d_{90} \quad (4)$$

where η = factor of safety =1.2 for concrete dams with no concern of erosion on the downstream face and 1.5 in case of emergency spillway on embankment dams prone to erosion (taking into account the increase of the spray height in the prototype due to higher turbulence).

Other method of calculation of height of side wall:

$$\frac{ya}{y} = [1 + 2(C - 0.25)^2] \quad (1)$$

where C = mean air concentration =$0.75\sin\alpha^{0.75}$ (Hager 1991)
ya=aerated flow depth
y=depth of water without mixing of air
α =slope of stepped spillways
so the height of side wall will be:

$$hd = \eta y \quad (2)$$

where η is the factor of safety as described above

2.15 Comparison between nappe and skimming flow regimes regarding energy dissipation:

If the spillways channel is long enough (i.e. if uniform flow conditions are obtained) and for identical conditions and for large dam heights (Hdam/dc > 35 and slope > 30°) the skimming flow regime dissipates more energy than nappe flow regime. On steeper chutes the flow aeration reduces the flow resistance and hence the rate of energy dissipation.

In short chutes and small height dams the nappe flow regime dissipate more energy than skimming flow regime.

CHAPTER- 3

EXPERIMENTAL STUDY OF FLOW PATTERNS IN MULTI-SLOPE STEPPED SPILLWAYS

Chapter-3

Experimental study of flow patterns in multi-slope stepped spillways

3.1 Introduction:

Multi-slope stepped spillways are those chute/spillways, which have more than one longitudinal channel slopes with different step geometries in their faces.

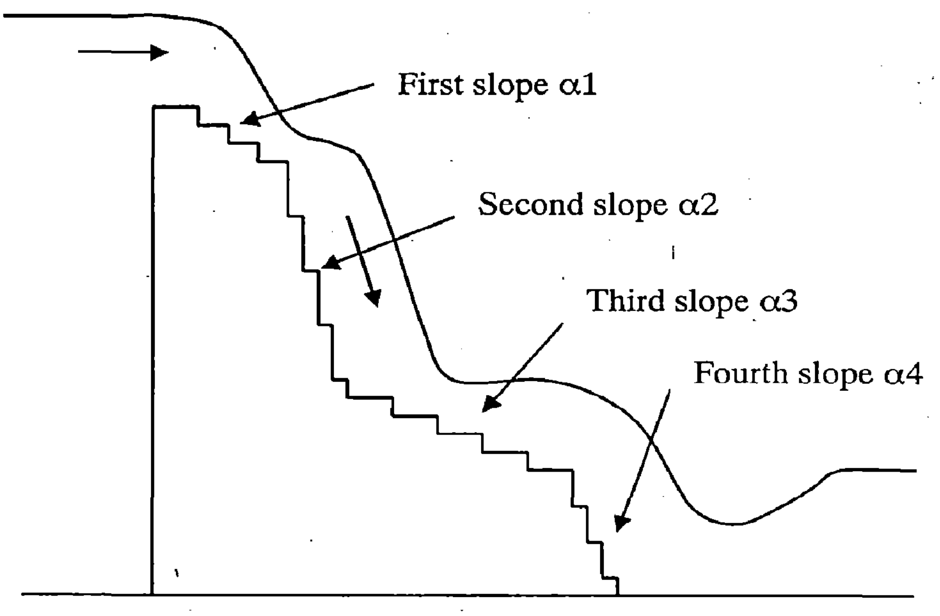


Fig. 29 Multi-slope stepped spillways: With four L-slopes

The experimental study of flow patterns as envisaged under the objectives were conducted in River Engineering Laboratory of WRDTC, IIT, Roorkee. The suppressor plates, the experimental set-up, procedures, observation records, analysis of results, and flow patterns are described briefly below.

3.2 Model laws (Similarity laws) and scale ratios

Models are the small replicas of the actual structure (i.e. the prototype) where model studies are usually conducted to find solutions to numerous complicated problems in hydraulic engineering and fluid mechanics. The results obtained in the model studies correctly represent the behavior of the prototype. The results may be transferred to the prototype by the use of model laws, which may be developed, from the principles of different similarities (Geometric, Kinematics and Dynamic similarities), which are described briefly below.

a. **Geometric similarity**: For geometric similarity to exist between the model and the prototype the ratio of corresponding lengths in the model and in the prototype must be same and the included angles between two corresponding sides must be the same. Models, which are not geometrically similar, are known as geometrically distorted models. The ratios are defined as scale ratios and may be written as:

$$\text{Length scale ratio} = Lr = \frac{Lm}{Lp} = \frac{bm}{bp} = \frac{dm}{dp} \text{ etc} \qquad (1)$$

Area scale ratio $= Ar = \frac{Am}{Ap} = \left(\frac{Lm * bm}{Lp * bp}\right) = Lr^2$ (2)

Volume scale ratio $= Vr = \left(\frac{Lm * bm * dm}{Lp * bp * dp}\right) = Lr^3$ (3)

in which the subscripts m and p correspond to model and prototype respectively.

b. **Kinematic similarity**: Kinematic similarity is similarity of motion. If at the corresponding (or homologous) points in the model and in the prototype, the velocity or the acceleration ratios are same and the velocity or acceleration vectors point in the same direction, the two flows are said to be kinematically similar. A few useful scale ratios are as follows:

Time scale ratio $= Tr = \frac{Tm}{Tp}$ (1)

Velocity scale ratio $= Vr = \frac{Vm}{Vp} = \frac{\frac{Lm}{Tm}}{\frac{Lp}{Tp}} = \frac{Lr}{Tr}$ (2)

Acceleration ratio $= ar = \frac{am}{ap} = \frac{\frac{Lm}{Tm^2}}{\frac{Lp}{Tp^2}} = \frac{Lr}{Tr^2}$ (3)

Discharge scale ratio $= Qr = \frac{Qm}{Qp} = \frac{\frac{Lm^3}{Tm}}{\frac{Lp^3}{Tp}} = \frac{Lr^3}{Tr}$ (4)

c. **Dynamic similarity:** It is the similarity of forces. The flows in the model and in the prototype are dynamically similar if at all the corresponding points, identical types of forces are parallel and bear the same ratio. In dynamic similarity, the force polygons of the two flows can be superimposed by change in force scale.

In the problems concerning fluid flow, the forces (mass*acceleration, Ma) acting may be one or a combination of the several of the following forces:

(i) Inertial forces, Fi
(ii) Friction or viscous forces, Fv
(iii) Gravity forces, Fg
(iv) Pressure forces, Fp
(v) Elastic forces, Fe
(vi) Surface tension forces, Fs

The ratio of the inertia forces of the two systems must also be equal to the ratio of individual component forces i.e. the following relationship will be developed:

(i) $\left(\frac{Ma}{Fv}\right)_m = \left(\frac{Ma}{Fv}\right)_p$ (1)

(ii) $\left(\frac{Ma}{Fg}\right)_m = \left(\frac{Ma}{Fg}\right)_p$ (2)

(iii) $\left(\frac{Ma}{Fp}\right)_m = \left(\frac{Ma}{Fp}\right)_p$ (3)

(iv) $\left(\frac{Ma}{Fe}\right)_m = \left(\frac{Ma}{Fe}\right)_p$ (4)

(v) $\left(\frac{Ma}{Fs}\right)_m = \left(\frac{Ma}{Fs}\right)_p$ (5)

It may thus be mentioned that when the two systems are geometrically, kinematically and dynamically similar, then they are said to be completely similar or complete similitude exists between the two systems.

Model laws:

Types of model laws:

(i) Reynolds model law
(ii) Froude model law
(iii) Euler model law
(iv) Mach model law
(v) Weber model law

Among these the brief descriptions of Reynolds, Froude, and Weber model laws are given below:

(i) **Reynolds model law**: For the flows where in addition to inertia, viscous force is the only other predominant force, the similarity of flow in the model and its prototype can be established if the Reynolds number (Rn) is same for both the systems. This is known as Reynolds model law, according to which:

$$(Rn)_m = (Rn)_p$$

$$\text{or, } \frac{\rho_m V_m L_m}{\mu_m} = \frac{\rho_p V_p L_p}{\mu_p} \quad (1)$$

$$\text{or, } \frac{\rho_r V_r L_r}{\mu_r} = 1 \quad (2)$$

$$\text{or, } \frac{V_r L_r}{\mu_r} = 1 \quad (3)$$

(ii) **Froude model law :** When the force of gravity can be considered to be the only predominant force which controls the motion in addition to the force of inertia, the similarity of the flow in any two such systems can be established if the Froude number for both the systems is the same. This is known as Froude model law according to which;

$$(Fr)_m = (Fr)_p$$

$$\text{or, } \frac{Vm}{\sqrt{g_m L_m}} = \frac{Vp}{\sqrt{g_p L_p}} \quad (1)$$

$$\text{or, } \frac{Vr}{\sqrt{g_r L_r}} = 1$$

$$\text{or, } V_r = \sqrt{g_r L_r} \quad (2)$$

or, $V_r = \sqrt{L_r}$ since gr = 1 (3)

(iii) **Weber model law:** When surface tension effects predominate in addition to inertia force the pertinent similitude law is obtained by equating the Weber number for the model and its prototype, which is known as Weber model law. Thus according to this model law,

(We)m = (We)p

$$\text{or, } \frac{V_m}{\sqrt{\left(\frac{\sigma_m L_m}{\rho_m}\right)}} = \frac{V_p}{\sqrt{\left(\frac{\sigma_p L_p}{\rho_p}\right)}} \qquad (1)$$

$$\text{or, } \frac{Vr}{\sqrt{\left(\frac{\sigma_r L_r}{\rho_r}\right)}} = 1 \qquad (2)$$

Types of models:

(i) Undistorted models
(ii) Distorted models

(i) **An undistorted model** is that which is geometrically similar to its prototype that is, the scale ratios for corresponding linear dimensions of the model and its prototype are same.

(ii) **Distorted models** are those in which one or more terms of the models are not identical with their counterparts in the prototype.
A distorted model may have either geometrical distortion, or material distortion, or distortion of hydraulic quantities or a combination of these.

Scale ratios:

Scale ratios for models governed by Reynolds and Froude model laws:

Description of quantities	Scale ratios	
	Reynolds law	Froude law
Length	L_r	L_r
Velocity	$\frac{\mu_r}{L_r \rho_r}$	$L_r^{\frac{1}{2}} g_r^{\frac{1}{2}}$
Time	$\frac{L_r^2 \rho_r}{\mu_r}$	$\frac{L_r^{\frac{1}{2}}}{g_r^{\frac{1}{2}}}$
Acceleration	$\frac{\mu_r^2 L_r^3}{\rho_r^2}$	g_r
Discharge	$\frac{L_r \mu_r}{\rho_r}$	$L_r^{\frac{5}{2}} g_r^{\frac{1}{2}}$
Force	$\frac{\mu_r^2}{\rho_r}$	$\rho_r L_r^3 g_r$
Work, Energy and Torque	$\frac{\mu_r^2 L_r}{\rho_r}$	$\rho_r L_r^4 g_r$
Pressure intensity	$\frac{\mu_r^2}{L_r^2 \rho_r}$	$\rho_r g_r L_r$
Power	$\frac{\mu_r^3 L_r}{\rho_r^2}$	$\rho_r g_r^{\frac{3}{2}} L_r^{\frac{7}{2}}$

3.3 The suppressor plate:

The suppressor plate is that structure which is placed above the surface of flow of water above the junction point of the two different slopes of multislope stepped spillways attached or fixed to the side walls of the spillways to suppress, concentrate and align the sprayed flow uniformly at a constant depths D/S of the spillways channels so that the height of the side walls can be reduced comparatively to the side walls of stepped channels without suppressor.
The design of suppressor can be of hydraulic and structural. The hydraulic design is governed by the toe velocity and the clear water depth of the chute just U/S of the junction points of the slopes of the spillways. The structural design is governed by the uplift water pressure head at the underneath of the suppressor where the surface of the flow of water touches the suppressor. This uplift water pressure is taken as uniformly distributed load across the width wise of the suppressor and designed like a beam fixed at the two ends at the sidewalls of the spillways.
The suppressors are of different types such as circular, elliptical, angular etc according to the requirements suitability of the working sites. Some design principles are given below.

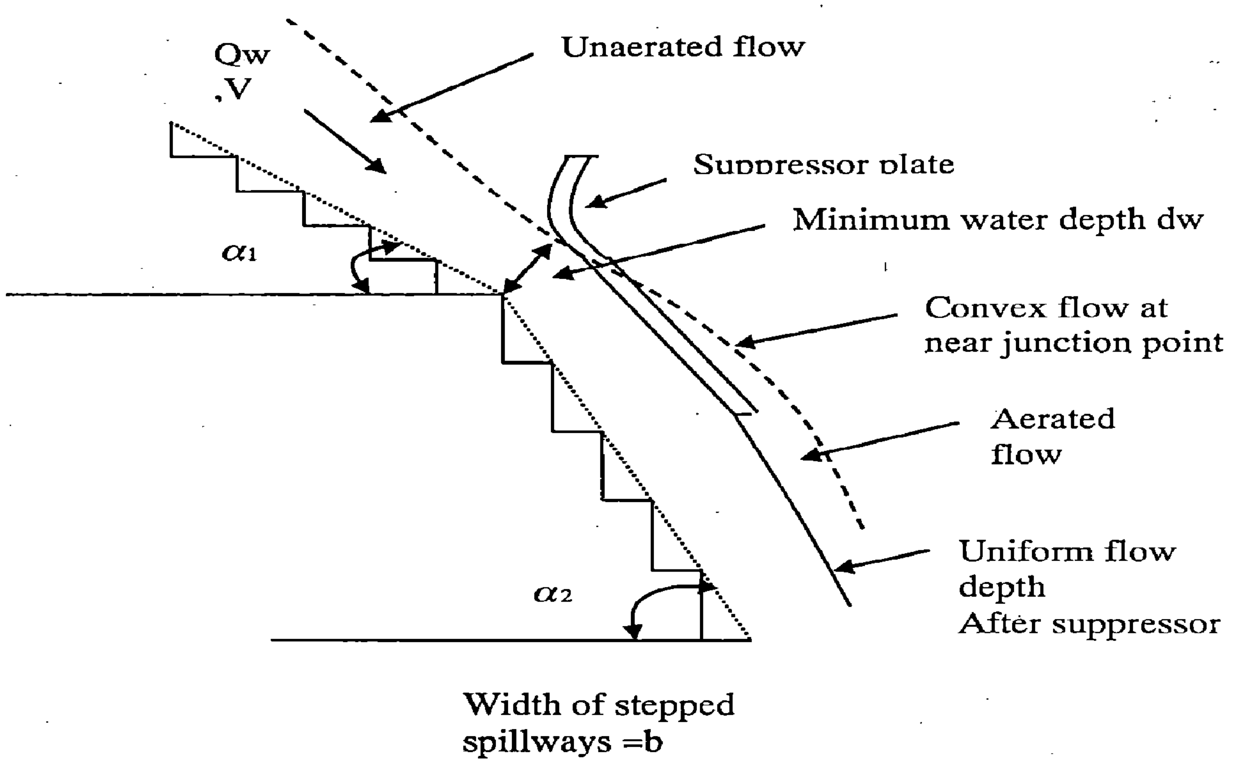


Fig.30 Multislope stepped spillways with suppressor plate: Showing the effect of the plate in making the flow with uniform depths after it.

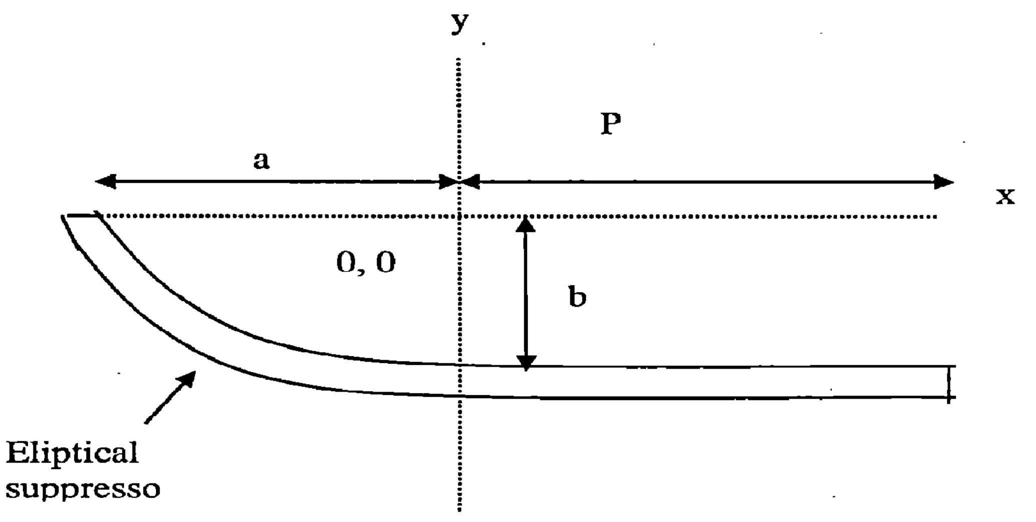
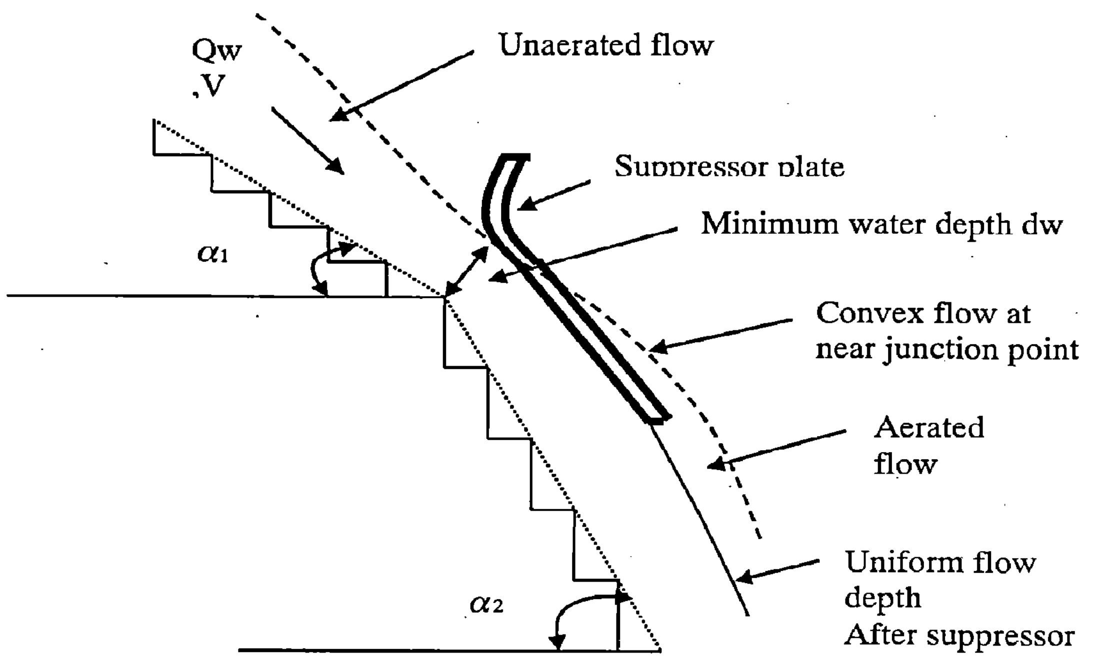


Fig 31 Section of elliptical suppressor plate (general)

3.3.1. Design of suppressor plates:

The design of suppressor can be of **hydraulic and structural**. The hydraulic design is governed by the toe velocity and the clear water depth of the chute just U/S of the junction points of the slopes of the spillways. The structural design is governed by the uplift water pressure head at the underneath of the suppressor where the surface of the flow of water touches the suppressor. This uplift water pressure is taken as uniformly distributed load across the width wise of the suppressor and designed like a beam fixed at the two ends at the sidewalls of the spillways.

The suppressors are of different **types** such as **circular, elliptical, angular** etc according to the requirements suitability of the working sites. Some design principles are given below.



Width of stepped
spillways =b

Fig.32 Multislope stepped spillways with suppressor plate: Showing the effect of the plate in making the flow with uniform depths after it.

(i). Design of elliptical suppressor:

Suppose we have the design discharge, Q velocity of flow u/s of the junction point where the suppressor is to be placed, Vw the depth of clear water at the point, dw the slope of spillways, α. Suppose a and b are the horizontal distance covered by the incoming flow with the velocity of flow Vw and vertical distance covered by the flow in the trajectory path (projectile motion of the flow) respectively then we have;

$$a = \frac{Vw^2}{2g}\sin 2\alpha \qquad (1)$$

$$b = \frac{Vw^2}{2g}\sin^2\alpha \qquad (2)$$

P = straight portion
=equal to dw
= equal to a
= equal to (a+dw) (3)

For elliptical design,

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \qquad (4)$$

from this equation the ordinates of elliptical portion of suppressor can be designed i.e.

$$\frac{y^2}{b^2} = 1 - \frac{x^2}{a^2}$$

$$\text{or } y = b\sqrt{(1 - \frac{x^2}{a^2})} \qquad (5)$$

Putting different values of x we can get different values of y.

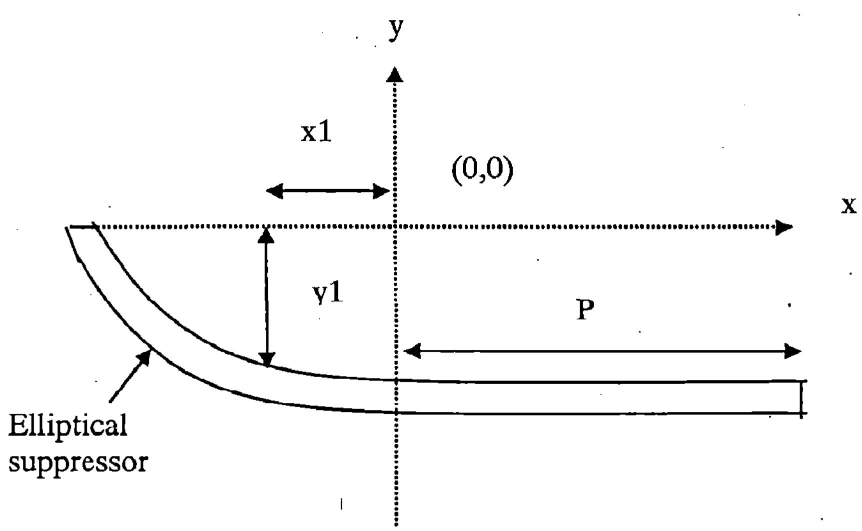


Fig. 33 Section of designed elliptical suppressor plate

(ii). Design of circular suppressor:

As in design of elliptical suppressor suppose a and b are the horizontal distance covered by the incoming flow with the velocity of flow Vw and vertical distance covered by the flow in the trajectory path (projectile motion of the flow) respectively then we have;

$$a = \frac{Vw^2}{2g}\sin 2\alpha \qquad (1)$$

$$b = \frac{Vw^2}{2g}\sin^2\alpha \qquad (2)$$

P = straight portion
=equal to dw
= equal to a
= equal to (a+dw) (3)

Let us take the first junction point of the multislope spillways where the milder slope of the chute meets with the steeper slope of the chute. At this point the flow pattern will be curved and sprayed type of convex nature as shown in fig. below. When the flow leaves the milder slope the flow starts moving with its residual momentum energy and follows the trajectory path and after consumption of the energy the flow starts falling vertically downward to meet the d/s chute slope. If we join the tangents of the curved path drawn at the starting of the curve and end point of the curve then we can calculate the radius of curvature by the following concepts:

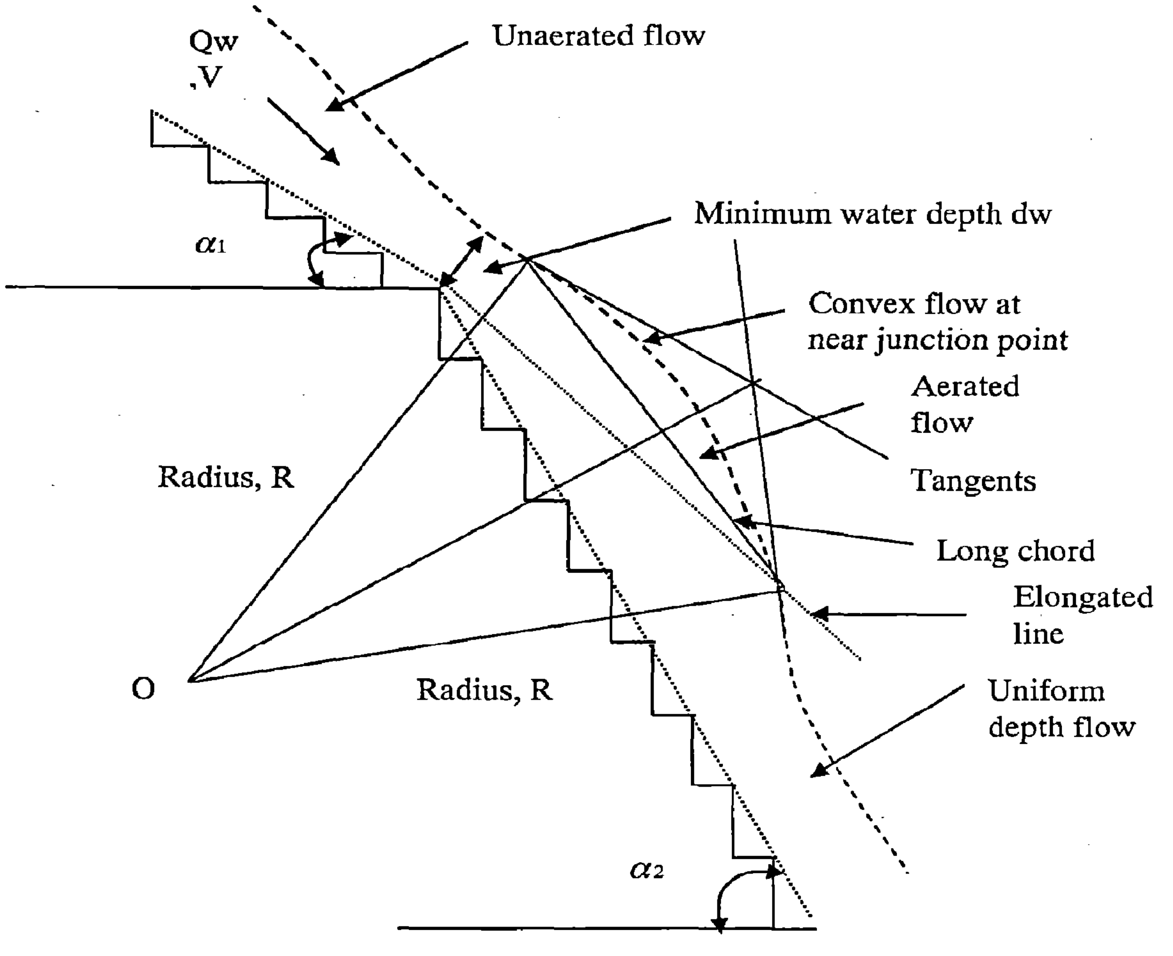


Fig.34 Multislope stepped spillways with curved (convex) flow at the junction point: Showing the elements of curve setting to find out the radius of curvature of flow.

Computation of radius of curvature of circular suppressor plate using the "simple curve setting" methods:

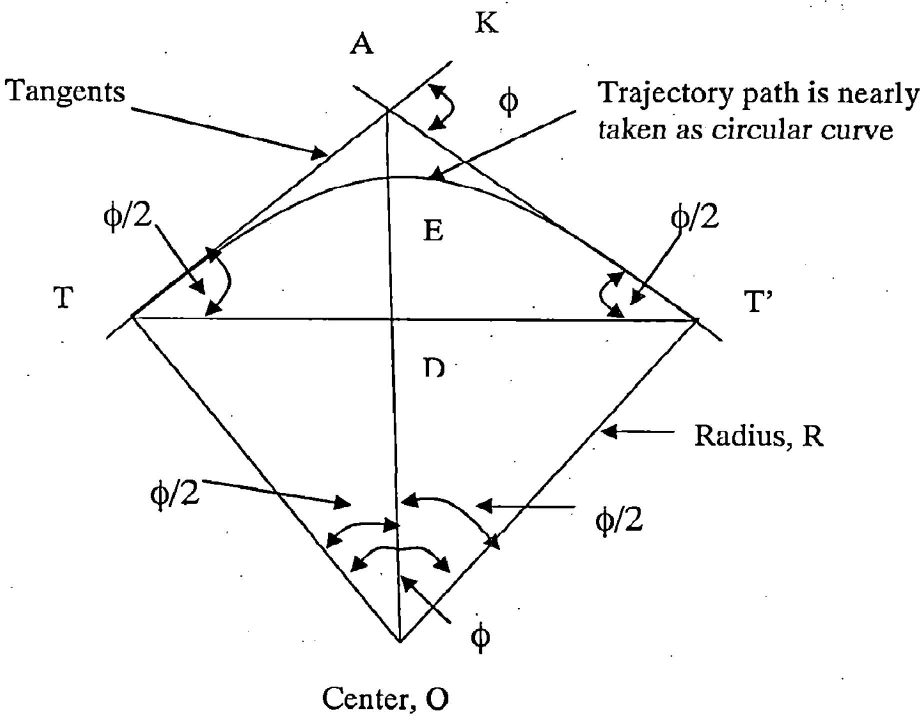


Fig. 35 Elements of simple circular curve

Notations:
T= starting point of curve and tangent TA can be drawn.
T'=end of curve and tangent T'A can be drawn
A=the point of intersection
$\angle$KAT'= ϕ, is the angle of deflection
TT'=long chord
O=center of circular curve
OT=OT'= radius R, of circular curve
D=is the point of intersection on the long chord by the line joining A to O
DE=distance of apex curve from long chord
AE= apex distance

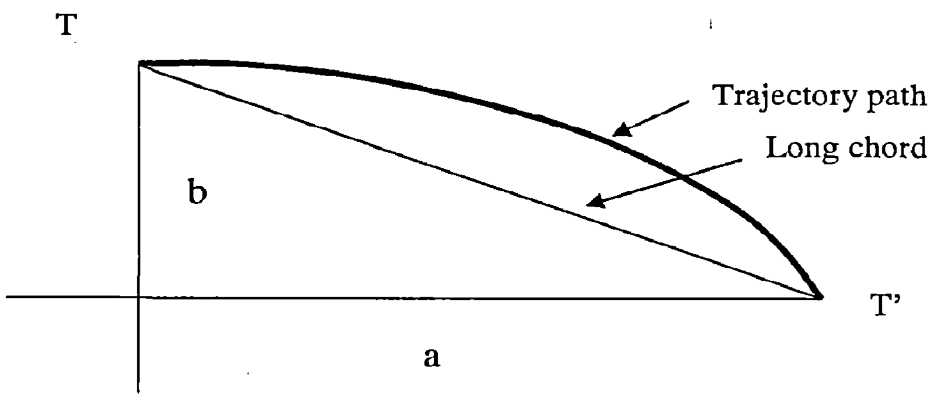


Fig. 36 Detail of convex curve at the junction point

Now long chord = TT'= $\sqrt{(a^2+b^2)}$

$$=\sqrt{(\frac{V^2}{2g}\sin 2\alpha)^2+(\frac{V^2}{2g}\sin^2\alpha)^2} \qquad (1)$$

where α is the spillway slope. And

$$\tan\frac{\phi}{2}=\frac{b}{a}=\frac{\frac{V^2}{2g}\sin 2\alpha}{\frac{V^2}{2g}\sin^2\alpha} \qquad (2)$$

From right angle triangle Δ TOD,

$$\frac{TD}{TO}=\sin\frac{\phi}{2}$$

and we know TT'= 2 TD

$$=2TO\sin\frac{\phi}{2}$$

$$=2R\sin\frac{\phi}{2} \qquad (3)$$

From equations (1) and (2) we have

or $$\sqrt{(\frac{V^2}{2g}\sin 2\alpha)^2+(\frac{V^2}{2g}\sin^2\alpha)^2} = 2R\sin\frac{\phi}{2}$$

or $$R=\frac{\sqrt{(\frac{V^2}{2g}\sin 2\alpha)^2+(\frac{V^2}{2g}\sin^2\alpha)^2}}{2\sin\frac{\phi}{2}} \qquad (4)$$

The value of ϕ can be found out by equation (2). Other parameters such as V and α are known. Therefore the equation (4) gives the radius of the curve, which can be used as a radius of curvature for the circular suppressor plate. The value of P can be taken as in elliptical suppressor plate.

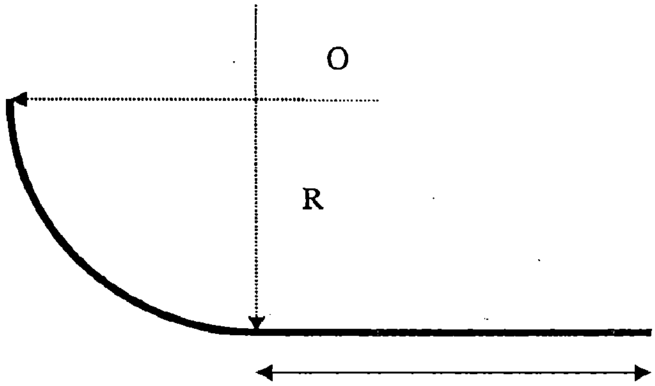


Fig. 37 Section of designed circular suppressor plate

(iii). Design of angular suppressor:

The horizontal distance and vertical distance covered by the flow can be taken as the parameter to find out the slope of angular suppressor plate. i.e.

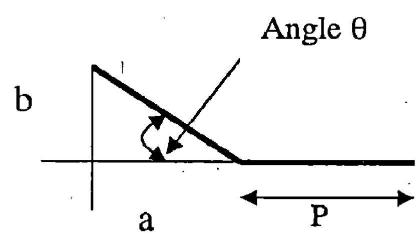


Fig. 38 Section of designed angular suppressor plate

Now the angle θ can be computed as

$$\tan\theta = \frac{b}{a} = \frac{\frac{V^2}{2g}\sin 2\alpha}{\frac{V^2}{2g}\sin^2\alpha} \qquad (1)$$

The value of P can be taken as in elliptical suppressor plate. The horizontal and the vertical lengths of the angular suppressor are a and b respectively. The angle θ is calculated by the equation (1).

3.3.2 Positioning of the suppressor plate

The suppressor plates are placed at the junction point of the two changed slopes of the spillway channel (i.e. it can be at the convex region or at concave region). The straight portion of the suppressor plate (denoted by letter P) is placed parallel to the d/s slope of the channel. The front tip of the curved / ellipsoid / angled portion of the suppressor plate should be placed in such a way that the maximum height of the curved flow at the convex / concave region shouldn't overflow the tip of the suppressor plate. The placement height of the suppressor plate should be fixed to the water depth formed at the toe of the respective slope of the spillway channel.

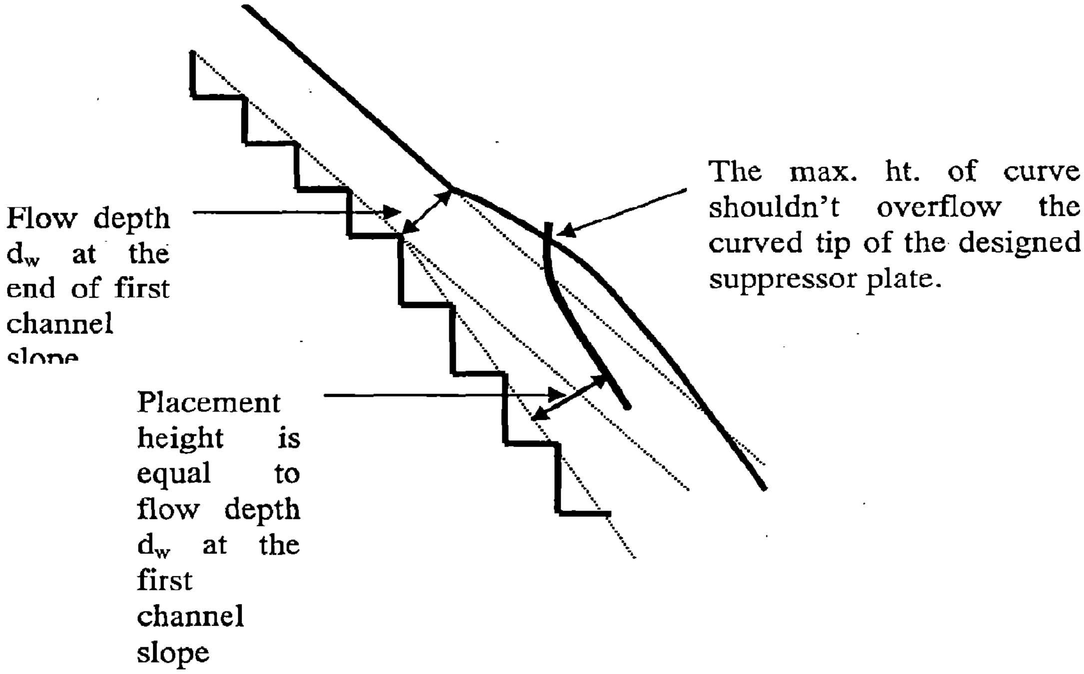


Fig.39. Placement position of suppressor plate at the convex junction point of the multislope stepped spillways

3.4 Experimental set up:

A schematic view of the experimental set up is shown in fig. 41 below. Experiments were conducted in a recirculating pipe with reservoir tank, water collection tank, and multislope stepped spillways systems (with the three slopes), which is the model of Rammam hydel project stage-II, Darjilling, West Bengal electricity board, India. The model is geometrically similar model with the scale ratio of 1:15. The model's Reynold's number, Re Froude no., Fr and Weber no.,W are $1*10^5$, 3.72 and 178 respectively. The prevalent flow regime in this model is skimming flow regime.

The set up consists of venturimeter pipe with mercury manometer, which is used to measure the discharge flowing through the pipe over the stepped spillways.

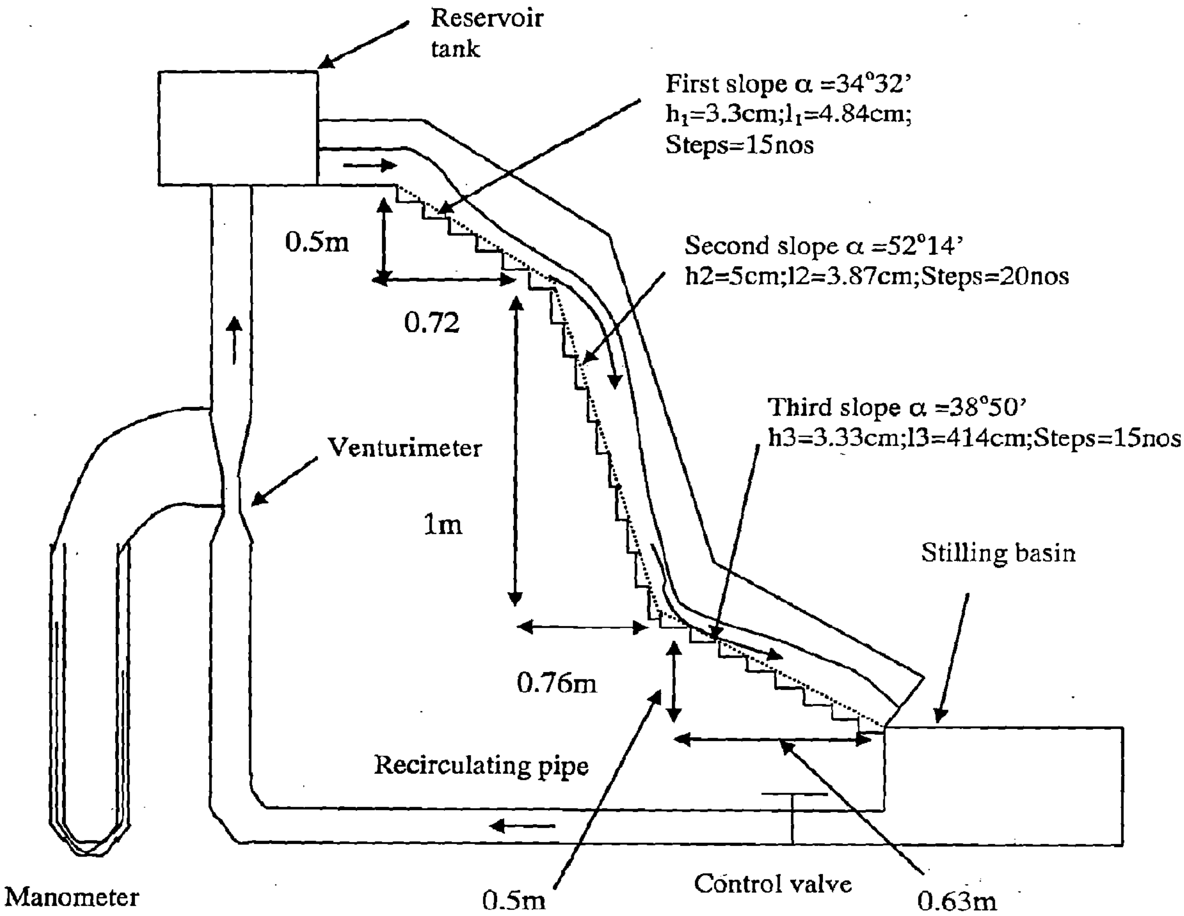


Fig.40 Experimental set up: Multislope stepped spillways

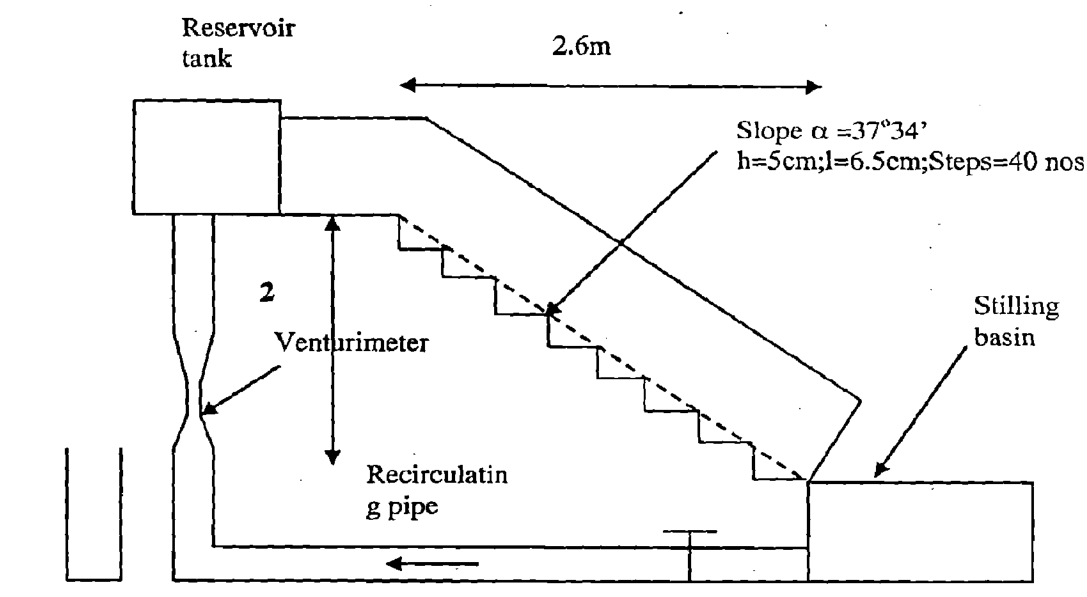


Fig.41 Experimental set up: Monoslope stepped spillways

3.5 Experimental procedure:

Before starting the experiments, the manometer reading (attached to venturimeter) was adjusted to zero settings. All the points at the channel bottom of the spillways where the water pressures were to be observed for the study of cavitations risk, were joined with piezometers of small pipes. The air bubbles inside the piezometric pipes were taken out by keeping water into the piezometers. After completing these works different discharge rates ranging from 4 to 20 lps of flow of water were allowed to pass through the spillways and then the water depths perpendicular to pseudo bottom and piezometric head were observed and noted down. The flow patterns such undular and glassy flow, gradually varied flow, recirculating vortex flow, inception point of air entrainment with bubbles, uniform flow, spray of the flow, formation of air cavities, convexity and concavity of flow etc were observed at the smaller and higher flow rates. Rate of head loss or energy dissipation at the spillways and residual head at the toe of spillways were also studied and compared.

3.6 Analysis of results:

3.6.1 Introductions:

The experimental data were collected for the study of flow patterns, rate of energy dissipation, residual energy at the toe of the spillways, cavitations risk in the spillways and are given in tabular forms below in this section.

3.6.2 Experimental data and calculations:

3.6.2.1 Venturimeter Calculation:

$h = x*(\gamma/\gamma_w-1)$ where x is difference of level of Hg in manometer limbs.

$h = x*(13.6/1-1)$

$h = x*(13.6-1)$

$\mathbf{h = 12.6*x}$

We have,

$Q = \{C_d*a_1*a_2*(2gh)^{1/2}\}/(a_1^2-a_2^2)^{1/2}$

Where,

$a_1=PI/4*(0.1)^2=7.854*10^{-3}=0.007854$

$a_2=PI/4*(0.06)^2=2.827*10^{-3}=0.002827$

$C_d=0.98$

Now,

$Q=\{0.98*7.854*2.827*10-6*(2*9.81*1206x)^{1/2}\}/\{(7.854*10^{-3})^2-(2.827*10^{-3})^2\}^{1/2}$

$Q=0.0466*(x)^{1/2}$

$x=460.5*Q^2$ in MKS System

Table of relation between x & Q:

Sn	Q(m3/s)	x(m)	x(cm)
1	0.004	0.0074	0.74
2	0.006	0.0166	1.66
3	0.008	0.0295	2.95
4	0.01	0.0461	4.61
5	0.012	0.0663	6.63
6	0.014	0.0903	9.03
7	0.016	0.1179	11.79
8	0.018	0.1492	14.92
9	0.02	0.1842	18.42

3.6.2.2 Experiment no.1: (Water flow depths(perpendicular to pseudobottom) in multislope stepped spillways) : Without use of suppressor

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	2	2	2	2	2	2.3	2.4	2.5	2.5	2.5	2.6	2.6	2.8	3					
					Min.	2	1.9	1.9	1.9	1.9	1.9	1.9	2	2	2	2	2	2	2	2					
					Max.	3	2	2	2	2	2	2.3	2.4	2.5	2.5	2.5	2.6	2.6	2.8	3					
					Min.	2	1.9	1.9	1.9	1.9	1.9	1.9	2	2	2	2	2	2	2	2					
					Aver.(d_{wps})	2.6	2	2	2	2	2	2.1	2.2	2.3	2.25	2.3	2.3	2.3	2.4	2.5					
					Inception																				
					length(cm)	46																			
					Flow patt	No air cavities,weak recirculating vortices were generated in all steps.																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	5	6.5	7.5	7.5	7.5	7	6.5	6	5.5	5.5	5.5	5	4.5	4.5	4.5	4	4	3.8	3
					Min.	2	3.5	5	6	6	6	5.5	5	4	3.8	3.5	3.5	3.5	3.5	3.5	3.5	3	3	3	2.5
					Max.	3.5	5	6.5	7	8	7.5	7	6.5	6	5.8	5.5	5.5	5.5	5	4.5	4.5	4.5	4	3.6	3
1	1.65	0.006	0.2	0.03	Min.	2	3.5	5	5.5	6	5.8	5.5	5	4	4	3.5	3.5	4	4	3.5	3.4	3.5	3	2.8	2.5
					Aver.(d_{wps})	2.8	4.3	5.8	6.5	6.9	6.7	6.3	5.8	5	4.78	4.5	4.5	4.5	4.25	4	4	3.8	3.5	3.3	2.75
					Inception																				
					length(cm)	65																			
					Flow patt	100% air cavities					25%air			50% rec.vortex								100% recir.vortices			
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	3	5.5	7	7.5	8	7.5	7.5	6.5	6	5	4	3	3	3					
					Min.	2.5	2.5	3.5	4.5	5	5	4.5	4.5	4	4	3	2.5	2.5	2.5	2.5					
					Max.	3.5	3	5	6.5	6.5	6.7	6.8	7	6	5.5	4.5	4	3	3	3					
					Min.	2.5	2.5	3	4	5	5.2	5.3	5	4.5	4.2	3	2.5	2.5	2.5	2.5					
					Aver.(d_{wps})	3	2.8	4.3	5.5	6	6.2	6	6	5.3	4.93	3.9	3.3	2.75	2.75	2.8					
					Inception																				
					length(cm)	50																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways $\alpha_1 = 34^{0}32'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.8	3.5	3.5	2.5	2.5	2.5	3	3	3	3	3	3	3	3	3					
					Min.	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2					
					Max.	3.8	3.5	3.5	2.5	2.5	2.5	3	3	3	3	3	3	3	3	3					
					Min.	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2					
					Aver.(d_{wps})	3.4	3.3	3.3	2.3	2.3	2.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Inception																				
					length(cm)	50																			
					Flow patt	No air cavities,weak recirculating vortices were generated in all steps.																			
					Slope of stepped spillways $\alpha_2 = 52^{0}14'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	5.5	7	8	8.5	8.5	8.5	8	7.5	6.5	6.5	6	6	6	6.5	5.5	5.5	5	4.6	4
					Min.	2.5	4	6	6.5	6.5	6.5	7	6.5	6	5	4.5	4.5	4.5	4.5	4.5	4.5	4.2	4	4	3
					Max.	3.5	5	6.5	8	8.5	8.5	8.5	8	7	6.5	6.5	6	6	6	6.5	5.5	5.5	5	4.6	4
2	2.95	0.008	0.2	0.04	Min.	2.5	3.8	5.5	6	6.5	6.5	7	6.5	5	5	4.5	4.5	4	4	4.5	4.5	4.2	4	4	3
					Aver.(d_{wps})	3	4.6	6.3	7.1	7.5	7.5	7.8	7.3	5.5	5.75	5.5	5.3	5.13	5.13	5.5	5	4.9	4.5	4.3	3.5
					Inception																				
					length(cm)	90																			
					Flow patt	100% air cavities					25%air			50% rec.vortex								100% recir.vortices			
					Slope of stepped spillways $\alpha_3 = 38^{0}50'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	3.5	5	6.5	7.5	7.5	7.5	7.5	7	7	7	6	5.5	4	4					
					Min.	3	3	3.5	4.5	5.5	5.5	5.5	5.5	5	5	4.5	4.5	3.5	3.5	3.5					
					Max.	3.5	3	4.5	6.5	6.5	7.5	7.5	7.5	7	7	6	6	5	4.5	4.5					
					Min.	2.5	2.5	3	4.5	5	5.5	5.5	5.5	5	5	4.5	4.5	3.5	3.5	3.5					
					Aver.(d_{wps})	3.3	3	4	5.5	6.1	6.5	6.5	6.5	6	6	5.5	5.3	4.38	3.88	3.9					
					Inception																				
					length(cm)	50																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	5	4	3	3	3	3	3	4	4	4.5	4.5	4.5	4.5	4.5					
					Min.	2.5	2.5	3.5	2.8	2.8	2.8	2.8	2.5	2.5	2.5	3	3	3	3	3					
					Max.	5	5	4	3	3	3	3	3	3	3	3	3.5	3.5	3.5	3.5					
					Min.	2.5	2.5	3.5	2.8	2.8	2.8	2.8	2.5	2	2	2.5	2.5	2.5	2.5	2.5					
					Aver.(d_{wps})	3.8	3.8	3.8	2.9	2.9	2.9	2.9	2.8	2.9	2.88	3.3	3.4	3.38	3.38	3.4					
					Inception																				
					length(cm)	50																			
					Flow patt	No air cavities,weak recirculating vortices were generated in all steps.																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	6	7	8	9	9	9.5	10	11	11	10	9	8	7	7	7	7	6.5	6	6
					Min.	3	4	5	5.5	6.5	6.5	6.5	7	7	7	6	5	5	4.5	4	4	4	3.5	3.5	3.5
					Max.	4	6	7	8	9	9	9.5	9.5	10	10	9	8.5	7	6.5	6.5	6.5	6.5	6.5	6	6
3	4.61	0.01	0.2	0.05	Min.	3	4	5	5.5	6.5	6.5	6.5	6.5	6.5	6.5	5	4.5	4	4	3.5	3.5	3.5	3.5	3.5	3.8
					Aver.(d_{wps})	3.5	5	6	6.8	7.8	7.8	8	8.3	5.5	8.63	7.5	6.8	6	5.5	5.3	5.3	5.3	5	4.75	4.83
					Inception																				
					length(cm)	90																			
					Flow patt	100% air cavities					25%air			50% rec.vortex								100% recir.vortices			
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	4	5	7	8	8	9	10	9	8	8.5	8.5	7	7	7					
					Min.	4	3	4	4.5	5	5.5	5.5	6	6	5.5	5	5	4	4	4					
					Max.	5	4	4.5	5.5	6.5	7	7	7.5	7.5	7.5	7	7	6.5	5.5	5.5					
					Min.	3.5	2.5	3.5	4	4.5	4.5	4.6	5	4.6	4.6	4.5	4	4	3.5	3.5					
					Aver.(d_{wps})	4.4	3.4	4.3	5.3	6	6.3	6.5	7.1	6.8	6.4	6.3	6.1	5.38	5	5					
					Inception																				
					length(cm)	60																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	6	5	5	5	5	4	4	4	4	4	4	4.5	4.5	4.5					
					Min.	5	5	4	4	4	4	3	3	3	3	3	3.5	3.5	3.3	3					
					Max.	6	6	5	5	5	5	4	4	4	4	4	4.2	4.2	4.2	5					
					Min.	5	5	4	4	4	4	3	3	3	3	3	3.2	3.2	3.2	3.7					
					Aver.(d_{wps})	5.5	5.5	4.5	4.5	4.5	4.5	3.5	3.5	3.5	3.5	3.5	3.7	3.85	3.8	4.1					
					Inception																				
					length(cm)	60																			
					Flow patt	No air cavities,weak recirculating vorticesup to 12thstep&strong vortices onwards.																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	7	8.5	10	11	11	11	11	12.5	12.5	12	11.5	11	10	10	9.5	9.5	8	7	6.5
					Min.	3.5	5.5	6.5	8	9	9	9	9	10	10	9	8.5	6.5	6	6	6	5.5	5	5	5
					Max.	5.5	6.5	8.5	9.5	11	11	11	11	12.5	13	12	11.5	11.5	10.5	9.5	10	9.5	8	7	6.5
4	6.63	0.012	0.2	0.06	Min.	4	4.5	6.5	7.5	9.5	9	9	9	9.5	9.5	9	8.5	7	6.5	5.5	6.5	5.5	5	5	5
					Aver.(d_{wps})	4.5	5.9	7.5	8.8	9.9	10	10	10	11	11.3	11	10	9	8.25	7.8	8	7.5	6.5	6	5.75
					Inception																				
					length(cm)	120																			
					Flow patt	100% air cavities					25%air			50% rec.vortex			100% recir.vortices								
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	5	5.5	6.5	9	11	9.5	10	11	11.5	8.5	8	8	8	7.5					
					Min.	5	4	4	4.5	5.5	6	6	6.5	7	7	5	4	4	4	4.5					
					Max.	6.5	5.5	5.6	6.5	5.5	10	10	11	11.5	12	9	8.5	8.5	7.5	7.6					
					Min.	4.5	3.5	3.5	4	5	6.5	6.5	7	7.5	7.5	5.5	4.5	4.5	4	4					
					Aver.(d_{wps})	5.5	4.5	4.7	5.4	6.3	8.3	8	8.6	9.3	9.5	7	6.3	6.25	5.88	5.9					
					Inception																				
					length(cm)	70																			
					Flow patt	100% recirculating vortices in all steps																			

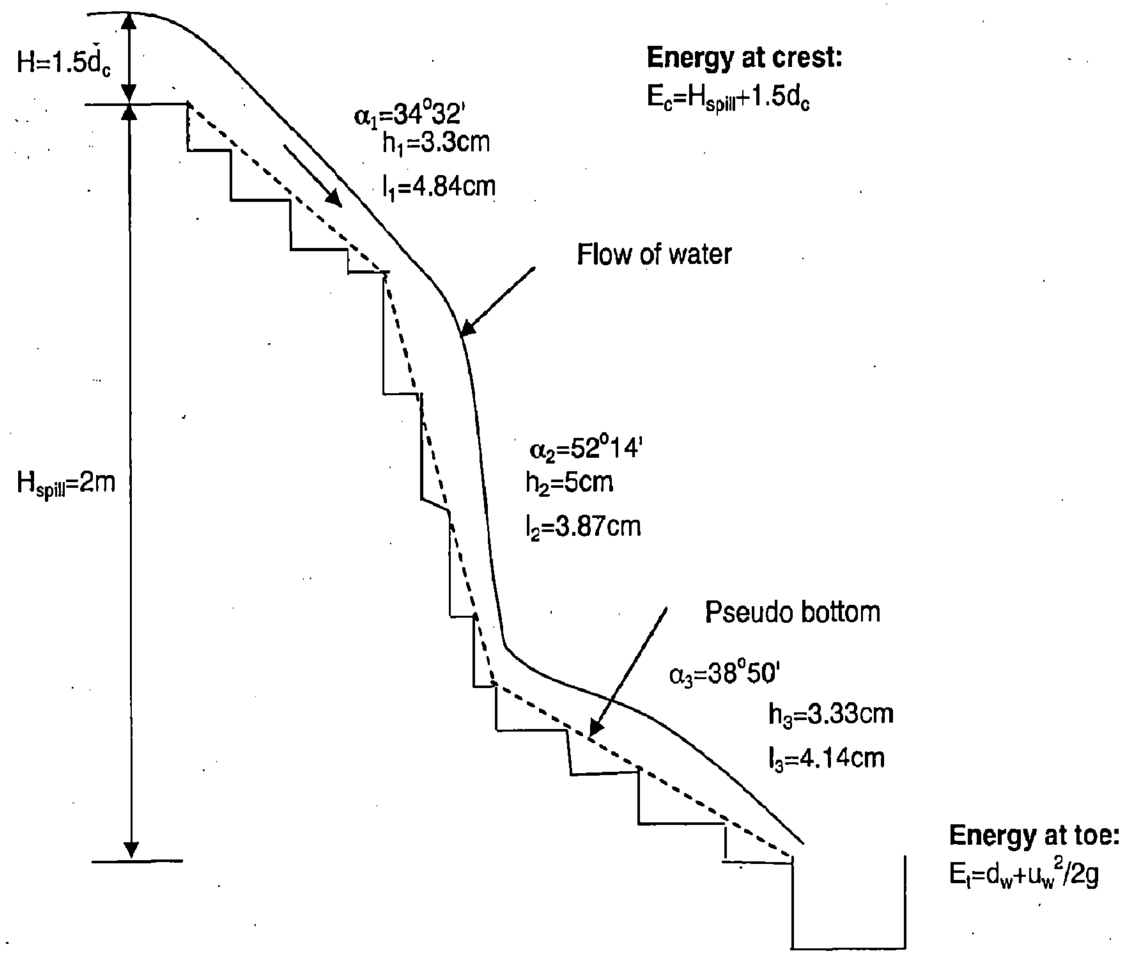
SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	7	6	6	6	5	5	5	5	5	4.6	4.6	4.6	4.6	4.6	4.6					
					Min.	4.5	4	4	4	3	3	3	3	3	3.5	3.5	3.5	3.5	3.5	3.5					
					Max.	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5					
					Min.	4	4	4	4	3	3	3	3	3	3.5	3.5	3.5	3.5	3.5	3.5					
					Aver.(d_{wps})	5.4	5	5	5	4	4	4	4	4	4.15	4.2	4.2	4.15	4.15	4.2					
					Inception																				
					length(cm)	60																			
					Flow patt	No air cavities,weak recirculating vorticesup to 14thstep&strong vortices onwards.																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	7	8.8	9.5	11	12	13	14	14	15	14	13	13	12	11	11	11	10	9.5	9.5
					Min.	3.5	5.5	7	8	9	9.5	10	11	11	11	10	10	9	7.5	7	6	6	5.5	5	5
					Max.	5.5	7	9	10	11	12	13	13	15	16	15	14	14	13	12	12	12	11	10	10
5	9.03	0.014	0.2	0.07	Min.	3.5	5.5	7	8	9.5	9	10	10	11	10.5	11	10	9.5	8	7	7	7	6	5.5	5.5
					Aver.(d_{wps})	4.4	6.3	8	8.9	9.9	11	11	12	13	13.1	13	12	11.4	10.1	9.3	9	9	8.1	7.5	7.5
					Inception																				
					length(cm)	120																			
					Flow patt	100% air cavities					25%air			50% rec.vortex			100% recir.vortices								
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	5.5	5	7	9	10	10	11	11	10	10	10	8.5	8	7					
					Min.	5	4	4	4.5	6	5.8	6.5	7.5	7.5	7	7	6.5	5.5	5	4.5					
					Max.	6.5	5.5	5	7.5	9	11	11	11	11	10	10	10	9	8	7.5					
					Min.	4.5	3.5	4.5	5	5.5	6	7	8	8	7	7	6.5	6.5	5.5	5					
					Aver.(d_{wps})	5.5	4.6	4.6	6	7.4	8.1	8.5	9.3	9.3	8.5	8.5	8.3	7.38	6.63	6					
					Inception																				
					length(cm)	80																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	7.5	7	7	6	6	5	5	5	4.5	4.5	4.5	4.8	5	5	4.8					
					Min.	6	6	5	5	5	4	4	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Max.	10	9	7	6	6	5	5	5	4.5	4.5	4.5	5	5	5	5					
					Min.	8	7	6	5	5	4	4	4	3.5	3.5	3.5	4	4	4	3.8					
					Aver.(d_{wps})	7.9	7.3	6.3	5.5	5.5	4.5	4.5	4.5	4	4	4	4.3	4.38	4.38	4.3					
					Inception																				
					length(cm)	60																			
					Flow patt	No air cavities,weak recirculating vorticesup to 12thstep&strong vortices onwards.																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	7	8.5	10	11	13	13	13	15	15	14	14	13	13	13	12	12	11	11	11
					Min.	3.8	5.5	7	8	9	10	11	11	12	12	11	10	9	9	9	9	7	6	6	6
					Max.	5.5	7	9	11	11	12	13	14	17	17	15	15	14	14	13	14	13	12	11	10.5
6	11.8	0.016	0.2	0.08	Min.	4	5.5	6.5	8	9.5	9.5	11	10	11	11	11	11	9	9	9	9	7	6	6	6
					Aver.(d_{wps})	4.6	6.3	7.8	9.1	9.9	11	12	12	14	13.8	13	13	11.3	11.3	11	11	9.8	8.8	8.5	8.38
					Inception																				
					length(cm)	120																			
					Flow patt	100% air cavities					90%air		50% rec.vortex				100% recir.vortices								
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	8	6.5	6	7.5	9.5	10	13	13	12	13	12	12	12	12	12					
					Min.	6	4.5	4.5	5	6	6.5	7	8	8.5	9	8	7	6	6	6					
					Max.	7.5	6	5.5	7.5	10	10	13	14	15	16	14	13	12	12	12					
					Min.	5.5	4.5	4.5	5	6	6	7	7.5	8	8	8	7	6	6	6					
					Aver.(d_{wps})	6.8	5.4	5.1	6.3	7.9	8.1	9.9	11	11	11.5	11	9.8	9	9	9					
					Inception																				
					length(cm)	80																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Manometre reading (x cm)	Disch. (Q) (cum)	Width of spillways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	9	9	7	7	5.5	5	5	5	5	5	5	5	5	5	5					
					Min.	7	7	5.5	5	4.5	4	4	4	4	4	4	4	4	4	4					
					Max.	9	9	7	7	5	5	5	5	5	5	5	5	5	5	5					
					Min.	7	7	5.5	5	4	4	4	4	4	4	4	4	4	4	4					
					Aver.(d_{wps})	8	8	6.3	6	4.8	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Inception																				
					length(cm)	60																			
					Flow patt	No air cavities,weak recirculating vorticesup to 6thstep&strong vortices onwards.																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5.5	7.5	9	11	11	12	13	14	15	15	15	15	13	13	13	13	13	12	12	12
					Min.	4	5.5	7	8.5	9	10	11	12	12	12	12	12	10	10	10	10	10	8	8	8
					Max.	6	8	9.5	11	11	12	13	14	15	16	16	16	14	14	14	13	13	12	12	12
7	14.92	0.018	0.2	0.09	Min.	4	6	7	8.5	9.5	10	11	11	11	12	12	12	11	11	11	10	9	9	8	8
					Aver.(d_{wps})	4.9	6.8	8.1	9.5	9.9	11	12	13	13	13.8	14	14	12	12	12	12	11	10	10	10
					Inception																				
					length(cm)	120																			
					Flow patt	100% air cavities					90%air		50% rec.vortex				100% recir.vortices								
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	8	7	6.5	8	10	12	13	13	13	14	14	12	12	11.5	12					
					Min.	6	5.5	5	6	6.5	8	7.5	8.5	9	9	9	8	8	8	8					
					Max.	7.5	6	6	8	11	12	13	13	14	15	15	14	13	13	13					
					Min.	5.5	5	5	6	7	7.5	8	8	9	9	9	9	8	7.5	8					
					Aver.(d_{wps})	6.8	5.9	5.6	7	8.6	9.8	10	11	11	11.8	12	11	10.3	10	10					
					Inception																				
					length(cm)	80																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways $\alpha_1 = 34^0 32'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	10	10	9.5	8	6.5	6	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5					
					Min.	8	8	7.5	6	4.5	4.5	4.5	4.5	4	4	4	4	4	4	4					
					Max.	10	9	9	8	6	6	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5					
					Min.	8	7.5	7	6	4.5	4.5	4.5	4	4	4	4	4	4	4	4					
					Aver.(d_{wps})	9	8.6	8.3	7	5.4	5.3	5	4.9	4.8	4.75	4.8	4.8	4.75	4.75	4.8					
					Inception																				
					length(cm)	60																			
					Flow patt	No air cavities,weak recirculating vorticesup to 3thstep&strong vortices onwards.																			
					Slope of stepped spillways $\alpha_2 = 52^0 14'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	7.5	9	11	11	12	13	14	14	15	15	14	14	13	12	12	11.5	11	11	11
					Min.	4.3	5.5	7	8.5	9	11	11	11	12	12	12	11	11	11	10	10	10	8	7.5	7.5
					Max.	6	8	9.5	11	12	14	14	15	15	16	16	16	14.5	14	14	13	13	12	11	11
8	18.42	0.02	0.2	0.1	Min.	4.5	6	7	8.5	9.5	11	11	11	11	12	12	11	10.5	11	11	10	9	8	7	7
					Aver.(d_{wps})	5.2	6.8	8.1	9.5	10	12	12	13	13	13.8	14	13	12.5	12.3	12	11	11	9.8	9.13	9.13
					Inception																				
					length(cm)	120																			
					Flow patt	100% air cavities					90%air		50% rec.vortex				100% recir.vortices								
					Slope of stepped spillways $\alpha_3 = 38^0 50'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	8	7	6.5	7.5	10	11	12	12	13	12.5	12.5	12.5	12.5	12	12					
					Min.	6.5	6	5.5	6	7.5	7.5	8	8.5	9	9	9	9	9	8	8					
					Max.	8.5	7.5	7	8	11	11	13	13	14	14	13.5	13.5	13.5	12	12					
					Min.	6.5	6	6	6.5	7	7.5	8	8	9	9	9	9	9	8	8					
					Aver.(d_{wps})	7.4	6.6	6.3	7	8.9	9.1	10	10	11	11.1	11	11	11	10	10					
					Inception																				
					length(cm)	80																			
					Flow patt	100% recirculating vortices in all steps																			

3.6.2.3 Calculation of rate of energy dissipation and residual head:



Data:

q_w=0.02cum/0.2m=0.1cum/m

Equations to be solved:

Tatewar & Ingle (1996) &Knight & Mc Donald(1979) Methods

$z^{0.1}/ng^{0.5}=0.25+19\log(\lambda/l)+5.75\log(z^{0.6}/k)$ ……………(1)

$z=qn/(\sin\alpha)^{0.5}$………………(2)

$y=\{qn/(\sin\alpha)^{0.5}\}^{0.6}$ …………(.3)

$v=q/y$………………………… (4)

$k=h*\cos\alpha$ (5)

$\lambda=(h^2+l^2)^{0.5}$………………………(6)

$E_c=H_{spill}+1.5d_c$………………(7)

$E_l=d_w+u_o^2/2g$ ………………(8)

$\Delta E=E_c-E_l$………………………(9)

Calculations:

Critical depth (dc)=$(q_w^2/g)^{1/3}$

q_w	$d_{c\,(m)}$		H_{spill}
0.1	0.10		2
0.21	l	λ (m)	
0.033	0.041	0.053	
α	sinα	cosα	k(m)
38.83	0.627	0.779	0.026

Solving Manning's n from eq.(1)

n	z	λ/l	LHS
0.05	0.006	1.2788	3.84801193
{z^0.6/k}			log(λ/l)
1.862			0.10680811
log{z^0.6/k}			RHS
0.27			3.83236537

Put different values of n & check whether LHS=RHS

n	LHS	RHS
0.04	4.704	3.498
0.05	**3.848**	**3.832**

Hence value of n is 0.05

Therefore equvalent water depth, $d_w=\{q_w n/\sin\alpha^{0.5}\}^{0.6}$

$d_{w\,(m)}$

0.048

Uniform velocity,uw =qw/dw

$u_{w\,(m/s)}$

2.09

Change in energy between crest and toe of spillways: ΔE=Ec-Et

Ec =Hspill+1.5dc	**Ec(m)**
	2.151
$Et = d_w + u_w^2/2g$	**Et(m)**
	0.270
	ΔE(m)
	1.881

Energy dissipated=ΔE/Ec*100 = 87.4 %

Residual head =Et =0.27m

3.6.2.4 Experiment no.2: (Water flow depths in multislope stepped spillways)

With the use of circular suppressor

SN	Manometre reading (x cm)	Disch. (Q) (cum)	Width of spillways (b m)	Disch. perunit length (q) cum/m	**Slope of stepped spillways α_1 =34°32'**																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Min.	2.4	2.4	2.2	2.2	2.2	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5					
					Max.	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Min.	2.4	2.4	2.2	2.2	2.2	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5					
					Aver.(d_{wps})	2.5	2.5	2.4	2.4	2.4	2	2	2	2	2	2	2	2	2	2					
					Inception																				
					length(cm)	30																			
					Flow patt	No air cavities,weak recirculating vortices,neither nappe nor skimming flow																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.5	4	4.5	5.5	5.5	5.5	5.5	5.5	5.5	9	10	10	9	8	8.5	8	7	5	5	4.5
					Min.	1.5	3	4	4.5	5	5	4	4	4	3.5	3.5	3	3	3	2.5	2.5	2.5	2.5	2.5	2.5
					Max.	2.5	4	4.5	5.5	5.5	5.5	5.5	5.5	5.5	9	10	10	9	8	8.5	8	7	5	5	4.5
1	0.75	0.004	0.2	0.02	Min.	1.5	3	4	4.5	5	5	4	4	4	3.5	3.5	3	3	3	2.5	2.5	2.5	2.5	2.5	2.5
					Aver.(d_{wps})	2	3.5	4.3	5	5.3	5.3	4.8	4.8	4.8	6.25	6.8	6.5	6	5.5	5.5	5.3	4.8	3.8	3.75	3.5
					Inception																				
					length(cm)	35																			
					Flow patt	100% air cavities				10%to40% vortex				100% recir.vortices											
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.5	2.5	5	6.5	7.5	7.2	7.5	7.5	7	6	5	4.5	3.5	3	3					
					Min.	2	2	3	4.5	5	4.5	5	4.5	3.5	3	3	2.5	2.5	2	2					
					Max.	2.5	2.5	4.5	5.5	6.5	7	7	6.5	6	4.5	5	4.5	3.5	4	3.5					
					Min.	1.5	1.5	2.5	3.5	4	4	5	3.5	3	2.5	3	2.5	2.5	2.5	2.5					
					Aver.(d_{wps})	2.1	2.1	3.8	5	5.8	5.7	6.1	5.5	4.9	4	4	3.5	3	2.88	2.8					
					Inception																				
					length(cm)	10																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Manometre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	3	3	3	2	2	2	2	2	2.5	2.5	2.5	2.5	2.5	3					
					Min.	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2					
					Max.	3.5	3	3	3	2	2	2	2	2	2.5	2.5	2.5	2.5	2.5	3					
					Min.	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2					
					Aver.(d_{wps})	3.3	2.5	2.5	2.5	2	2	2	2	2	2.25	2.3	2.3	2.25	2.25	2.5					
					Inception																				
					length(cm)	40																			
					Flow patt	No air cavities,weak recirculating vortices,neither nappe nor skimming flow																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3	4.5	5	6.5	6.5	6.5	6	6	6	6	5.5	5.5	5.5	5.5	5.5	4.5	4.5	4.5	4.5	4.5
					Min.	2	3	4.5	5	5	5	5.5	5.5	5.5	5	4	4	4	4	4	3	3	3	3	3
					Max.	3	4.5	5	6.5	6.5	6.5	6	6	6	6	5.5	5.5	5.5	5.5	5.5	4.5	4.5	4.5	4.5	4.5
2	1.66	0.006	0.2	0.03	Min.	2	3	4.5	5	5	5	5.5	5.5	5.5	5	4	4	4	4	4	3	3	3	3	3
					Aver.(d_{wps})	2.5	3.8	4.8	5.8	5.8	5.8	5.8	5.8	5.8	5.5	4.8	4.8	4.75	4.75	4.8	3.8	3.8	3.8	3.75	3.75
					Inception																				
					length(cm)	35																			
					Flow patt	100% air cavities				10%to40% vortex				100% recir.vortices											
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.3	2.5	4.5	5.5	5.5	5.5	5.5	5.5	5	5	5	5	4.5	4.5	4.5					
					Min.	2	2	3.5	4	4.5	4	4	4	3	3	3	3	3	3	3					
					Max.	3.3	2.5	4.5	5.5	5.5	5.5	5.5	5.5	5	5	5	5	4.5	4.5	4.5					
					Min.	2	2	3.5	4	4.5	4	4	4	3	3	3	3	3	3	3					
					Aver.(d_{wps})	2.7	2.3	4	4.8	5	4.8	4.8	4.8	4	4	4	4	3.75	3.75	3.8					
					Inception																				
					length(cm)	10																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	3.5	3.5	3.5	2.5	2.5	2.5	2.5	2.5	3	3	3	3	3	3					
					Min.	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2					
					Max.	4	3.5	3.5	3.5	2.5	2.5	2.5	2.5	2.5	3	3	3	3	3	3					
					Min.	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2					
					Aver.(d_{wps})	3.5	3.3	3.3	3.3	2.3	2.3	2.3	2.3	2.3	2.5	2.5	2.5	2.5	2.5	2.5					
					Inception																				
					length(cm)	45																			
					Flow patt	No air cavities,weak recirculating vortices,neither nappe nor skimming flow																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	4.5	5	6.5	6.5	5	5	5	5	5	5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Min.	2.5	4	5	6	6	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
					Max.	3.5	4.5	5	6.5	6.5	5	5	5	5	5	5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
3	2.95	0.008	0.2	0.04	Min.	2.5	4	5	6	6	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
					Aver.(d_{wps})	3	4.3	5	6.3	6.3	4.8	4.8	4.8	4.8	4.75	4.8	4.8	5	5	5	5	5	5	5	5
					Inception																				
					length(cm)	40																			
					Flow patt	100% air cavities				10%to40% vortex				100% recir.vortices											
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	3.5	5	5.5	6	6.5	7	6.5	6	6	5.5	4.5	4.5	4.5	4.5					
					Min.	3	3	3.5	4.5	5	5.5	5.5	5	3.5	3.5	3.5	3	3	3	3					
					Max.	4	3.5	5	5.5	6	6.5	7	6.5	6	6	5.5	4.5	4.5	4.5	4.5					
					Min.	3	3	3.5	4.5	5	5.5	5.5	5	3.5	3.5	3.5	3	3	3	3					
					Aver.(d_{wps})	3.5	3.3	4.3	5	5.5	6	6.3	5.8	4.8	4.75	4.5	3.8	3.75	3.75	3.8					
					Inception																				
					length(cm)	8																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	**Slope of stepped spillways α_1 =34°32'**																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	5	4	3	3	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Min.	3	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Max.	5	5	4	3	3	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Min.	3	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Aver.(d_{wps})	4	4	3.3	2.8	2.8	3	3	3	3	3	3	3	3	3	3					
					Inception																				
					length(cm)	45																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	4.5	5	6	6	6	6	6	5.8	5.8	5.8	5.8	5.8	5.8	5.5	5.5	5.5	5.5	5.5	5.5
					Min.	2.8	4	4.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5	5	5	5	5	5
					Max.	4	4.5	5	6	6	6	6	6	5.8	5.8	5.8	5.8	5.8	5.8	5.5	5.5	5.5	5.5	5.5	5.5
4	4.61	0.01	0.2	0.05	Min.	2.8	4	4.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5	5	5	5	5	5
					Aver.(d_{wps})	3.4	4.3	4.8	5.8	5.8	5.8	5.8	5.8	5.7	5.65	5.7	5.7	5.65	5.65	5.3	5.3	5.3	5.3	5.25	5.25
					Inception																				
					length(cm)	40																			
					Flow patt	100% air cavities				40%to80% vortex				100% recir.vortices											
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4	5	6	6.5	7	6.5	6.5	6.5	6	6	6	5.5	5.5	5.5					
					Min.	3	3	4	4.5	4.5	5	5	5	5	5	4.5	4.5	3.5	3.5	3.5					
					Max.	4.5	4	5	6	6.5	7	6.5	6.5	6.5	6	6	6	5.5	5.5	5.5					
					Min.	3	3	4	4.5	4.5	5	5	5	5	5	4.5	4.5	3.5	3.5	3.5					
					Aver.(d_{wps})	3.8	3.5	4.5	5.3	5.5	6	5.8	5.8	5.8	5.5	5.3	5.3	4.5	4.5	4.5					
					Inception																				
					length(cm)	5																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways $\alpha_1 = 34^o32'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	6	6	5	5	5	4	4	4	4	4	4.5	4.5	4.5	4.5					
					Min.	5	5	4	4	4	4	3	3	3	3	3	3	3	3	3					
					Max.	6	6	6	5	5	5	4	4	4	4	4	4.5	4.5	4.5	4.5					
					Min.	5	5	4	4	4	4	3	3	3	3	3	3	3	3	3					
					Aver.(d_{wps})	5.5	5.5	5	4.5	4.5	4.5	3.5	3.5	3.5	3.5	3.5	3.8	3.75	3.75	3.8					
					Inception																				
					length(cm)	50																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways $\alpha_2 = 52^o14'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4.5	5.5	5.5	5.5	6	6	6	6	6	6	6	6	6	6	6.5	6.5	6.5	6.5	6.5
					Min.	3	4.5	5.5	5.5	5.5	5.5	5.5	5.5	5	5	5	5	5	5	5	5	5	5	5	5
					Max.	4.5	4.5	5.5	5.5	5.5	6	6	6	6	6	6	6	6	6	6	6.5	6.5	6.5	6.5	6.5
5	6.63	0.012	0.2	0.06	Min.	3	4.5	5.5	5.5	5.5	5.5	5.5	5.5	5	5	5	5	5	5	5	5	5	5	5	5
					Aver.(d_{wps})	3.8	4.5	5.5	5.5	5.5	5.8	5.8	5.8	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.8	5.8	5.8	5.75	5.75
					Inception																				
					length(cm)	40																			
					Flow patt	100% air cavities				40%to80% vortex				100% recir.vortices											
					Slope of stepped spillways $\alpha_3 = 38^o50'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5.5	4.5	5	6	6.5	6.8	7	7	7	7	7	6.8	6	6	6					
					Min.	4	4	4	5	5	5.5	5.5	5.5	5.5	5	5	5	4.5	4.5	4.5					
					Max.	5.5	4.5	5	6	6.5	6.8	7	7	7	7	7	7	6	6	6					
					Min.	4	4	4	5	5	5.5	5.5	5.5	5.5	5	5	5	4.5	4.5	4.5					
					Aver.(d_{wps})	4.8	4.3	4.5	5.5	5.8	6.2	6.3	6.3	6.3	6	6	6	5.25	5.25	5.3					
					Inception																				
					length(cm)	5																			
					Flow patt	100% recirculating vortices in all steps																			

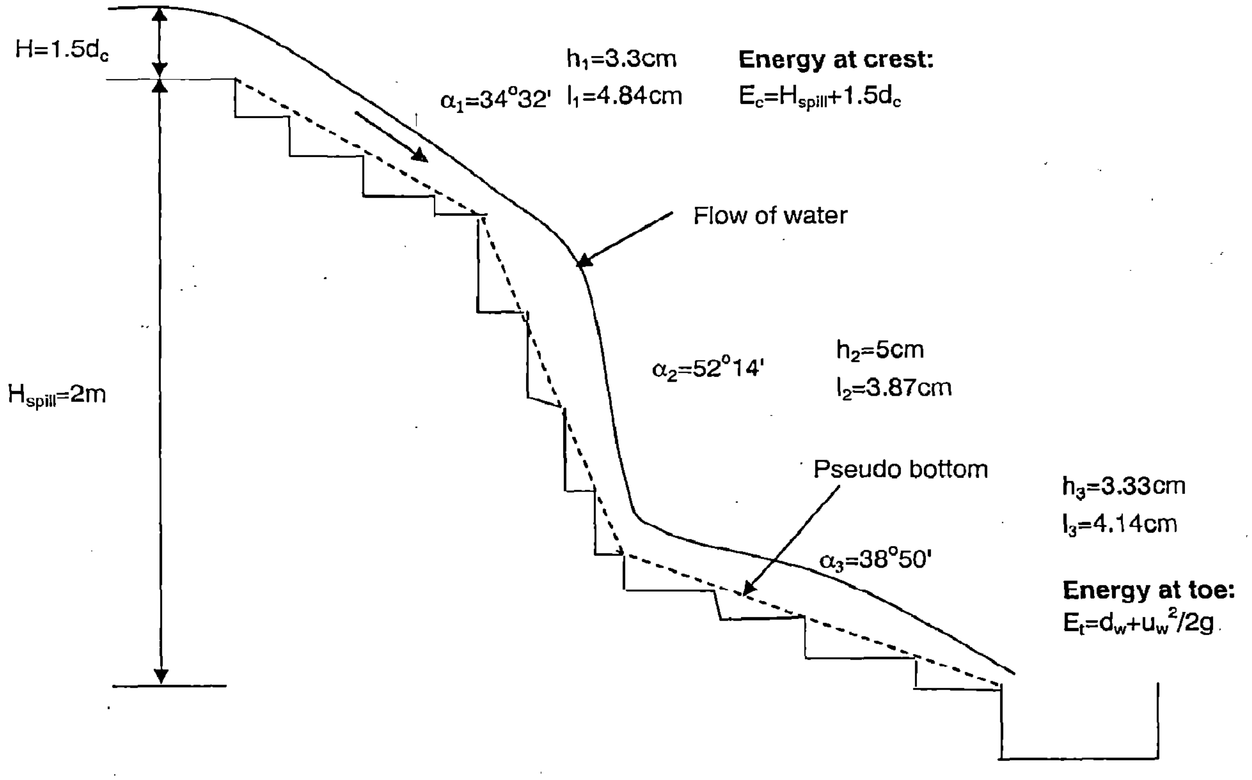
SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6.5	6	6	6	5	5	5	4	4	4	3.5	4	4	4	4					
					Min.	4.5	4	4	4	3.5	3	3	3	3	3	3	3	3	3	3					
					Max.	6.5	6	6	6	5	5	5	4	4	4	3.5	4	4	4	4					
					Min.	4.5	4	4	4	3.5	3	3	3	3	3	3	3	3	3	3					
					Aver.(d_{wps})	5.5	5	5	5	4.3	4	4	3.5	3.5	3.5	3.3	3.5	3.5	3.5	3.5					
					Inception																				
					length(cm)	50																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	4.5	5	5.5	6	6	6	6	6	6	6	6	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
					Min.	3.5	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Max.	4	4.5	5	5.5	6	6	6	6	6	6	6	6	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
6	9.03	0.014	0.2	0.07	Min.	3.5	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Aver.(d_{wps})	3.8	4.5	5	5.5	5.8	5.8	5.8	5.8	5.8	5.75	5.8	5.8	6	6	6	6	6	6	6	6
					Inception																				
					length(cm)	30																			
					Flow patt	100% air	40% vortex			100% recir.vortices															
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	4.5	5	6	6.5	7	8	8	8	8	7.5	7	7	6.5	6.5					
					Min.	4	4	4	5	5.5	5.5	6	6	6	6	5.5	5.2	5.2	5	5					
					Max.	5	4.5	5	6	6.5	7	8	8	8	8	7.5	7	6.8	6.5	6.5					
					Min.	4	4	4	5	5.5	5.5	6	6	6	6	5.5	5	5	5	5					
					Aver.(d_{wps})	4.5	4.3	4.5	5.5	6	6.3	7	7	7	7	6.5	6.1	6	5.75	5.8					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	8	7	7	6	6	5	5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	6	6	5	5	5	4	4	4	3.8	3.5	3.5	3.5	3.5	3.5	3.5					
					Max.	8	7	7	6	6	5	5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	6	6	5	5	5	4	4	4	3.8	3.5	3.5	3.5	3.5	3.5	3.5					
					Aver.(d_{wps})	7	6.5	6	5.5	5.5	4.5	4.5	4.5	4.2	4	4	4	4	4	4					
					Inception																				
					length(cm)	50																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	4.5	5	5.5	6	6	6	6	6	6	6	6	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
					Min.	3	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Max.	4	4.5	5	5.5	6	6	6	6	6	6	6	6	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
7	11.8	0.016	0.2	0.08	Min.	3	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Aver.(d_{wps})	3.5	4.5	5	5.5	5.8	5.8	5.8	5.8	5.8	5.75	5.8	5.8	6	6	6	6	6	6	6	6
					Inception																				
					length(cm)	30																			
					Flow patt	90% air		20%vortex	100% recir.vortices																
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6.5	5.5	5	6	6.5	7.5	7	7.5	8	8	8	8	7.5	7.5	7.5					
					Min.	4.5	4	4	4.5	5	5.5	5.5	6	6.5	6.5	6.5	6	5.5	5.5	5.5					
					Max.	6.5	5.5	5	6	6.5	7.7	7	7.5	8	8	8	7	7.5	7.5	7.5					
					Min.	4.5	4	4	4.5	5	5.5	5.5	6	6.5	6.5	6.5	6	5.5	5.5	5.5					
					Aver.(d_{wps})	5.5	4.8	4.5	5.3	5.8	6.6	6.3	6.8	7.3	7.25	7.3	6.8	6.5	6.5	6.5					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	9	9	7	7	5	5	5	5	5	5	5	5	5	5	5					
					Min.	7	7	5.5	5.5	4	4	4	4	4	4	4	4	4	4	4					
					Max.	9	9	7	7	5	5	5	5	5	5	5	5	5	5	5					
					Min.	7	7	5.5	5.5	4	4	4	4	4	4	4	4	4	4	4					
					Aver.(d_{wps})	8	8	6.3	6.3	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Inception																				
					length(cm)	50																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4.5	5.5	6	6.5	7	7	9	8	8	8	8	8	8	8	8	8.5	8.5	8.5	8.5
					Min.	4.5	4.5	5	5.5	5.5	6	6.5	5.4	6	6	6	6	6	6	6	6	6.7	6.7	6.7	6.7
					Max.	4.5	4.5	5.5	6	6.5	7	7	9	8	8	8	8	8	8	8	8	8.5	8.5	8.5	8.5
8	14.92	0.018	0.2	0.09	Min.	4.5	4.5	5	5.5	5.5	6	6.5	5.4	6	6	6	6	6	6	6	6	6.5	6.5	6.5	6.5
					Aver.(d_{wps})	4.5	4.5	5.3	5.8	6	6.5	6.8	7.2	7	7	7	7	7	7	7	7	7.6	7.6	7.55	7.55
					Inception																				
					length(cm)	30																			
					Flow patt	80% air	100% recir.vortices																		
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	7.5	6.5	6	7	7.5	9	9	8.5	8.2	8.2	8	7.5	7	7	7					
					Min.	5.5	5	4.8	5	6	6.5	6.5	6.5	6.2	6.2	5.5	5.5	5.5	5.5	5.5					
					Max.	7.5	6.5	6	7	7.5	9	8.8	8.5	8.5	8.5	8	7.5	7	7	7					
					Min.	5.5	5	4.5	5	6	6.5	5.5	6.5	6.2	6.2	5.5	5.5	5.5	5.5	5.5					
					Aver.(d_{wps})	6.5	5.8	5.3	6	6.8	7.8	7.5	7.5	7.3	7.28	6.8	6.5	6.25	6.25	6.3					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Manometre reading (x cm)	Disch. (Q) (cum)	Width of spillways (b m)	Disch. perunit length (q) cum/m)	**Slope of stepped spillways α_1 =34°32'**																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	9.5	10	9	8	6	6	6	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5					
					Min.	8	8	7	6	5	5	5	4	4	4	4	4	4	4	4					
					Max.	10	10	9	8	6	6	6	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5					
					Min.	8	8	7	6	5	5	5	4	4	4	4	4	4	4	4					
					Aver.(d_{wps})	8.9	9	8	7	5.5	5.5	5.5	4.8	4.8	4.75	4.8	4.8	4.75	4.75	4.8					
					Inception																				
					length(cm)	55																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4.5	5.5	6	6.5	6.5	7	7	7	6.5	6.5	6.5	7	7.5	7.5	7.5	7	7.5	7.5	7.5
					Min.	4	5	5	5.5	5.5	5.5	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5	5.5	5.5	5.5
					Max.	5.5	4.5	5.5	6	6	6	6	6	6	5	5	5	5	5	5	5.5	4	5	5	5
9	18.42	0.02	0.2	0.1	Min.	4.5	4.5	5	5.5	5	5	5	5	5	4	4	4	4	4	4	4.5	5	4	4	4
					Aver.(d_{wps})	4.6	4.6	5.3	5.8	5.8	5.8	5.9	5.9	5.9	5.25	5.3	5.3	5.38	5.5	5.5	5.8	5.3	5.5	5.5	5.5
					Inception																				
					length(cm)	20																			
					Flow patt	25% air	100% recir.vortices																		
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	8.5	7	6.5	6.5	7.5	8.5	9.5	10	11	12	13	13	11.5	11	11					
					Min.	6.5	5	5	5	5.5	5.5	6.5	7	7.5	8	8.5	8	7	7	7					
					Max.	8	7	6	6.5	6.5	7	8	8.5	8.5	8.6	8.7	9	7.5	7.5	7.5					
					Min.	5.5	5	4.5	5	5	5.5	6	6.5	6.5	6.8	6.8	7	5.5	5.4	5.4					
					Aver.(d_{wps})	7.1	6	5.5	5.8	6.1	6.6	7.5	8	8.4	8.85	9.1	9.1	7.88	7.73	7.7					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

3.6.2.5 Calculation of rate of energy dissipation and residual head:



(a) Tatewar & Ingle (1996) &Knight & Mc Donald(1979) Methods:

Case:Only final slope α =38°50' and step sizes are taken.

Data:

q_w=0.02cum/0.2m=0.1cum/m

Equations to be solved:

$z^{0.1}/ng^{0.5}=0.25+19\log(\lambda/l)+5.75\log(z^{0.6}/k)$ ... ...(1)

$z=qn/(\sin a)^{0.5}$ ... ...(2)

$y=\{qn/(\sin a)^{0.5}\}^{0.6}$ ... ...(.3)

$v=q/y$ ... ... (4)

$k=h*\cos a$ ... ...(5)

$\lambda=(h^2+l^2)^{0.5}$ ... ...(6)

$E_c=H_{spill}+1.5d_c$ ... ...(7)

$E_t=d_w+u_o^2/2g$ ... ...(8)

$\Delta E=E_c-E_t$ ... ...(9)

Calculations:

Critical depth $(dc)=(q_w^2/g)^{1/3}$

q_w	$d_{c\,(m)}$		H_{spill}
0.1	0.10		2
h	l	λ (m)	
0.033	0.04	0.052	
α	sinα	cosα	k(m)
38.83	0.627	0.779	0.026

Solving Manning's n from eq.(1)

n	z	λ/l	LHS
0.05	0.006	1.296	3.84802584
{z^0.6/k}			log(λ/l)
1.862			0.11273541
log{z^0.6/k}			RHS
0.27			3.94492144

Put different values of n & check whether LHS=RHS

n	LHS	RHS
0.04	4.704	3.498
0.05	**3.848**	**3.832**

Hence value of n is 0.05

Therefore equivalent water depth, $d_w = \{q_w n/\sin\alpha^{0.5}\}^{0.6}$

$d_{w\,(m)}$
0.048

Uniform velocity,uw =qw/dw

$u_{w\,(m/s)}$
2.09

Change in energy between crest and toe of spillways: ΔE=Ec-Et

Ec =Hspill+1.5dc	**Ec(m)**
	2.151
$Et = d_w + u_w^2/2g$	**Et(m)**
	0.270
	ΔE(m)
	1.881

Energy dissipated=ΔE/Ec*100 = 87.4 %
Residual head =Et =0.27m

(b) Chanson (1994) methods:

$\alpha = 38^o50'$; h =3.33cm;l =4.14cm.

Average equilibrium air concentration (Ce) =0.9*sin α

Ce
0.564

Self aerated friction factor, fe/f =0.5[1+tanh{0.628*(0.514-Ce)/(Ce(1-Ce))}]
or, $fe/f = 0.5[1+(e^x-e^{-x})/(e^x+e^{-x})]$
where x = {0.628*(0.514-Ce)/(Ce(1-Ce))}
f = 1;a non aereted friction factor

(1-Ce)	(0.514-(	Ce(1-C	x	
0.436	-0.05	0.246	-0.1278747	
f	e^x	e^{-x}	e^x-e^{-x}	e^x+e^{-x}
1	0.88	1.136	-0.256447	2.0164

fe
0.436

Uniform aereted flow depth,dwu =dc*$\{fe/(8\sin\alpha)\}^{1/3}$

8sinα	d_{wu}
5.014	0.045

Charactiristic depth (bulk depth), $d_{90}=dc*\{fe/(8(1-Ce)^3\sin\alpha)\}^{1/3}$

$8(1-Ce)^3$sina	d_{90}(m)
0.415	0.102

But it has come 0.065m from experiment.So questionable?
Rate of energy dissipation;
ΔH/Hmax =1-[{(fe/8sina)1/3*cosa+Ec/2(fe/8sina)-2/3}/(1.5+Hdam/dc) ;where Ec=(N+1)^3/{N^2*(N+3)
where N=3.5 to 4, Ec=1.1 for N=3.5; Hmax=Hdam+1.5*dc

{fe/(8sina)}1/3	{fe/(8sina)}-2/3	(1.5+Hdam/dc)
0.443	5.083	21.368

ΔH/Hmax
0.853

ie, rate of energy dissipation is 85.30%

Residual energy, H_{res}:
Hres/dc=(fe/8sina)^1/3+Ec/2(fe/8sina)^-2/3

H_{res}(m)
0.316

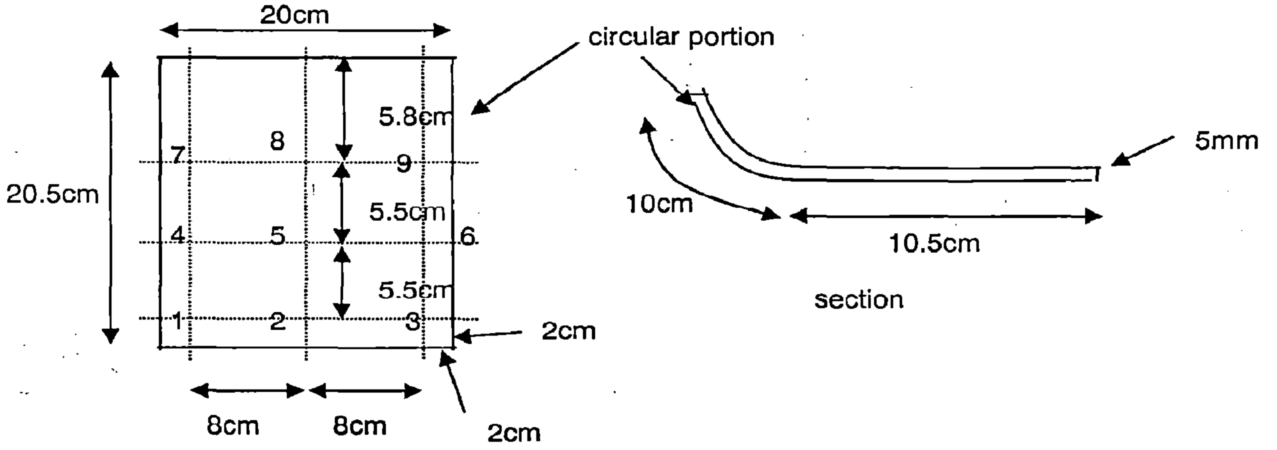
ie,energy lost by stepped spillways is:
H_{loss}=Hmax-Hres=Hspill+1.5*dc-Hres

H_{loss}(m)
1.835
Result:

α	h	l	ΔH/Hmax	Hmax	Hloss	Hres	dw(m)	V(m/s)
34.53	0.033	0.048	0.5719	0.65	0.372	0.279	0.049	2.03
52.23	0.05	0.039	0.5456	1.549	1.026	0.523	0.045	2.24
38.83	0.033	0.041	0.514	0.545	0.229	0.316	0.048	2.09

3.6.2.6 Experiment no. 3 (uplift water pressure at circular/elliptical suppressor plate)

i.uplift water pressure at circular suppressor plate:



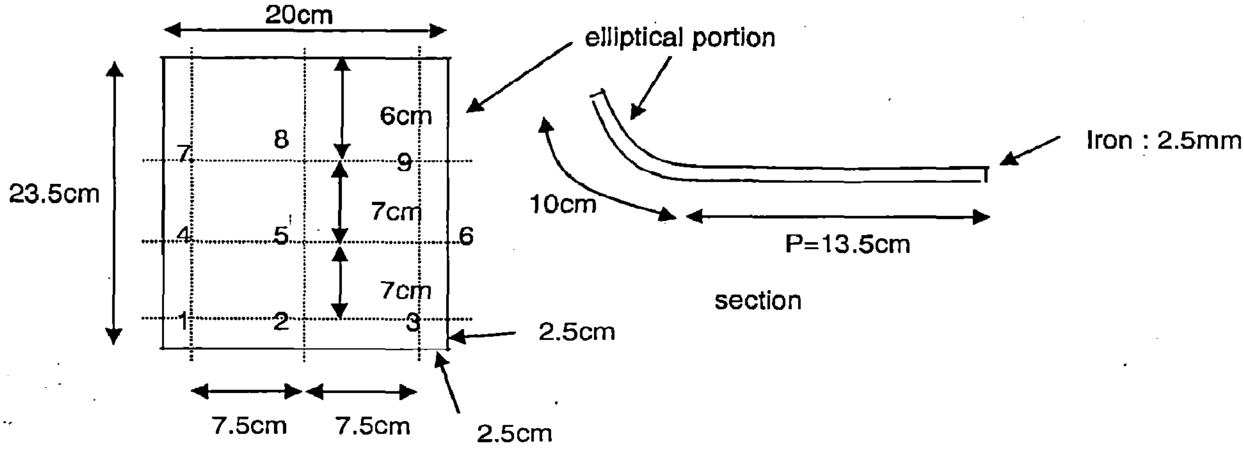
plan of circular suppressor plate

Uplift water pressure at circular suppressor plate:

Disch. (m3/s)	Points	1	2	3	4	5
0.004	Piezom. head (cm)	2.2	-2.5	2.7	1.5	0.5
	Points	6	7	8	9	
	Piezom. head (cm)	4.1	1	0.7	0.8	
0.006	Points	1	2	3	4	5
	Piezom. head (cm)	2.4	-2.5	2.7	1.5	0.6
	Points	6	7	8	9	
	Piezom. head (cm)	4.1	1	1.5	1.7	
0.008	Points	1	2	3	4	5
	Piezom. head (cm)	2.5	-2.5	2	1.5	0.5
	Points	6	7	8	9	
	Piezom. head (cm)	4.2	0.7	1.4	1.5	
0.01	Points	1	2	3	4	5
	Piezom. head (cm)	2	-2.5	2.4	1.5	0.5
	Points	6	7	8	9	
	Piezom. head (cm)	4.1	1	1.5	1.5	

0.012	Points	1	2	3	4	5
	Piezom. head (cm)	4	-2.5	1.7	1.5	0.5
	Points	6	7	8	9	
	Piezom. head (cm)	4.2	1	1.5	1.6	
0.014	Points	1	2	3	4	5
	Piezom. head (cm)	4.3	-2.1	2.1	1	0.5
	Points	6	7	8	9	
	Piezom. head (cm)	4.5	0.7	1.5	1.5	
0.016	Points	1	2	3	4	5
	Piezom. head (cm)	4.5	-2.3	1.7	1.7	0.7
	Points	6	7	8	9	
	Piezom. head (cm)	4.5	0.8	1.5	1.4	
0.018	Points	1	2	3	4	5
	Piezom. head (cm)	5.2	-5.5	2.2	1.3	0
	Points	6	7	8	9	
	Piezom. head (cm)	4	0.5	1.2	0	
0.02	Points	1	2	3	4	5
	Piezom. head (cm)	4.3	-6.75	0.8	1.5	-1.1
	Points	6	7	8	9	
	Piezom. head (cm)	2.6	0.3	1.1	0.4	

ii.uplift water pressure at elliptical suppressor plate(P=135mm):



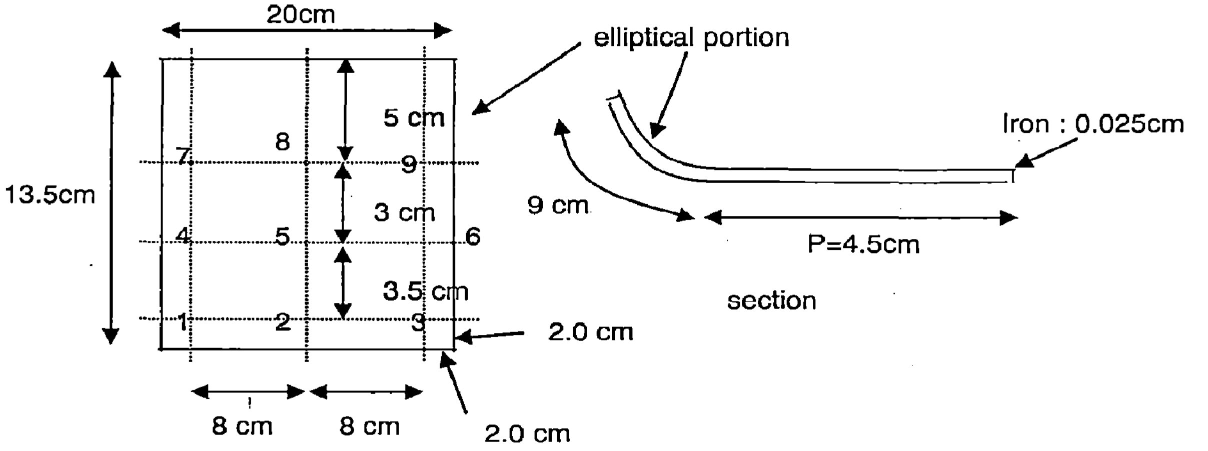
plan of elliptical suppressor plate

Uplift water pressure at elliptical suppressor plate(P=135mm):

Disch. (m3/s)	Points	1	2	3	4	5
	Piezom. head (cm)	-1	-5.8	-3	1.8	1.8
0.006	Points	6	7	8	9	
	Piezom. head (cm)	1.9	0.5	1	0.5	
	Points	1	2	3	4	5
0.008	Piezom. head (cm)	-1	-5.8	-2.9	1.8	1.9
	Points	6	7	8	9	
	Piezom. head (cm)	2	0.5	1	0.5	
	Points	1	2	3	4	5
0.01	Piezom. head (cm)	-1	-6	-3.2	1.8	1.8
	Points	6	7	8	9	
	Piezom. head (cm)	1.8	0.5	1	0.5	

0.012	Points	1	2	3	4	5
	Piezom. head (cm)	-0.9	-6	-3.2	2	2
	Points	6	7	8	9	
	Piezom. head (cm)	2.1	0.5	1	0.5	
0.014	Points	1	2	3	4	5
	Piezom. head (cm)	-1	-6.5	-3.5	2	2
	Points	6	7	8	9	
	Piezom. head (cm)	2	0.4	1	0.4	
0.016	Points	1	2	3	4	5
	Piezom. head (cm)	-1	-6.5	-3.5	1.8	1.9
	Points	6	7	8	9	
	Piezom. head (cm)	2.1	0.5	1	0.5	
0.018	Points	1	2	3	4	5
	Piezom. head (cm)	-1.5	-7	-3.5	2.1	2.5
	Points	6	7	8	9	
	Piezom. head (cm)	2	0.4	1.1	0.4	
0.02	Points	1	2	3	4	5
	Piezom. head (cm)	-1.5	-7.5	3.8	2	2.2
	Points	6	7	8	9	
	Piezom. head (cm)	1.5	0.5	1.1	0	

iii.Uplift water pressure at elliptical suppressor plate(P=45mm):



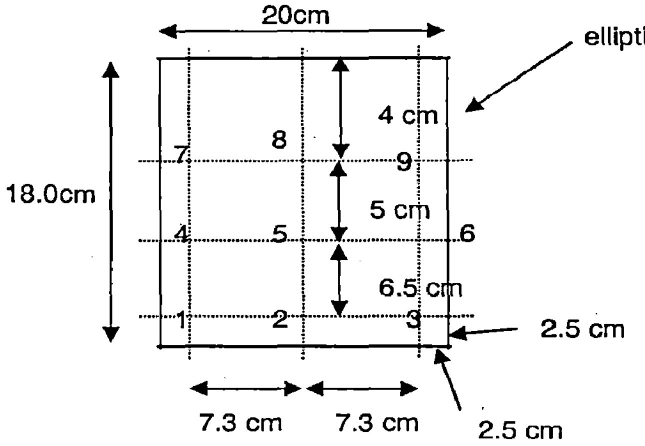
plan of elliptical suppressor plate

Uplift water pressure at elliptical suppressor plate(P=45mm):

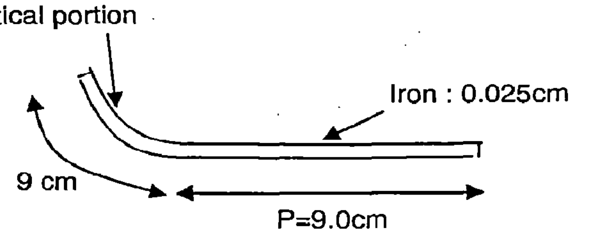
Disch. (m3/s)	Points	1	2	3	4	5
	Piezom. head (cm)	-1.4	-7.5	1.6	-5	-11
0.006	Points	6	7	8	9	
	Piezom. head (cm)	-1.1	1.1	2.1	3.5	
	Points	1	2	3	4	5
0.008	Piezom. head (cm)	-1.4	-7.5	1.5	-5	-11
	Points	6	7	8	9	
	Piezom. head (cm)	-1.6	1.1	2.1	3.5	
	Points	1	2	3	4	5
0.01	Piezom. head (cm)	-1.5	-7.5	1.5	-5	-11
	Points	6	7	8	9	
	Piezom. head (cm)	-1.8	1.1	2.1	3.6	

	Points	1	2	3	4	5
0.012	Piezom. head (cm)	-1.5	-7.5	1.5	-5	-11
	Points	6	7	8	9	
	Piezom. head (cm)	-2.6	1.1	2.1	3.6	
	Points	1	2	3	4	5
0.014	Piezom. head (cm)	-1.5	-7.8	1.5	-5	-11.3
	Points	6	7	8	9	
	Piezom. head (cm)	-3	1.1	2.2	3.5	
	Points	1	2	3	4	5
0.016	Piezom. head (cm)	-1.8	-8.5	1.5	-5.4	12
	Points	6	7	8	9	
	Piezom. head (cm)	-5.2	1.4	2.5	4	
	Points	1	2	3	4	5
0.018	Piezom. head (cm)	-1.8	-8.5	1.5	-5.5	-12
	Points	6	7	8	9	
	Piezom. head (cm)	-6.5	1.5	2.4	3.4	
	Points	1	2	3	4	5
0.02	Piezom. head (cm)	-3	-9.5	1.1	-6.4	-13.2
	Points	6	7	8	9	
	Piezom. head (cm)	-8.5	1	2	2.8	

iv.Uplift water pressure at elliptical suppressor plate(P=90mm):



plan of elliptical suppressor plate



section

Uplift water pressure at elliptical suppressor plate(P=90mm):

Disch. (m3/s)	Points	1	2	3	4	5
0.006	Piezom. head (cm)	0	-2.2	-2.3	0.6	1.5
	Points	6	7	8	9	
	Piezom. head (cm)	3.4	0.9	1.2	0.5	
0.008	Points	1	2	3	4	5
	Piezom. head (cm)	0	-2.1	-2.2	0.6	1.5
	Points	6	7	8	9	
	Piezom. head (cm)	3.7	0.7	1.3	0.5	
0.01	Points	1	2	3	4	5
	Piezom. head (cm)	0	-2.2	-2.2	0.6	1.5
	Points	6	7	8	9	
	Piezom. head (cm)	3.8	0.8	1.3	0.4	

0.012	Points	1	2	3	4	5
	Piezom. head (cm)	0.1	-2.3	-2.4	0.6	1.5
	Points	6	7	8	9	
	Piezom. head (cm)	4	0.7	1.2	0.4	
0.014	Points	1	2	3	4	5
	Piezom. head (cm)	0	-2.6	-2.6	0.6	2
	Points	6	7	8	9	
	Piezom. head (cm)	4.1	0.8	1.3	0.3	
0.016	Points	1	2	3	4	5
	Piezom. head (cm)	0	-3	-2.8	0.6	2.6
	Points	6	7	8	9	
	Piezom. head (cm)	4.3	0.7	1.1	0.3	
0.018	Points	1	2	3	4	5
	Piezom. head (cm)	-1.2	-5	-3.5	0.5	2.4
	Points	6	7	8	9	
	Piezom. head (cm)	4.1	0	0.9	0	
0.02	Points	1	2	3	4	5
	Piezom. head (cm)	0	-3.1	-3.2	0.7	1.8
	Points	6	7	8	9	
	Piezom. head (cm)	3.5	1	1.9	0.3	

3.6.2.7 Prediction of the flow regimes:

Chanson (2001):

dc/h=0.89-0.4*h/l … … Nappe to Transition (NA-TRA)

dc/h=1.2-0.325*h/l … Transition to Skimming (TRA-SK)

Boes & Hager (2003):

dc/h=0.91-0.14*h/l … … … Onset of Skimming (SK)

Critical depth(dc):

$dc=(q2/g)^{1/3}$

Table:1 (Theoretical)

q (m3/s)	Slope (α)	Step height (h)m	Step length (l)m	h/l	dc(m)	dc/h	dc/h (onset) Chanson NA-TRA	Chanson TRA-SK	Boes & Hager	Flow regimes
0.02	34o32'	0.033	0.0484	0.682	0.034	**1.043**	0.617	0.978	0.815	SK
0.02	52o14'	0.05	0.0387	1.292	0.034	**0.689**	0.373	0.780	0.729	TRA
0.02	38o50'	0.0333	0.0414	0.804	0.034	**1.034**	0.568	0.939	0.797	SK
0.03	34o32'	0.033	0.0484	0.682	0.045	**1.367**	0.617	0.978	0.815	SK
0.03	52o14'	0.05	0.0387	1.292	0.045	**0.902**	0.373	0.780	0.729	SK
0.03	38o50'	0.0333	0.0414	0.804	0.045	**1.355**	0.568	0.939	0.797	SK
0.04	34o32'	0.033	0.0484	0.682	0.055	**1.656**	0.617	0.978	0.815	SK
0.04	52o14'	0.05	0.0387	1.292	0.055	**1.093**	0.373	0.780	0.729	SK
0.04	38o50'	0.0333	0.0414	0.804	0.055	**1.641**	0.568	0.939	0.797	SK
0.05	34o32'	0.033	0.0484	0.682	0.063	**1.922**	0.617	0.978	0.815	SK
0.05	52o14'	0.05	0.0387	1.292	0.063	**1.268**	0.373	0.780	0.729	SK
0.05	38o50'	0.0333	0.0414	0.804	0.063	**1.904**	0.568	0.939	0.797	SK

0.06	34o32'	0.033	0.0484	0.682	0.072	**2.170**	0.617	0.978	0.815	SK
0.06	52o14'	0.05	0.0387	1.292	0.072	**1.432**	0.373	0.780	0.729	SK
0.06	38o50'	0.0333	0.0414	0.804	0.072	**2.151**	0.568	0.939	0.797	SK
0.07	34o32'	0.033	0.0484	0.682	0.079	**2.405**	0.617	0.978	0.815	SK
0.07	52o14'	0.05	0.0387	1.292	0.079	**1.587**	0.373	0.780	0.729	SK
0.07	38o50'	0.0333	0.0414	0.804	0.079	**2.383**	0.568	0.939	0.797	SK
0.08	34o32'	0.033	0.0484	0.682	0.087	**2.629**	0.617	0.978	0.815	SK
0.08	52o14'	0.05	0.0387	1.292	0.087	**1.735**	0.373	0.780	0.729	SK
0.08	38o50'	0.0333	0.0414	0.804	0.087	**2.605**	0.568	0.939	0.797	SK
0.09	34o32'	0.033	0.0484	0.682	0.094	**2.844**	0.617	0.978	0.815	SK
0.09	52o14'	0.05	0.0387	1.292	0.094	**1.877**	0.373	0.780	0.729	SK
0.09	38o50'	0.0333	0.0414	0.804	0.094	**2.818**	0.568	0.939	0.797	SK
0.1	34o32'	0.033	0.0484	0.682	0.101	**3.050**	0.617	0.978	0.815	SK
0.1	52o14'	0.05	0.0387	1.292	0.101	**2.013**	0.373	0.780	0.729	SK
0.1	38o50'	0.0333	0.0414	0.804	0.101	**3.023**	0.568	0.939	0.797	SK

Table:2

Observational:Without suppressor

q (m3/s)	Slope (α)	Step height (h)m	Step length (l)m	h/l	dc(m)	dc/h	**Flow patterns**
0.02	34o32'	0.033	0.0484	0.682	0.034	1.043	Undulating skim flow,Invisible vortices,Inception length=45cm.
0.02	52o14'	0.05	0.0387	1.292	0.034	0.689	Strong undulating transition flow,full vortices at lower steps,Incept.L=60cm.
0.02	38o50'	0.0333	0.0414	0.804	0.034	1.034	Full vortices in all steps,concave skim flow at junction,incept.L=45cm.
0.03	34o32'	0.033	0.0484	0.682	0.045	1.367	Undulating skim flow,Invisible vortices,Inception length=48cm.
0.03	52o14'	0.05	0.0387	1.292	0.045	0.902	Strong undulating skim flow,full vortices at lower steps,Incept.L=65cm.
0.03	38o50'	0.0333	0.0414	0.804	0.045	1.355	Full vortices in all steps,concave skim flow at junction,incept.L=50cm.
0.04	34o32'	0.033	0.0484	0.682	0.055	1.656	Step1 had 75% vortex,rests had full vortices& looked like a skim flows.
0.04	52o14'	0.05	0.0387	1.292	0.055	1.093	Strong undulating skim flow,full vortices at lower steps,Incept.L=90cm.
0.04	38o50'	0.0333	0.0414	0.804	0.055	1.641	Full vortices in all steps,concave skim flow at junction,incept.L=60cm.
0.05	34o32'	0.033	0.0484	0.682	0.063	1.922	Step1 had 90% vortex,rests had full vortices& looked like a skim flows.
0.05	52o14'	0.05	0.0387	1.292	0.063	1.268	Strong airmixed skim flow,full vortices at lower steps,Incept.L=90cm.
0.05	38o50'	0.0333	0.0414	0.804	0.063	1.904	Full vortices in all steps,concave skim flow at junction,incept.L=60cm.
0.06	34o32'	0.033	0.0484	0.682	0.072	2.170	Full vortices after step12,rests weak vortices,skim flow,incept.L=60cm.
0.06	52o14'	0.05	0.0387	1.292	0.072	1.432	Full vortices after step12,rests weak vortices,skim flow,incept.L=90cm.
0.06	38o50'	0.0333	0.0414	0.804	0.072	2.151	Full vortices in all steps,concave skimf low at junction,incept.L=70cm.
0.07	34o32'	0.033	0.0484	0.682	0.079	2.405	Full vortices after step15,rests weak vortices,skimmingflow,incept.L=60cm.
0.07	52o14'	0.05	0.0387	1.292	0.079	1.587	Full vortices after step12,rests weak vortices,skim.flow,incept.L=120cm.
0.07	38o50'	0.0333	0.0414	0.804	0.079	2.383	Full vortices in all steps,concave skimflow at junction,incept.L=70cm.
0.08	34o32'	0.033	0.0484	0.682	0.087	2.629	Full vortices after step13,rests weak vortices,skimmingflow,incept.L=60cm.
0.08	52o14'	0.05	0.0387	1.292	0.087	1.735	Full vortices after step12,rests partial,skim.flow,convexflow,Li=120cm.
0.08	38o50'	0.0333	0.0414	0.804	0.087	2.605	Full vortices in all steps,concave skimflow at junction,incept.L=70cm.
0.09	34o32'	0.033	0.0484	0.682	0.094	2.844	Full vortices after step13,rests weak vortices,skimmingflow,incept.L=60cm.
0.09	52o14'	0.05	0.0387	1.292	0.094	1.877	Full vortices after step12,rests partial,skim.flow,convexflow,Li=120cm.
0.09	38o50'	0.0333	0.0414	0.804	0.094	2.818	Full vortices in all steps,concave skimflow at junction,incept.L=70cm.
0.1	34o32'	0.033	0.0484	0.682	0.101	3.050	Full vortices after step13,rests weak vortices,skimmingflow,incept.L=60cm.
0.1	52o14'	0.05	0.0387	1.292	0.101	2.013	Full vortices after step12,rests partial,skim.flow,convexflow,Li=120cm.
0.1	38o50'	0.0333	0.0414	0.804	0.101	3.023	Full vortices in all steps,concave skimflow at junction,incept.L=70cm.

Table:3

Observational: With circular suppressor

q (m3/s)	Slope (α)	Step height (h)m	Step length (l)m	h/l	dc(m)	dc/h	**Flow patterns**
0.02	34o32'	0.033	0.0484	0.682	0.034	1.043	Undulating skim flow,Invisible vortices,Inception length=45cm.
0.02	52o14'	0.05	0.0387	1.292	0.034	0.689	Strong undulating skim flow,full vortices at lower steps,Incept.Li=60cm.
0.02	38o50'	0.0333	0.0414	0.804	0.034	1.034	Full vortices in all steps,concave skim flow at junction,incept.Li=40cm.
0.03	34o32'	0.033	0.0484	0.682	0.045	1.367	Undulating skim flow,Invisible vortices,Inception length=48cm.
0.03	52o14'	0.05	0.0387	1.292	0.045	0.902	Strong undulating skim flow,full vortices at lower steps,Incept.Li=55cm.
0.03	38o50'	0.0333	0.0414	0.804	0.045	1.355	Full vortices in all steps,concave skim flow at junction,incept.L=38cm.
0.04	34o32'	0.033	0.0484	0.682	0.055	1.656	All steps had full vortices& looked like a skim flows,Li=45cm
0.04	52o14'	0.05	0.0387	1.292	0.055	1.093	Air cavities at first few steps,uniformdepth flow,full vortices at lower steps,Li=50cm.
0.04	38o50'	0.0333	0.0414	0.804	0.055	1.641	Full vortices in all steps,concave skim flow at junction,incept.Li=35cm.
0.05	34o32'	0.033	0.0484	0.682	0.063	1.922	All steps had full vortices& looked like a skim flows,Li=45cm.
0.05	52o14'	0.05	0.0387	1.292	0.063	1.268	Air cavities at first few steps,uniform depth flow,full vortices at lower steps,Li=50cm.
0.05	38o50'	0.0333	0.0414	0.804	0.063	1.904	Full vortices in all steps,concave skim flow at junction,incept.Li=35cm.
0.06	34o32'	0.033	0.0484	0.682	0.072	2.170	All steps had full vortices& looked like a skim flows,Li=45cm.
0.06	52o14'	0.05	0.0387	1.292	0.072	1.432	Air cavities at first few steps,uniform depth flow,full vortices at lower steps,Li=55cm.
0.06	38o50'	0.0333	0.0414	0.804	0.072	2.151	Full vortices in all steps,concave at junction,uniform skim flow ,incept.Li=40cm.
0.07	34o32'	0.033	0.0484	0.682	0.079	2.405	Full vortices after step15,rests weak vortices,skimmingflow,incept.Li=60cm.
0.07	52o14'	0.05	0.0387	1.292	0.079	1.587	Full vortices after step5,rests weak vortices,uniform skim.flow,incept.Li=20cm.
0.07	38o50'	0.0333	0.0414	0.804	0.079	2.383	Full vortices in all steps,concave at junction, uniform skimflow, incept.Li=10cm.
0.08	34o32'	0.033	0.0484	0.682	0.087	2.629	Full vortices after step13,rests weak vortices,skimming flow,incept.Li=60cm.
0.08	52o14'	0.05	0.0387	1.292	0.087	1.735	Full vortices after step4,rests weak vortices,uniform skim.flow,incept.Li=20cm.
0.08	38o50'	0.0333	0.0414	0.804	0.087	2.605	Full vortices in all steps,concave at junction, uniform skimflow, incept.Li=10cm.
0.09	34o32'	0.033	0.0484	0.682	0.094	2.844	Full vortices after step13,rests weak vortices,skimming flow,incept.Li=60cm.
0.09	52o14'	0.05	0.0387	1.292	0.094	1.877	Full vortices after step3,rests weak vortices,uniform skim.flow,incept.Li=10cm.
0.09	38o50'	0.0333	0.0414	0.804	0.094	2.818	Full vortices in all steps,concave at junction, uniform skim flow, incept.Li=5cm.
0.1	34o32'	0.033	0.0484	0.682	0.101	3.050	Full vortices after step13,rests weak vortices,skimming flow,incept.Li=60cm.
0.1	52o14'	0.05	0.0387	1.292	0.101	2.013	Full vortices after 2ndstep,rest partial,uniform skim.flow,convexflow,Li=5cm.
0.1	38o50'	0.0333	0.0414	0.804	0.101	3.023	Full vortices in all steps,concave at junction, uniform skim flow, incept.Li=0cm.

Table:4

Observational: With elliptical suppressor (P =135 mm)

q (m3/s)	Slope (α)	Step height (h)m	Step length (l)m	h/l	dc(m)	dc/h	**Flow patterns**
0.03	34o32'	0.033	0.0484	0.682	0.045	1.367	Undulating skim flow,Invisible vortices,Inception length=20cm.
0.03	52o14'	0.05	0.0387	1.292	0.045	0.902	Strong undulating skim flow,full vortices at lower steps,incept.
0.03	38o50'	0.0333	0.0414	0.804	0.045	1.355	Full vortices in all steps,concave skim flow at junction,incept.
0.04	34o32'	0.033	0.0484	0.682	0.055	1.656	All steps had full vortices& looked like a skim flows,Li=20cm
0.04	52o14'	0.05	0.0387	1.292	0.055	1.093	Air cavities at first few steps,nearly uniformdepth flow,full vortices at lower steps,
0.04	38o50'	0.0333	0.0414	0.804	0.055	1.641	Full vortices in all steps,concave skim flow at junction,incept.
0.05	34o32'	0.033	0.0484	0.682	0.063	1.922	All steps had full vortices& looked like a skim flows,Li=25cm.
0.05	52o14'	0.05	0.0387	1.292	0.063	1.268	Air cavities at first few steps,nearly uniform depth flow,full vortices at lower steps,
0.05	38o50'	0.0333	0.0414	0.804	0.063	1.904	Full vortices in all steps,concave skim flow at junction,incept.
0.06	34o32'	0.033	0.0484	0.682	0.072	2.170	All steps had full vortices& looked like a skim flows,Li=30cm.
0.06	52o14'	0.05	0.0387	1.292	0.072	1.432	Air cavities at first few steps,nearly uniform depth flow,full vortices at lower steps,
0.06	38o50'	0.0333	0.0414	0.804	0.072	2.151	Full vortices in all steps,concave at junction,non uniform skim flow ,incept.
0.07	34o32'	0.033	0.0484	0.682	0.079	2.405	Full vortices after step5,rests weak vortices,skimmingflow,incept.Li=35cm.
0.07	52o14'	0.05	0.0387	1.292	0.079	1.587	Full vortices after step5,rests weak vortices,nearly uniform skim.flow,incept.
0.07	38o50'	0.0333	0.0414	0.804	0.079	2.383	Full vortices in all steps,concave at junction, non uniform skimflow, incept.
0.08	34o32'	0.033	0.0484	0.682	0.087	2.629	Full vortices after step5,rests weak vortices,skimming flow,incept.Li=35cm.
0.08	52o14'	0.05	0.0387	1.292	0.087	1.735	Full vortices after step4,rests weak vortices,nearly uniform skim.flow,incept.
0.08	38o50'	0.0333	0.0414	0.804	0.087	2.605	Full vortices in all steps,concave at junction, non uniform skimflow, incept.
0.09	34o32'	0.033	0.0484	0.682	0.094	2.844	Full vortices after step 5,rests weak vortices,skimming flow,incept.Li=38cm.
0.09	52o14'	0.05	0.0387	1.292	0.094	1.877	Full vortices after step 5,rests weak vortices,nearly uniform skim.flow,incept.
0.09	38o50'	0.0333	0.0414	0.804	0.094	2.818	Full vortices in all steps,concave at junction, non uniform skim flow, incept.
0.1	34o32'	0.033	0.0484	0.682	0.101	3.050	Full vortices after step 7,rests weak vortices,skimming flow,incept.Li=40cm.
0.1	52o14'	0.05	0.0387	1.292	0.101	2.013	Full vortices after 4th step,rest partial,nearly uniform skim.flow,convexflow,
0.1	38o50'	0.0333	0.0414	0.804	0.101	3.023	Full vortices in all steps,concave at junction, non uniform skim flow, incept.

Table:5

Observational: With elliptical suppressor (P =90 mm)

q (m3/s)	Slope (α)	Step height (h)m	Step length (l)m	h/l	dc(m)	dc/h	**Flow patterns**
0.03	34o32'	0.033	0.0484	0.682	0.045	1.367	All steps had full weak vortices & skim flows,Li=15cm
0.03	52o14'	0.05	0.0387	1.292	0.045	0.902	Air cavities at first few steps,nearly uniformdepth flow,full vortices at lower steps
0.03	38o50'	0.0333	0.0414	0.804	0.045	1.355	Full vortices in all steps,concave skim flow at junction,incept.Li=0cm.
0.04	34o32'	0.033	0.0484	0.682	0.055	1.656	All steps had full weak vortices& skim flows,Li=18cm.
0.04	52o14'	0.05	0.0387	1.292	0.055	1.093	Air cavities at first few steps,nearly uniform depth flow,full vortices at lower steps,
0.04	38o50'	0.0333	0.0414	0.804	0.055	1.641	Full vortices in all steps,concave skim flow at junction,incept.Li=0cm.
0.05	34o32'	0.033	0.0484	0.682	0.063	1.922	All steps had full vortices& looked like a skim flows,Li=20cm.
0.05	52o14'	0.05	0.0387	1.292	0.063	1.268	Air cavities at first few steps,nearly uniform depth flow,full vortices at lower steps,
0.05	38o50'	0.0333	0.0414	0.804	0.063	1.904	Full vortices in all steps,concave at junction,non uniform skim flow ,incept.Li=0cm.
0.06	34o32'	0.033	0.0484	0.682	0.072	2.170	Full vortices after step5,rests weak vortices,skimmingflow,incept.Li=25cm.
0.06	52o14'	0.05	0.0387	1.292	0.072	1.432	Full vortices after step5,rests weak vortices,nearly uniform skim.flow,
0.06	38o50'	0.0333	0.0414	0.804	0.072	2.151	Full vortices in all steps,concave at junction, non uniform skimflow, incept.Li=0cm.
0.07	34o32'	0.033	0.0484	0.682	0.079	2.405	Full vortices after step5,rests weak vortices,skimming flow,incept.Li=25cm.
0.07	52o14'	0.05	0.0387	1.292	0.079	1.587	Full vortices after step4,rests weak vortices,nearly uniform skim.flow,incept.
0.07	38o50'	0.0333	0.0414	0.804	0.079	2.383	Full vortices in all steps,concave at junction, non uniform skimflow, incept.Li=0cm.
0.08	34o32'	0.033	0.0484	0.682	0.087	2.629	Full vortices after step 5,rests weak vortices,skimming flow,incept.Li=25cm.
0.08	52o14'	0.05	0.0387	1.292	0.087	1.735	Full vortices after step 5,rests weak vortices,nearly uniform skim.flow,incept.
0.08	38o50'	0.0333	0.0414	0.804	0.087	2.605	Full vortices in all steps,concave at junction, non uniform skim flow, incept.Li=0cm.
0.09	34o32'	0.033	0.0484	0.682	0.094	2.844	Full vortices after step 7,rests weak vortices,skimming flow,incept.Li=30cm.
0.09	52o14'	0.05	0.0387	1.292	0.094	1.877	Full vortices after 4th step,rest partial,nearly uniform skim.flow,convexflow,
0.09	38o50'	0.0333	0.0414	0.804	0.094	2.818	Full vortices in all steps,concave at junction, non uniform skim flow, incept.Li=0cm.
0.1	34o32'	0.033	0.0484	0.682	0.101	3.050	Full vortices after step13,rests weak vortices,skimming flow,incept.Li=40cm.
0.1	52o14'	0.05	0.0387	1.292	0.101	2.013	Full vortices after 2ndstep,rest partial,uniform skim.flow,convexflow,
0.1	38o50'	0.0333	0.0414	0.804	0.101	3.023	Full vortices in all steps,concave at junction, uniform skim flow, incept.Li=0cm.

Table:6

Observational: With elliptical suppressor (P =45 mm)

q (m3/s)	Slope (α)	Step height (h)m	Step length (l)m	h/l	dc(m)	dc/h	**Flow patterns**
0.03	34o32'	0.033	0.0484	0.682	0.045	1.367	Undulating skim flow,Invisible vortices,Inception length=15cm.
0.03	52o14'	0.05	0.0387	1.292	0.045	0.902	Strong undulating skim flow,full vortices at lower steps,Incept.
0.03	38o50'	0.0333	0.0414	0.804	0.045	1.355	Full vortices in all steps,concave skim flow at junction,incept.L=0cm.
0.04	34o32'	0.033	0.0484	0.682	0.055	1.656	All steps had full vortices& looked like a skim flows,Li=20cm
0.04	52o14'	0.05	0.0387	1.292	0.055	1.093	Air cavities at first few steps,uniformdepth flow,full vortices at lower steps,
0.04	38o50'	0.0333	0.0414	0.804	0.055	1.641	Full vortices in all steps,concave skim flow at junction,incept.Li=0cm.
0.05	34o32'	0.033	0.0484	0.682	0.063	1.922	All steps had full vortices& looked like a skim flows,Li=25cm.
0.05	52o14'	0.05	0.0387	1.292	0.063	1.268	Air cavities at first few steps,nearly uniform depth flow,full vortices at lower steps,
0.05	38o50'	0.0333	0.0414	0.804	0.063	1.904	Full vortices in all steps,concave skim flow at junction,incept.Li=0cm.
0.06	34o32'	0.033	0.0484	0.682	0.072	2.170	All steps had full vortices& looked like a skim flows,Li=30cm.
0.06	52o14'	0.05	0.0387	1.292	0.072	1.432	Air cavities at first few steps,uniform depth flow,full vortices at lower steps,
0.06	38o50'	0.0333	0.0414	0.804	0.072	2.151	Full vortices in all steps,concave at junction,uniform skim flow ,incept.Li=0cm.
0.07	34o32'	0.033	0.0484	0.682	0.079	2.405	Full vortices after step5,rests weak vortices,skimmingflow,incept.Li=35cm.
0.07	52o14'	0.05	0.0387	1.292	0.079	1.587	Full vortices after step5,rests weak vortices,uniform skim.flow,incept.
0.07	38o50'	0.0333	0.0414	0.804	0.079	2.383	Full vortices in all steps,concave at junction, uniform skimflow, incept.Li=0cm.
0.08	34o32'	0.033	0.0484	0.682	0.087	2.629	Full vortices after step5,rests weak vortices,skimming flow,incept.Li=38cm.
0.08	52o14'	0.05	0.0387	1.292	0.087	1.735	Full vortices after step4,rests weak vortices,uniform skim.flow,incept.
0.08	38o50'	0.0333	0.0414	0.804	0.087	2.605	Full vortices in all steps,concave at junction, uniform skimflow, incept.Li=0cm.
0.09	34o32'	0.033	0.0484	0.682	0.094	2.844	Full vortices after step 5,rests weak vortices,skimming flow,incept.Li=40cm.
0.09	52o14'	0.05	0.0387	1.292	0.094	1.877	Full vortices after step 5,rests weak vortices,uniform skim.flow,incept.
0.09	38o50'	0.0333	0.0414	0.804	0.094	2.818	Full vortices in all steps,concave at junction, uniform skim flow, incept.Li=0cm.
0.1	34o32'	0.033	0.0484	0.682	0.101	3.050	Full vortices after step 6,rests weak vortices,skimming flow,incept.Li=40cm.
0.1	52o14'	0.05	0.0387	1.292	0.101	2.013	Full vortices after 4th step,rest partial,nearly uniform skim.flow,convexflow,
0.1	38o50'	0.0333	0.0414	0.804	0.101	3.023	Full vortices in all steps,concave at junction, uniform skim flow, incept.Li=0cm.

3.6.2.8 Experiment no.4

Experimental study of flow patterns in single slope (monoslope) stepped spillways:

α = 37°34'; h = 5cm; l = 6.5cm ;No.of steps = 40 nos.

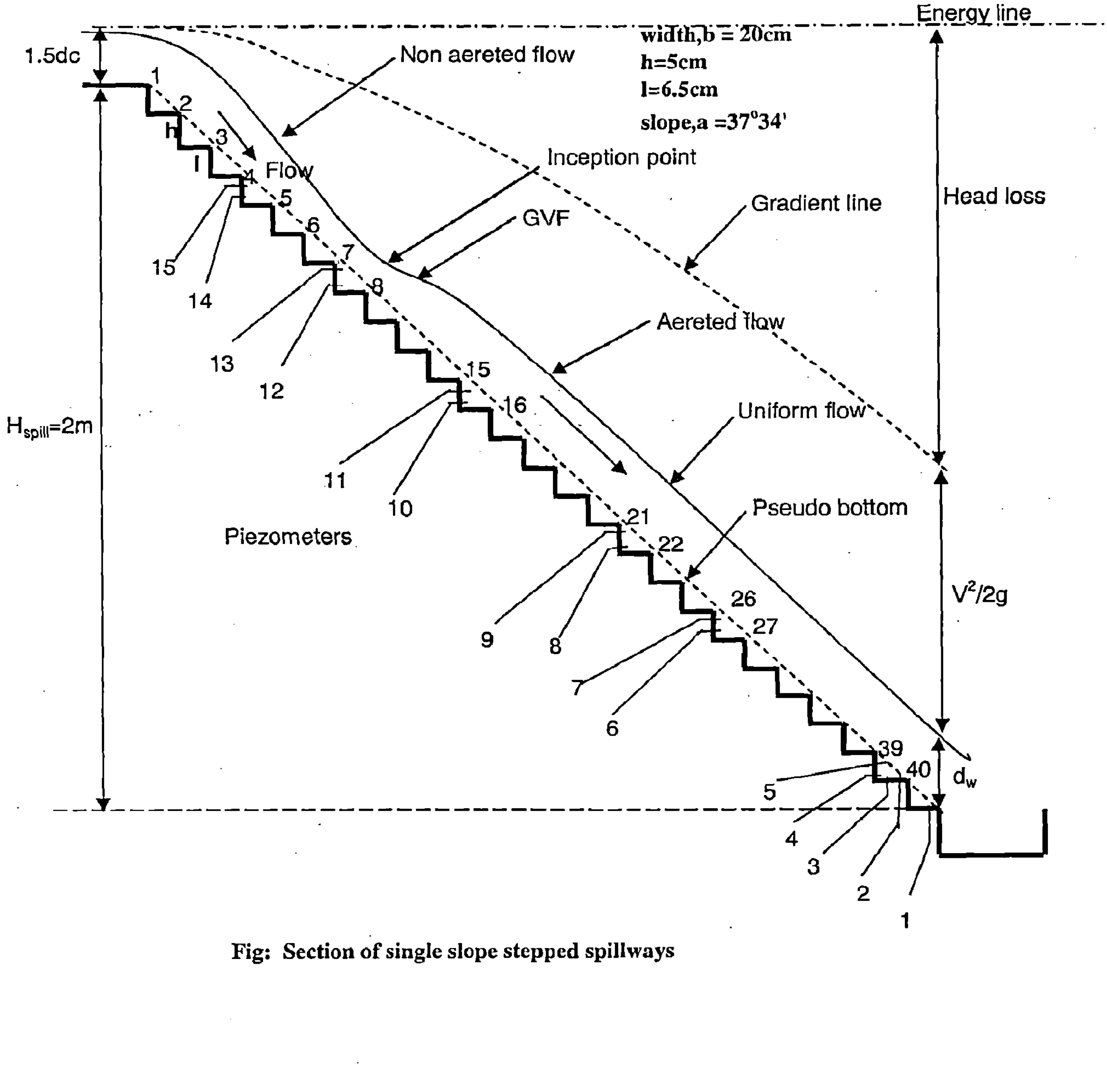


Fig: Section of single slope stepped spillways

Experimental study of flow patterns in single slope (monoslope) stepped spillways:Flow water depths:

α =37°34' ; h = 5cm; l = 6.5cm ;No.of steps = 40 nos

SN	Q (m3/s)	Steps no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.006	d_w (cm)	2.8	2.8	3.5	3.8	3.5	3	2.8	2.7	2.6	2.6	2.6	2.6	2.6	2.6	2.6
		Piezometer reading(cm)	0.4	2.3	9.5	-0.5	2.9	2.4	-0.5	1.4	-0.8	1.3	-0.8	2.3	-0.5	1.6	-1
		Steps no.	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
		d_w (cm)	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
		Steps no.	31	32	33	34	35	36	37	38	39	40					
		d_w (cm)	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6					
		Flow pattern	Inception length=15cm,vortex generated after 3rd step,50%vortex in some steps and fluctuation flows,100% air cavity ie no water at 40th step.														
2	0.01	Steps no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		d_w (cm)	7	7	6	5	4	4.2	4.3	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
		Piezometer reading(cm)	8.3	2.3	13.4	-0.5	3	2.6	-1	3.2	-0.8	3	-1	4.2	-0.3	4.4	-0.1
		Steps no.	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
		d_w (cm)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
		Steps no.	31	32	33	34	35	36	37	38	39	40					
		d_w (cm)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
		Flow pattern	Incept. length=35cm,vortex generated after 7th step and there was full vortices in all steps.														
3	0.014	Steps no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		d_w (cm)	9	7	7	6	5	4.5	4.5	4.5	4.8	4.8	4.8	4.8	4.8	4.8	4.8
		Piezometer reading(cm)	11	2	16.5	-0.5	2.8	2.7	-0.7	3.1	-1.1	2.8	-1.1	4.6	0	5.5	0.7
		Steps no.	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
		d_w (cm)	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
		Steps no.	31	32	33	34	35	36	37	38	39	40					
		d_w (cm)	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8					
		Flow pattern	Incept.length=45cm,0%vortex at first step,50% at 2nd step,aerated flow and full vortices from 3rd to last steps.														
4	0.018	Steps no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		d_w (cm)	10	9.5	8	7	7	6	5.5	5.5	5.8	5.8	5.8	5.8	5.8	5.8	5.8
		Piezometer reading(cm)	13.4	2	18.1	-0.5	2.8	3	-0.6	3.5	-0.7	2.9	-1	5.2	0.6	5.6	1.2
		Steps no.	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
		d_w (cm)	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
		Steps no.	31	32	33	34	35	36	37	38	39	40					
		d_w (cm)	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8					
		Flow pattern	Incept.length=60cm,0%vortex at first step,50% at 2nd step,aerated flow and full vortices from 3rd to last steps.														
5	0.02	Steps no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		d_w (cm)	11	10	9	8.5	8	7.5	7	6	6	6.5	6.5	6.5	6.5	6.5	6.5
		Piezometer reading(cm)	13.4	2	18.1	-0.5	2.8	3	-0.6	3.5	-0.7	2.9	-1	5.2	0.6	5.6	1.2
		Steps no.	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
		d_w (cm)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
		Steps no.	31	32	33	34	35	36	37	38	39	40					
		d_w (cm)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5					
		Flow pattern	Incept.length=65cm,0%vortex at first step,50% at 2nd step,aerated flow and full vortices from 3rd to last steps.														

3.6.2.9 Calculation of rate of energy dissipation and residual head in monoslope stepped spillways:

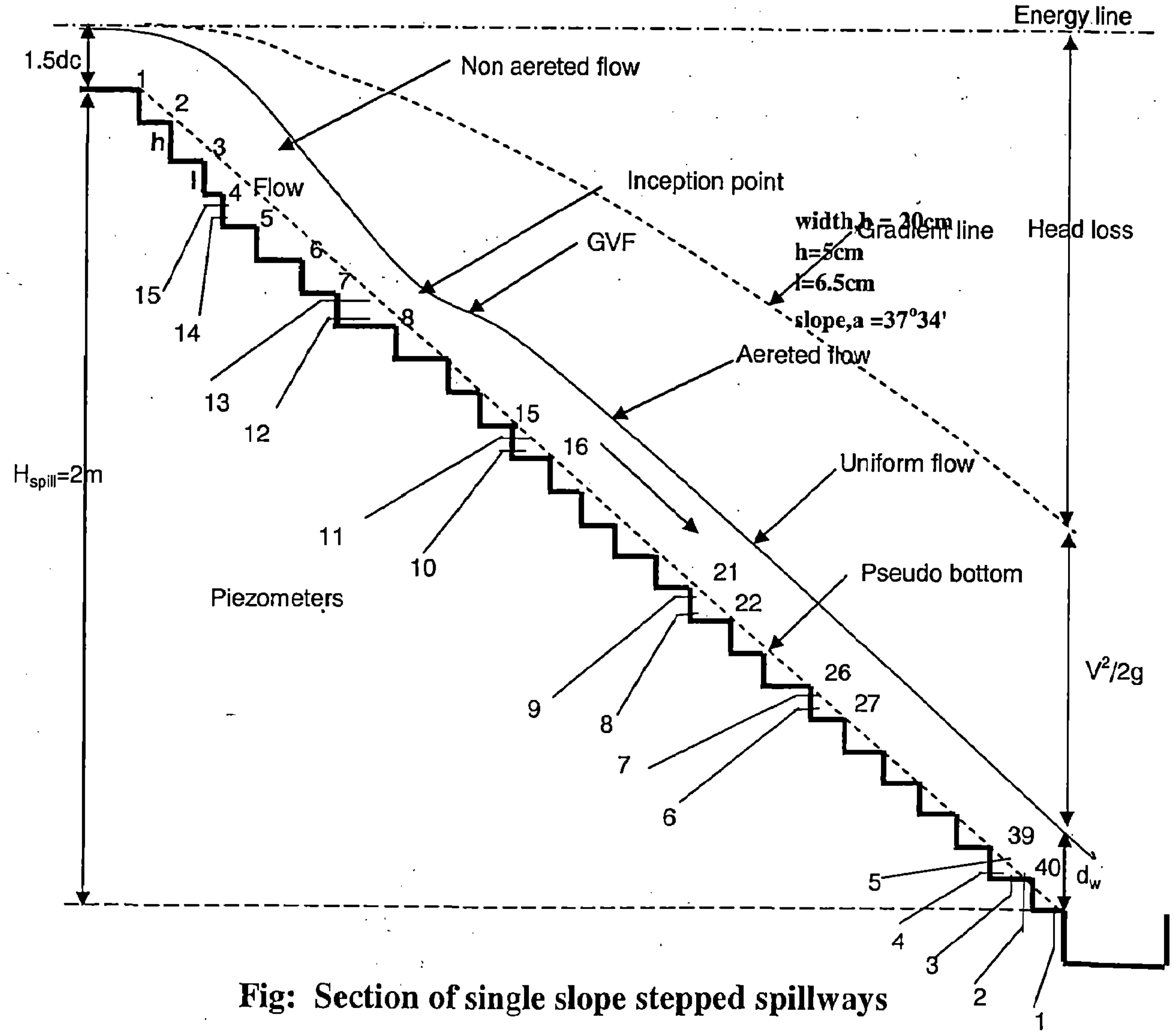


Fig: Section of single slope stepped spillways

(a)Tatewar & Ingle (1996)&Knight & McDonald(1979) Methods:

Data:	**Energy at crest:**	**Energy at toe:**
q_w=0.02cum/0.2m=0.1cum/m	$E_c=H_{spill}+1.5d_c$	$E_t=d_w+u_w^2/2g$

Equations to be used:

$z^{0.1}/ng^{0.5}=0.25+19\log(l/l)+5.75\log(z^{0.6}/k)$ ... ...(1)

$z=qn/(\sin a)^{0.5}$ ... ...(2)

$y=\{qn/(\sin a)^{0.5}\}^{0.6}$ ... ... (.3)

$v=q/y$ ... ... (4)

$k=h*\cos a$ ... ...(5)

$\lambda=(h^2+l^2)^{0.5}$ ... ...(6)

$E_c=H_{spill}+1.5d_c$ ... ...(7)

$E_t=d_w+u_o^2/2g$ ... ...(8)

$\Delta E=E_c-E_t$ ... ...(9)

Calculations:

Critical depth (dc)=$(q_w^2/g)^{1/3}$

q_w	**$d_{c\,(m)}$**		H_{spill}
0.1	0.10		2
h	l	**λ (m)**	
0.05	0.065	0.082	
α	sinα	cosα	**k(m)**
37.566667	0.609	0.793	0.040

Solving Manning's n from eq.(1)

n	z	λ/l	LHS
0.06485	0.008307	1.26163	3.0493
{z^0.6/k}			log(l/l)
1.4240046			0.1009
log{z^0.6/k}			RHS
0.1535114			3.0504

Put different values of n & check whether LHS=RHS

n	LHS	RHS
0.06	3.27	2.934
0.06485	**3.049**	**3.05**

Hence value of n is 0.06485

Therefore equvalent water depth, $d_w = \{q_w n / \sin a^{0.5}\}^{0.6}$

$d_{w\,(m)}$
0.056

Uniform velocity,uw =qw/dw

$u_{w\,(m/s)}$
1.77

Change in energy between crest and toe of spillways:DE=Ec-Et

Ec =Hspill+1.5dc	**Ec(m)**
	2.151
$Et = d_w + u_w^2/2g$	**Et(m)**
	0.216
	ΔE(m)
	1.935

Energy dissipated=DE/Ec*100 = *89.9 %*
Residual head =Et =0.22m

(b) Chanson methods(1994):

Average equilibrium air concentration (Ce) =0.9*sinα

Ce
0.5484786

Self aerated friction factor, fe/f =0.5[1+tanh{0.628*(0.514-Ce)/(Ce(1-Ce))}]
or,fe/f =0.5[1+(e^x-e^{-x})/(e^x+e^{-x})]
where x = {0.628*(0.514-Ce)/(Ce(1-Ce))}
f = 1;a non aereted friction factor

(1-Ce)	(0.514-Ce)	Ce(1-Ce)	x	
0.4515214	-0.03448	0.24765	-0.087	
f	e^x	e^{-x}	e^x-e^{-x}	e^x+e^{-x}
1	0.916281	1.09137	-0.175	2.008

fe
0.456395

Uniform aereted flow depth,dwu =dc*{fe/(8sinα)}$^{1/3}$

8sinα	d_{wu}
4.875365	0.045711

Charactiristic depth (bulk depth), $d_{90}=dc*\{fe/(8(1-Ce)^3 \sin\alpha)\}^{1/3}$

$8(1-Ce)^3$sina	**d_{90}(m)**
0.4487891	0.10123

But it has come 0.065m from experiment.So questionable?

Rate of energy dissipation;

ΔH/Hmax =1-[{(fe/8sina)1/3*cosa+Ec/2(fe/8sina)-2/3}/(1.5+Hdam/dc) ;where $Ec=(N+1)^3/\{N^2*(N+3)$

where N=3.5 to 4, Ec=1.1 for N=3.5; Hmax=Hdam+1.5*dc

{fe/(8sina)}1/3	{fe/(8sina)}-2/3	(1.5+Hdam/dc)
0.4540938	4.84275	21.37

ΔH/Hmax
0.8585014

ie, rate of energy dissipation is 85.85%

Residual energy, H_{res}:

Hres/dc=(fe/8sina)^1/3+Ec/2(fe/8sina)^-2/3

H_{res}(m)
0.3043631

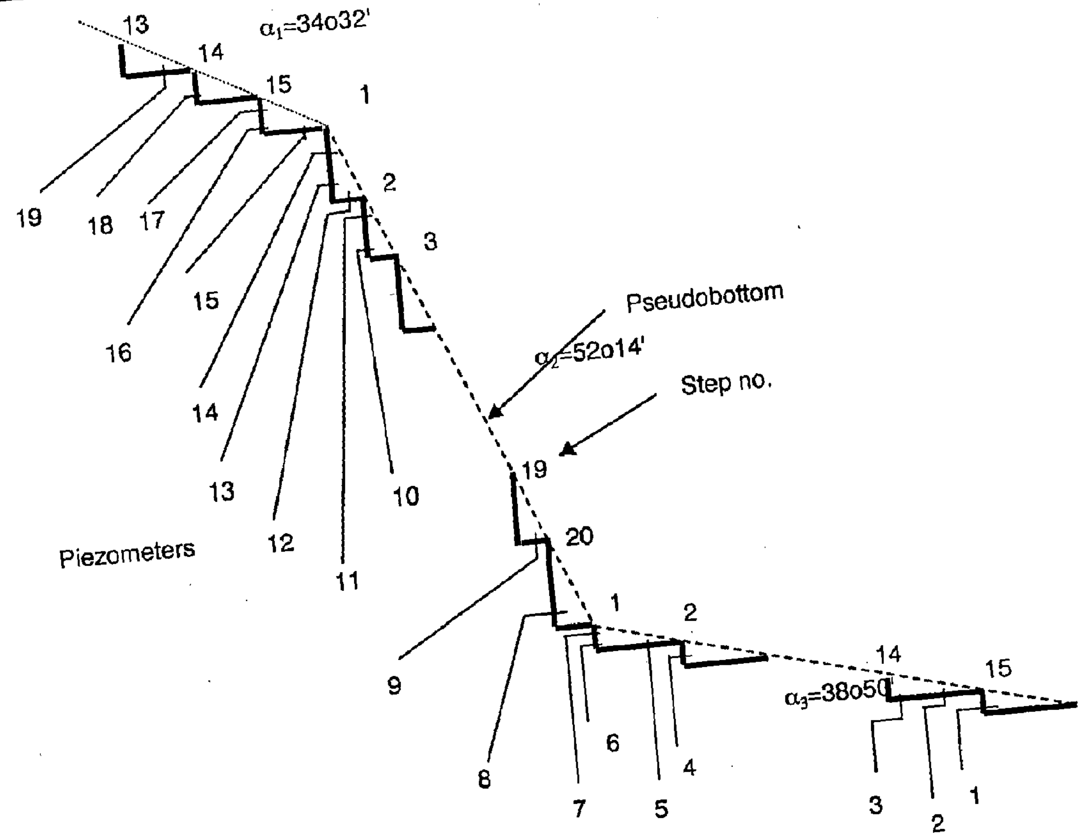
ie,energy lost by stepped spillways is:

H_{loss}=Hmax-Hres=Hspill+1.5*dc-Hres

H_{loss}(m)
1.8466337

3.6.2.10 Experiment no. 5

Water pressures at different points of steps for study of cavitations risks:



Experimental setup

Section of multislope stepped spillways showing the points in steps where the piezometric pressure head have been taken for cavitation risk study

Water pressures at different points of steps for study of cavitation risk (with use of circular suppressor):

SN	Disch.(Q)	Piezometric reading of diff.points in steps(cm)																		
	m3/s	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
1	0.004	0.5	4.1	1.6	0	13.5	4.8	0.7	2.4	2.5	0	0	0	0.4	0	4	1.5	-2	1.9	4.1
2	0.006	0.6	4.5	1.7	0	16	6.8	2.2	3	5.5	0	0	0	0.4	0	6.5	1.4	-2	2.1	7.5
3	0.008	1	5.5	1.7	0.8	16.5	7.9	3	3.4	5.5	0	0	0	0.4	0	6.5	1.5	-2	2.1	8.1
4	0.01	1.4	6	1.7	1.6	16.5	8.8	3.5	3.6	5.8	0	0	-0.1	0.4	0	7.7	1.6	-2	2.3	9.5
5	0.012	1.5	6.9	1.8	2.4	17.5	9.4	4.3	4.2	6.4	0	0	-0.3	0.2	0	11	2	-2	3.4	12.8
6	0.014	1.6	7.8	1.8	3.1	18.1	10.3	5.1	5.1	7.3	0	0	-0.6	0	0	12	2	-2	3.5	13.2
7	0.016	1.6	8.6	1.8	3.8	19.5	11.4	5.8	5.2	8	-0.5	-0.2	-1.1	-0.5	0	11.5	2	-1.9	4	12.7
8	0.018	1.6	9.5	2	4.4	19.8	11.9	6.5	5.7	8.8	-1	-1.7	-1.8	-1.3	0	11.5	2	-1.8	4	12.6
9	0.02	1.6	10	1.9	5	21.1	11.8	7	6	9.5	-2	-3	-3.1	-2.5	-0.3	12.6	1.9	-1.8	4.4	12.5

Water pressures at different points of steps for study of cavitation risk (without use of circular suppressor):

SN	Disch.(Q)	Piezometric reading of diff.points in steps(cm)																		
	m3/s	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
1	0.004	1.1	4.2	1.6	0	14	5.1	1.4	3	4.2	-1.4	-0.9	-2.4	0.4	0.3	3.6	1.5	-1.9	2	4.3
2	0.006	1.2	4.8	1.55	0.3	16.3	6.8	2.6	3.3	5.4	-1.4	-0.9	-2.4	0.4	0.3	7	1.5	-1.9	2.1	8.2
3	0.008	1.2	5.3	1.5	1.1	18	7.9	3.4	3.6	5.4	-1.4	-0.9	-2.4	0.4	0.3	7.3	1.8	-2	2.6	8.3
4	0.01	1.2	6	1.5	1.9	19.6	8.8	4	3.8	7	-1.4	-0.9	-2.4	0.3	0.25	8.2	1.9	-2	3.1	9.6
5	0.012	1.4	6.8	1.8	2.5	23.5	10	4.9	4.4	9.3	-1.4	-0.9	-2.4	0.2	0.2	11.2	2	-2.1	3.5	13.4
6	0.014	1.4	7.4	1.7	3	26	11.5	5.9	5.1	10.8	-1.4	-0.9	-2.4	0.1	0.1	11.8	2	-1.7	4	13.1
7	0.016	1.4	7.8	1.7	3.6	28	13	6.7	5.9	12.4	-1.4	-0.9	-2.4	0	0	11.3	2	-1.7	4.1	13.1
8	0.018	1.4	8.3	1.7	4.4	33.5	15	7.5	6.8	14.1	-1.4	-0.9	-2.4	0	0	11.5	2	-1.7	4.3	13
9	0.02	1.4	8.5	1.8	5.4	40	17	8.3	7.6	16.4	-1.4	-0.9	-2.4	0	0	12	2.4	-1.6	4.5	13.2

3.6.2.11 Experiment no.6: (Water flow depths in multislope stepped spillways)

With the use of Elliptical suppressor plate,No.1 i.e. P=135mm

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	**Slope of stepped spillways α_1 =34°32'**																				
1	1.66	0.006	0.2	0.03	Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	3	3	3	2	2	2	2	2	2	2	2	2	2	2					
					Min.	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2					
					Max.	3.5	3	3	3	2	2	2	2	2	2	2	2	2	2	2					
					Min.	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2					
					Aver.(d_{wps})	3.25	2.5	2.5	2.5	2	2	2	2	2	2	2	2	2	2	2					
					Inception																				
					length(cm)	30																			
					Flow patt	No air cavities,weak recirculating vortices,neither nappe nor skimming flow																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.5	3	5	5.5	5.4	5.3	5.2	5	4.8	4.5	4.3	4	5.5	5.5	5.5	4.5	4.5	4.5	4.5	3
					Min.	2	2.5	4.5	5	5	5	5	5	4.5	4	4	3	5	5	4.5	4	4	4	4	2.5
					Max.	2.5	3	5	5.5	5.4	5.3	5.2	5	4.8	4.5	4.3	4	5.5	5.5	5.5	4.5	4.5	4.5	4.5	3
					Min.	2	2.5	4.5	5	5	5	5	5	4.5	4	4	3	5	5	4.5	4	4	4	4	2.5
					Aver.(d_{wps})	2.25	2.75	4.75	5.3	5.2	5.2	5.1	5	4.65	4.25	4.15	3.5	5.25	5.25	5	4.25	4.25	4.25	4.25	2.8
					Inception																				
					length(cm)	35																			
					Flow patt	100% air cavities					25%to75% vortex				100% recir.vortices										
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.5	2	3.5	3.8	4	3.8	3.5	3.3	3.2	3	2.8	2.6	2.5	2.5	2.5					
					Min.	2	1.8	2.5	2.8	3	2.9	2.7	2.6	2.3	2	2	2	2	2	2					
					Max.	2.5	2	3.5	3.8	4	3.8	3.5	3.3	3.2	3	2.8	2.6	2.5	2.5	2.5					
					Min.	2	1.8	2.5	2.8	3	2.9	2.7	2.6	2.3	2	2	2	2	2	2					
					Aver.(d_{wps})	2.25	1.9	3	3.3	3.5	3.4	3.1	3	2.75	2.5	2.4	2.3	2.25	2.25	2.3					
					Inception																				
					length(cm)	10																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways $\alpha_1 = 34^0 32'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	3.5	3.5	3.5	2.5	2.5	2.5	2.5	2.5	3	3	3	3	3	3					
					Min.	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2					
					Max.	4	3.5	3.5	3.5	2.5	2.5	2.5	2.5	2.5	3	3	3	3	3	3					
					Min.	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2					
					Aver.(d_{wps})	3.5	3.25	3.25	3.3	2.25	2.3	2.3	2.3	2.25	2.5	2.5	2.5	2.5	2.5	2.5					
					Inception			-																	
					length(cm)	45																			
					Flow patt	No air cavities,weak recirculating vortices,neither nappe nor skimming flow																			
					Slope of stepped spillways $\alpha_2 = 52^0 14'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.5	4	4.5	5	4.5	4	3.5	3	3.5	3.8	4.2	4.5	4.2	4	3	3	3	3	3	3
					Min.	2	3.5	4.5	5	4	3	2.8	2.5	2.8	3	3.5	3.5	3.2	3	2.6	2.6	2.5	2.5	2.5	2.5
					Max.	2.5	4	4.5	5	4.5	4	3.5	3	3.5	3.8	4.2	4.5	4.2	4	3	3	3	3	3	3
2	2.95	0.008	0.2	0.04	Min.	2	3.5	4.5	5	4	3	2.8	2.5	2.8	3	3.5	3.5	3.2	3	2.6	2.6	2.5	2.5	2.5	2.5
					Aver.(d_{wps})	2.25	3.75	4.5	5	4.25	3.5	3.2	2.8	3.15	3.4	3.85	4	3.7	3.5	2.8	2.8	2.75	2.75	2.75	2.8
					Inception																				
					length(cm)	40																			
					Flow patt	100% air cavities					25%to75% vortex				100% recir.vortices										
					Slope of stepped spillways $\alpha_3 = 38^0 50'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3	2.5	4	4.2	4.4	4.5	4.5	4	3.5	3.2	3	3	3	3	3					
					Min.	2.5	2.2	3	3.2	3.4	3.5	3.5	3.2	2.8	2.2	2	2	2	2	2					
					Max.	3	2.5	4	4.2	4.4	4.5	4.5	4	3.5	3.2	3	3	3	3	3					
					Min.	2.5	2.2	3	3.2	3.4	3.5	3.5	3.2	2.8	2.2	2	2	2	2	2					
					Aver.(d_{wps})	2.75	2.35	3.5	3.7	3.9	4	4	3.6	3.15	2.7	2.5	2.5	2.5	2.5	2.5					
					Inception																				
					length(cm)	8																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Manometre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	**Slope of stepped spillways α_1 =34°32'**																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	5	4	3	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Min.	3	3	2.5	2.5	2.5	2	2	2	2	2	2	2	2	2	2					
					Max.	5	5	4	3	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Min.	3	3	2.5	2.5	2.5	2	2	2	2	2	2	2	2	2	2					
					Aver.(d_{wps})	4	4	3.25	2.8	2.75	2.3	2.3	2.3	2.25	2.25	2.25	2.25	2.25	2.25	2.3					
					Inception																				
					length(cm)	45																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.5	3.5	4	4.5	4	3.5	3	3.2	3.4	3.5	4.2	4.5	4.2	4	3.8	3.5	3.5	3.5	3.5	3.5
					Min.	2	3.5	3.8	4	3.5	3	2.5	2.6	2.8	3	3.3	3.5	3.2	3	2.8	2.5	2.5	2.5	2.5	2.5
					Max.	2.5	3.5	4	4.5	4	3.5	3	3.2	3.4	3.5	4.2	4.5	4.2	4	3.8	3.5	3.5	3.5	3.5	3.5
3	4.61	0.01	0.2	0.05	Min.	2	3.5	3.8	4	3.5	3	2.5	2.6	2.8	3	3.3	3.5	3.2	3	2.8	2.5	2.5	2.5	2.5	2.5
					Aver.(d_{wps})	2.25	3.5	3.9	4.3	3.75	3.3	2.8	2.9	3.1	3.25	3.75	4	3.7	3.5	3.3	3	3	3	3	3
					Inception																				
					length(cm)	40																			
					Flow patt	100% air cav.			25%to80% vort.			100% recir.vortices													
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	3	4	4.5	4.8	5	4.8	4.5	4	3.5	3	3	3	3	3					
					Min.	3	2.5	3	3.2	3.4	3.5	3.2	3	2.8	2.6	2.5	2.5	2.5	2.5	2.5					
					Max.	3.5	3	4	4.5	4.8	5	4.8	4.5	4	3.5	3	3	3	3	3					
					Min.	3	2.5	3	3.2	3.4	3.5	3.2	3	2.8	2.6	2.5	2.5	2.5	2.5	2.5					
					Aver.(d_{wps})	3.25	2.75	3.5	3.9	4.1	4.3	4	3.8	3.4	3.05	2.75	2.75	2.75	2.75	2.8					
					Inception																				
					length(cm)	5																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	6	6	5	5	5	4	4	4	4	4	4	4	4	4					
					Min.	5	5	4	4	4	4	3	3	3	3	3	3	3	3	3					
					Max.	6	6	6	5	5	5	4	4	4	4	4	4	4	4	4					
					Min.	5	5	4	4	4	4	3	3	3	3	3	3	3	3	3					
					Aver.(d_{wps})	5.5	5.5	5	4.5	4.5	4.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Inception																				
					length(cm)	50																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	3.5	4.5	5	4.8	4.5	4.6	4.7	4.8	4.9	4.9	4.9	5	4.8	4.5	4.5	4.5	4.5	4.5	4.5
					Min.	3	3.5	4	4.5	4.2	4	4	4	4	4	4	4	4	3.8	3.5	3.5	3.5	3.5	3.5	3.5
					Max.	3.5	3.5	4.5	5	4.8	4.5	4.6	4.7	4.8	4.9	4.9	4.9	5	4.8	4.5	4.5	4.5	4.5	4.5	4.5
4	6.63	0.012	0.2	0.06	Min.	3	3.5	4	4.5	4.2	4	4	4	4	4	4	4	4	3.8	3.5	3.5	3.5	3.5	3.5	3.5
					Aver.(d_{wps})	3.25	3.5	4.25	4.8	4.5	4.3	4.3	4.4	4.4	4.45	4.45	4.45	4.5	4.3	4	4	4	4	4	4
					Inception																				
					length(cm)	40																			
					Flow patt	100% air	40%to80% vort.		100% recir.vortices																
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	3.5	4	5	5.5	5.8	6	6	5.5	5	4.5	4	3.5	3.5	3.5					
					Min.	3	3	3	3	4	4	4	4	3.8	3.5	3.2	3	3	3	3					
					Max.	4	3.5	4	5	5.5	5.8	6	6	5.5	5	4.5	4	3.5	3.5	3.5					
					Min.	3	3	3	3	4	4	4	4	3.8	3.5	3.2	3	3	3	3					
					Aver.(d_{wps})	3.5	3.25	3.5	4	4.75	4.9	5	5	4.65	4.25	3.85	3.5	3.25	3.25	3.3					
					Inception																				
					length(cm)	5																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)																					
					Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6.5	6	6	6	5	5	5	4	4	4	3.5	4	4	4	4					
					Min.	4.5	4	4	4	3.5	3	3	3	3	3	3	3	3	3	3					
					Max.	6.5	6	6	6	5	5	5	4	4	4	3.5	4	4	4	4					
					Min.	4.5	4	4	4	3.5	3	3	3	3	3	3	3	3	3	3					
					Aver.(d_{wps})	5.5	5	5	5	4.25	4	4	3.5	3.5	3.5	3.25	3.5	3.5	3.5	3.5					
					Inception																				
					length(cm)	50																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	3.5	4	4.5	4.3	4.2	4	4.2	4.5	4.8	5	5.3	5.5	5	4	4	4	4	4	4
					Min.	3	3	3.5	4.5	4	4	3.5	3.8	4	4.2	4.3	4.5	4.5	4	3.5	3.5	3.5	3.5	3.5	3.5
					Max.	3.5	3.5	4	4.5	4.3	4.2	4	4.2	4.5	4.8	5	5.3	5.5	5	4	4	4	4	4	4
5	9.03	0.014	0.2	0.07	Min.	3	3	3.5	4.5	4	4	3.5	3.8	4	4.2	4.3	4.5	4.5	4	3.5	3.5	3.5	3.5	3.5	3.5
					Aver.(d_{wps})	3.25	3.25	3.75	4.5	4.15	4.1	3.8	4	4.25	4.5	4.65	4.9	5	4.5	3.8	3.75	3.75	3.75	3.75	3.8
					Inception																				
					length(cm)	30																			
					Flow patt	100% air		50% vort.		100% recir.vortices															
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	3.5	4.5	4.8	5	5.2	5.3	5.5	5	4.5	4	3.5	3.5	3.5	3.5					
					Min.	3	3	3.5	3.8	4	4.2	4.3	4.5	4	3.8	3.5	3.5	3.5	3.5	3.5					
					Max.	4	3.5	4.5	4.8	5	5.2	5.3	5.5	5	4.5	4	3.5	3.5	3.5	3.5					
					Min.	3	3	3.5	3.8	4	4.2	4.3	4.5	4	3.8	3.5	3.5	3.5	3.5	3.5					
					Aver.(d_{wps})	3.5	3.25	4	4.3	4.5	4.7	4.8	5	4.5	4.15	3.75	3.5	3.5	3.5	3.5					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	**Slope of stepped spillways α_1 =34°32'**																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	8	7	7	6	6	5	5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	6	6	5	5	5	4	4	4	3.8	3.5	3.5	3.5	3.5	3.5	3.5					
					Max.	8	7	7	6	6	5	5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	6	6	5	5	5	4	4	4	3.8	3.5	3.5	3.5	3.5	3.5	3.5					
					Aver.(d_{wps})	7	6.5	6	5.5	5.5	4.5	4.5	4.5	4.15	4	4	4	4	4	4					
					Inception																				
					length(cm)	50																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	4.5	5.5	5	4.5	4.5	4.5	4.8	5	5.3	5.3	5.4	5.5	5.3	5	5	5	5	5	5
					Min.	3.5	4.5	5	4.5	4.5	4	3.5	3.6	3.8	4	4.3	4.3	4.5	4.3	4	4	4	4	4	4
					Max.	4	4.5	5.5	5	4.5	4.5	4.5	4.8	5	5.3	5.3	5.4	5.5	5.3	5	5	5	5	5	5
6	11.8	0.016	0.2	0.08	Min.	3.5	4.5	5	4.5	4.5	4	3.5	3.6	3.8	4	4.3	4.3	4.5	4.3	4	4	4	4	4	4
					Aver.(d_{wps})	3.75	4.5	5.25	4.8	4.5	4.3	4	4.2	4.4	4.65	4.8	4.85	5	4.8	4.5	4.5	4.5	4.5	4.5	4.5
					Inception																				
					length(cm)	30																			
					Flow patt	90% air	20%vortex	100% recir.vortices																	
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	4.5	4.5	5	5.3	5.5	5.8	6	6	5.5	5.5	5.5	4.8	4.5	4.5					
					Min.	4	3.5	4	4	4.2	4.5	4.5	4.5	4.5	4.2	4	3.5	3.5	3.5	3.5					
					Max.	6.5	5.5	5	6	6.5	7.7	7	7.5	8	8	8	7	7.5	7.5	7.5					
					Min.	4.5	4	4	4.5	5	5.5	5.5	6	6.5	6.5	6.5	6	5.5	5.5	5.5					
					Aver.(d_{wps})	5	4.38	4.38	4.9	5.25	5.8	5.7	6	6.25	6.05	6	5.5	5.33	5.25	5.3					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	9	9	7	7	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	7	7	5.5	5.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Max.	9	9	7	7	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	7	7	5.5	5.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Aver.(d_{wps})	8	8	6.25	6.3	4	4	4	4	4	4	4	4	4	4	4					
					Inception																				
					length(cm)	50																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	4.5	4.5	5	4.8	4.6	4.5	4.5	4.5	4.8	5	5	5.3	5.2	6	5	5	5	5	5
					Min.	3.5	4.5	4	4	4	4	4	4	4	4.2	4.3	4.5	4.5	5	5	4.5	4.5	4.5	4.5	4.5
					Max.	3.5	4.5	4.5	5	4.8	4.6	4.5	4.5	4.5	4.8	5	5	5.3	5.2	6	5	5	5	5	5
7	14.92	0.018	0.2	0.09	Min.	3.5	4.5	4	4	4	4	4	4	4	4.2	4.3	4.5	4.5	5	5	4.5	4.5	4.5	4.5	4.5
					Aver.(d_{wps})	3.5	4.5	4.25	4.5	4.4	4.3	4.3	4.3	4.25	4.5	4.65	4.75	4.9	5.1	5.5	4.75	4.75	4.75	4.75	4.8
					Inception																				
					length(cm)	30																			
					Flow patt	80% air	100% recir.vortices																		
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	4.5	4.5	5	5.2	5.5	5.5	5.8	6	5.5	5	4.5	4.5	4.5	4.5					
					Min.	4	3.5	3.5	3.8	3.9	4	4.3	4.5	4.5	3.5	3.5	3.2	3.2	3.2	3.2					
					Max.	5	4.5	4.5	5	5.2	5.5	5.5	5.8	6	5.5	5	4.5	4.5	4.5	4.5					
					Min.	4	3.5	3.5	3.8	3.9	4	4.3	4.5	4.5	3.5	3.5	3.2	3.2	3.2	3.2					
					Aver.(d_{wps})	4.5	4	4	4.4	4.55	4.8	4.9	5.2	5.25	4.5	4.25	3.85	3.85	3.85	3.9					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways $\alpha_1 = 34^0 32'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	9.5	10	9	8	6	6	6	5	5	5	5	5	5	5	5					
					Min.	8	8	7	6	5	5	5	4	4	4	4	4	4	4	4					
					Max.	9.5	10	9	8	6	6	6	5	5	5	5	5	5	5	5					
					Min.	8	8	7	6	5	5	5	4	4	4	4	4	4	4	4					
					Aver.(d_{wps})	8.75	9	8	7	5.5	5.5	5.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Inception																				
					length(cm)	55																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways $\alpha_2 = 52^0 14'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4.7	5	5	5	4.8	4.5	4.7	4.9	5	5	5.3	5.5	6	6	6	6	6	6	6
					Min.	4.5	4.5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	5	5	5	5	5	5	5	5	5
					Max.	4.5	4.7	5	5	5	4.8	4.5	4.7	4.9	5	5	5.3	5.5	6	6	6	6	6	6	6
8	18.42	0.02	0.2	0.1	Min.	4.5	4.5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	5	5	5	5	5	5	5	5	5
					Aver.(d_{wps})	4.5	4.6	5	4.8	4.75	4.7	4.5	4.6	4.7	4.75	4.75	5.15	5.25	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Inception																				
					length(cm)	20																			
					Flow patt	25% air	100% recir.vortices																		
					Slope of stepped spillways $\alpha_3 = 38^0 50'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	5.5	5	5	5.5	6	6.3	6.8	7	6.5	6	5.5	5.3	5	5					
					Min.	4	3.5	4	4	4.5	5	5	5	5	5	5	4.5	4	4	4					
					Max.	6	5.5	5	5	5.5	6	6.3	6.8	7	6.5	6	5.5	5.3	5	5					
					Min.	4	3.5	4	4	4.5	5	5	5	5	5	5	4.5	4	4	4					
					Aver.(d_{wps})	5	4.5	4.5	4.5	5	5.5	5.7	5.9	6	5.75	5.5	5	4.65	4.5	4.5					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

3.6.2.12 Experiment no.7: (Water flow depths in multislope stepped spillways)

With the use of Elliptical suppressor plate,No.2 i.e. P=90mm

SN	Manometre reading (x cm)	Disch. (Q) (cum)	Width of spillways (b m)	Disch. perunit length (q) cum/m)	**Slope of stepped spillways α_1 =34°32'**																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	3.5	3.3	3	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8					
					Min.	3	3	2.5	2	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8					
					Max.	3.5	3.5	3.3	3	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8					
					Min.	3	3	2.5	2	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8					
					Aver.(d_{wps})	3.25	3.25	2.9	2.5	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3					
					Inception																				
					length(cm)	15																			
					Flow patt	No air cavities,weak recirculating vortices,with skimming flow																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3	4.5	5.5	6	5.5	5.5	5	4.5	4	4	4	4	4	4	3.5	3.5	3.5	3	3	3
					Min.	2	4	5.5	5	5	5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3	3	2	2	2	2
					Max.	3	4.5	5.5	6	5.5	5.5	5	4.5	4	4	4	4	4	4	3.5	3.5	3.5	3	3	3
1	1.66	0.006	0.2	0.03	Min.	2	4	5.5	5	5	5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3	3	2	2	2	2
					Aver.(d_{wps})	2.5	4.25	5.5	5.5	5.25	5.3	4.5	4	3.75	3.75	3.75	3.75	3.75	3.75	3.3	3.25	2.75	2.5	2.5	2.5
					Inception																				
					length(cm)																				
					Flow patt	100% air cavities				85to10% air cav.			100% recir.vortices												
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.5	2.5	4.5	5.5	6	5.5	5.5	4.5	4	4	3.5	6.5	3.25	3.25	3.3					
					Min.	2	2.5	3.5	4	4.5	4	3.5	3.5	3	3	2.5	2.5	2	2	2					
					Max.	2.5	2.5	4.5	5.5	6	5.5	5.5	4.5	4	4	3.5	6.5	3.25	3.25	3.3					
					Min.	2	2.5	3.5	4	4.5	4	3.5	3.5	3	3	2.5	2.5	2	2	2					
					Aver.(d_{wps})	2.25	2.5	4	4.8	5.25	4.8	4.5	4	3.5	3.5	3	4.5	2.63	2.63	2.6					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4.5	3.5	3.5	3	3	3	3	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Min.	3.5	3.5	2.5	2.5	2	2	2	2	2	2	2	2	2	2	2					
					Max.	4.5	4.5	3.5	3.5	3	3	3	3	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Min.	3.5	3.5	2.5	2.5	2	2	2	2	2	2	2	2	2	2	2					
					Aver.(d_{wps})	4	4	3	3	2.5	2.5	2.5	2.5	2.75	2.75	2.75	2.75	2.75	2.75	2.8					
					Inception																				
					length(cm)	18																			
					Flow patt	No air cavities,weak recirculating vortices,with skimming flow																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3	4.5	5.5	5.5	5.5	5.5	5	4	4	4.5	5	4.8	4.8	4.8	4.8	4.8	4.5	4	3.5	3.5
					Min.	2.5	4.5	5.5	5	5	4.5	4	3	3.5	4	4	3.6	3.6	3.6	3.6	3.6	3.5	3	3	3
					Max.	3	4.5	5.5	5.5	5.5	5.5	5	4	4	4.5	5	4.8	4.8	4.8	4.8	4.8	4.5	4	3.5	3.5
2	2.95	0.008	0.2	0.04	Min.	2.5	4.5	5.5	5	5	4.5	4	3	3.5	4	4	3.6	3.6	3.6	3.6	3.6	3.5	3	3	3
					Aver.(d_{wps})	2.75	4.5	5.5	5.3	5.25	5	4.5	3.5	3.75	4.25	4.5	4.2	4.2	4.2	4.2	4.2	4	3.5	3.25	3.3
					Inception																				
					length(cm)																				
					Flow patt	100% air cavities				50to10%air cav.			100% recir.vortices												
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	3	4.5	5.5	6	6.5	6	5.5	5.5	4.5	4	4	3.5	3.5	3.5					
					Min.	3	2.5	3.5	4.5	4.5	4.5	4.5	4	3.5	3	3	3	3	3	3					
					Max.	3.5	3	4.5	5.5	6	6.5	6	5.5	5.5	4.5	4	4	3.5	3.5	3.5					
					Min.	3	2.5	3.5	4.5	4.5	4.5	4.5	4	3.5	3	3	3	3	3	3					
					Aver.(d_{wps})	3.25	2.75	4	5	5.25	5.5	5.3	4.8	4.5	3.75	3.5	3.5	3.25	3.25	3.3					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Manometre reading (x cm)	Disch. (Q) (cum)	Width of spillways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	5	4	4	3.5	3	3	3	3	3	3.5	3.5	3.5	3.5	3.5					
					Min.	4	3.5	3	3	2.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Max.	5	5	4	4	3.5	3	3	3	3	3	3.5	3.5	3.5	3.5	3.5					
					Min.	4	3.5	3	3	2.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Aver.(d_{wps})	4.5	4.25	3.5	3.5	3.15	2.8	2.8	2.8	2.75	2.75	3	3	3	3	3					
					Inception																				
					length(cm)	28																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	4.5	5.5	5.5	5	5	5	5	5	5	5.5	5.5	5.5	5.5	5.5	5.5	4	4	4	4
					Min.	2.8	4.5	5	5	5	4	4	4	4	4	4.5	4.5	4.5	4.5	4.5	4.5	4	3	3	3
					Max.	3.5	4.5	5.5	5.5	5	5	5	5	5	5	5.5	5.5	5.5	5.5	5.5	5.5	4	4	4	4
3	4.61	0.01	0.2	0.05	Min.	2.8	4.5	5	5	5	4	4	4	4	4	4.5	4.5	4.5	4.5	4.5	4.5	4	3	3	3
					Aver.(d_{wps})	3.15	4.5	5.25	5.3	5	4.5	4.5	4.5	4.5	4.5	5	5	5	5	5	5	4	3.5	3.5	3.5
					Inception																				
					length(cm)																				
					Flow patt	100% air cav.			75to5% air cav.			100% recir.vortices													
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	3.5	4.5	5.5	5.6	6	6.5	6.5	6	5.5	5	4.5	4	4	4					
					Min.	3	2.8	3.5	4	4.5	5	5	5	4.5	4	3.8	3.5	3	3	3					
					Max.	4	3.5	4.5	5.5	5.6	6	6.5	6.5	6	5.5	5	4.5	4	4	4					
					Min.	3	2.8	3.5	4	4.5	5	5	5	4.5	4	3.8	3.5	3	3	3					
					Aver.(d_{wps})	3.5	3.15	4	4.8	5.05	5.5	5.8	5.8	5.25	4.75	4.4	4	3.5	3.5	3.5					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	6	5.5	5.5	4.5	4	4	4	4	4	4	4	4	4	4					
					Min.	5	5	4.5	4.5	3.5	3.5	3	3	3	3	3	3	3	3	3					
					Max.	6	6	5.5	5.5	4.5	4	4	4	4	4	4	4	4	4	4					
					Min.	5	5	4.5	4.5	3.5	3.5	3	3	3	3	3	3	3	3	3					
					Aver.(d_{wps})	5.5	5.5	5	5	4	3.8	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Inception																				
					length(cm)	30																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5	5	5
					Min.	3.5	4.5	5	5	4.5	4.5	4.5	4.5	4.5	4	4	4	4	4	4	4	4	4	4	4
					Max.	4	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5	5	5
4	6.63	0.012	0.2	0.06	Min.	3.5	4.5	5	5	4.5	4.5	4.5	4.5	4.5	4	4	4	4	4	4	4	4	4	4	4
					Aver.(d_{wps})	3.75	4.5	5	5.3	5	5	5	5	5	4.75	4.75	4.75	4.75	4.75	4.8	4.75	4.75	4.5	4.5	4.5
					Inception																				
					length(cm)																				
					Flow patt	100% air	60to10% air cav.			100% recir.vortices															
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	3.5	4.5	5.5	6.5	7	7	7	6.5	6	5.5	5.5	5	4.5	4.5					
					Min.	3.5	3	4	4.5	5.5	5.5	6	5.5	5.5	5	4.5	4	4.5	4	4					
					Max.	4.5	3.5	4.5	5.5	6.5	7	7	7	6.5	6	5.5	5.5	5	4.5	4.5					
					Min.	3.5	3	4	4.5	5.5	5.5	6	5.5	5.5	5	4.5	4	4.5	4	4					
					Aver.(d_{wps})	4	3.25	4.25	5	6	6.3	6.5	6.3	6	5.5	5	4.75	4.75	4.25	4.3					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways $\alpha_1 = 34^0 32'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	6	5.5	5	5	4.5	4	4	4	4	4	4	4	4	4					
					Min.	5	5	4	4	3.5	3	3	3	3	3	3	3	3	3	3					
					Max.	6	6	5.5	5	5	4.5	4	4	4	4	4	4	4	4	4					
					Min.	5	5	4	4	3.5	3	3	3	3	3	3	3	3	3	3					
					Aver.(d_{wps})	5.5	5.5	4.75	4.5	4.25	3.8	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Inception																				
					length(cm)	30																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways $\alpha_2 = 52^0 14'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Min.	3	4.5	5	5	5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
					Max.	4	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
5	9.03	0.014	0.2	0.07	Min.	3	4.5	5	5	5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
					Aver.(d_{wps})	3.5	4.5	5	5.3	5.25	5.3	5	5	5	5	5	5	5	5	5	5	5	5	5	5
					Inception																				
					length(cm)																				
					Flow patt	100% air	50to10%aircav.		100% recir.vortices from step 5																
					Slope of stepped spillways $\alpha_3 = 38^0 50'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5.5	4	4.5	5.5	6	6.5	7	6.5	6.5	6.5	6	5.5	5	5	5					
					Min.	4.5	3.5	4	4.5	5	5.5	5.5	5.5	5.5	5	4.5	4.5	4	4	4					
					Max.	5.5	4	4.5	5.5	6	6.5	7	6.5	6.5	6.5	6	5.5	5	5	5					
					Min.	4.5	3.5	4	4.5	5	5.5	5.5	5.5	5.5	5	4.5	4.5	4	4	4					
					Aver.(d_{wps})	5	3.75	4.25	5	5.5	6	6.3	6	6	5.75	5.25	5	4.5	4.5	4.5					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34^{0}32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	7	7.5	7	6	5	4	4	4	4	4	4	4	4	4	4					
					Min.	5	5.5	5	4	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Max.	7	7.5	7	6	5	4	4	4	4	4	4	4	4	4	4					
					Min.	5	5.5	5	4	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Aver.(d_{wps})	6	6.5	6	5	4.5	3.8	3.8	3.8	3.75	3.75	3.75	3.75	3.75	3.75	3.8					
					Inception																				
					length(cm)	32																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways α_2 =52^{0}14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4.5	5	5	5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Min.	3.5	4.5	4	4	4	4	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
					Max.	4.5	4.5	5	5	5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
6	11.8	0.016	0.2	0.08	Min.	3.5	4.5	4	4	4	4	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
					Aver.(d_{wps})	4	4.5	4.5	4.5	4.5	4.5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
					Inception																				
					length(cm)																				
					Flow patt	100to10% air cav. In step 1,2,3							100% recir.vortices from step 4 onward												
					Slope of stepped spillways α_3 =38^{0}50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5.5	4.5	4.5	5.5	6	6.5	7	7.5	7	6.5	6.5	6	5.5	5.5	5.5					
					Min.	4.5	4	4.5	4.5	5	5.5	6	6.5	6	5.5	5.5	5	4.5	4.5	4.5					
					Max.	5.5	4.5	4.5	5.5	6	6.5	7	7.5	7	6.5	6.5	6	5.5	5.5	5.5					
					Min.	4.5	4	4.5	4.5	5	5.5	6	6.5	6	5.5	5.5	5	4.5	4.5	4.5					
					Aver.(d_{wps})	5	4.25	4.5	5	5.5	6	6.5	7	6.5	6	6	5.5	5	5	5					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	9	10	8	7	6	5.5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	7	6	5.5	5	4.5	4.5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Max.	9	10	8	7	6	5.5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	7	6	5.5	5	4.5	4.5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Aver.(d_{wps})	8	8	6.75	6	5.25	5	4.5	4	4	4	4	4	4	4	4					
					Inception																				
					length(cm)	38																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4.5	5	5	5	5	5	5.5	5.5	6	6.5	6.5	6.5	6.5	7	7	7	6.5	6	6
					Min.	3.5	4.5	5	5	5	5	5	5	5	5	5.5	5.5	5.5	5.5	6	6	6	5.5	5	5
					Max.	4.5	4.5	5	5	5	5	5	5.5	5.5	6	6.5	6.5	6.5	6.5	7	7	7	6.5	6	6
7	14.92	0.018	0.2	0.09	Min.	3.5	4.5	5	5	5	5	5	5	5	5	5.5	5.5	5.5	5.5	6	6	6	5.5	5	5
					Aver.(d_{wps})	4	4.5	5	5	5	5	5	5.3	5.25	5.5	6	6	6	6	6.5	6.5	6.5	6	5.5	5.5
					Inception																				
					length(cm)																				
					Flow patt	100to5% air cavities in steps 1,2,3								100% recir.vortices from step 4 onwards											
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	5	5	5.5	6	7	8	8	8.5	8.5	7.5	7.5	6.5	5.5	5.5					
					Min.	5	4	4	4.5	5	5.5	6	6	6.5	6.5	6	6	5.5	4.5	4.5					
					Max.	6	5	5	5.5	6	7	8	8	8.5	8.5	7.5	7.5	6.5	5.5	5.5					
					Min.	5	4	4	4.5	5	5.5	6	6	6.5	6.5	6	6	5.5	4.5	4.5					
					Aver.(d_{wps})	5.5	4.5	4.5	5	5.5	6.3	7	7	7.5	7.5	6.75	6.75	6	5	5					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	**Slope of stepped spillways α_1 =34°32'**																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	9	9	8	7	6.5	6	5	5	5	5	5	5	5	5	5					
					Min.	7	6.5	6	5	5	4.5	4	4	4	4	4	4	4	4	4					
					Max.	9	9	8	7	6.5	6	5	5	5	5	5	5	5	5	5					
					Min.	7	6.5	6	5	5	4.5	4	4	4	4	4	4	4	4	4					
					Aver.(d_{wps})	8	7.75	7	6	5.75	5.3	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Inception																				
					length(cm)	40																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4.5	5	5	5	5	5	5.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
					Min.	4.5	4.5	4.5	4.5	4.5	4.5	4.5	5	6	6	6	6	6	6	6	6	6	6	6	6
					Max.	4.5	4.5	5	5	5	5	5	5.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
8	18.42	0.02	0.2	0.1	Min.	4.5	4.5	4.5	4.5	4.5	4.5	4.5	5	6	6	6	6	6	6	6	6	6	6	6	6
					Aver.(d_{wps})	4.5	4.5	4.75	4.8	4.75	4.8	4.8	5.3	6.75	6.75	6.75	6.75	6.75	6.75	6.8	6.75	6.75	6.75	6.75	6.8
					Inception																				
					length(cm)																				
					Flow patt	40 to 5% air cavity in step 1,2							100% recir.vortices from step 3 onwards												
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	7.5	6	5	5.5	6	7	8	8.5	9	9	9	8.5	8.5	8	8					
					Min.	5.5	5	4.5	4.5	5	5.5	6	6.5	7	7	7	6.5	6.5	6	6					
					Max.	7.5	6	5	5.5	6	7	8	8.5	9	9	9	8.5	8.5	8	8					
					Min.	5.5	5	4.5	4.5	5	5.5	6	6.5	7	7	7	6.5	6.5	6	6					
					Aver.(d_{wps})	6.5	5.5	4.75	5	5.5	6.3	7	7.5	8	8	8	7.5	7.5	7	7					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

3.6.2.13 Experiment no.8: (Water flow depths in multislope stepped spillways)

With the use of Elliptical suppressor plate,No.3 i.e. P=45mm

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	**Slope of stepped spillways α_1 =34°32'**																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	3	3	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Min.	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2					
					Max.	3.5	3	3	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Min.	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2					
					Aver.(d_{wps})	3.25	2.5	2.5	2.5	2.25	2.3	2.3	2.3	2.25	2.25	2.25	2.25	2.25	2.25	2.3					
					Inception																				
					length(cm)	25																			
					Flow patt	No air cavities,weak recirculating vortices,neither nappe nor skimming flow																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.5	3.5	4.5	5.5	6	5.5	5	4	4	4	4	4	4	4	4	4	4	4	4	4
					Min.	2	3	4.5	5.5	5	4.5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
					Max.	2.5	3.5	4.5	5.5	6	5.5	5	4	4	4	4	4	4	4	4	4	4	4	4	4
1	1.66	0.006	0.2	0.03	Min.	2	3	4.5	5.5	5	4.5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
					Aver.(d_{wps})	2.25	3.25	4.5	5.5	5.5	5	4.5	3.8	3.75	3.75	3.75	3.75	3.75	3.75	3.8	3.75	3.75	3.75	3.75	3.8
					Inception																				
					length(cm)																				
					Flow patt	100% air cavities					75 to 25% air			100% recir.vortices											
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.6	2.5	4	5.5	5.5	5.5	5.5	5	4.5	4	2.5	2.5	2.5	2.5	2.5					
					Min.	2	2	3	4.5	4.5	4.5	4.5	4	3.5	3	2	2	2	2	2					
					Max.	2.6	2.5	4	5.5	5.5	5.5	5.5	5	4.5	4	2.5	2.5	2.5	2.5	2.5					
					Min.	2	2	3	4.5	4.5	4.5	4.5	4	3.5	3	2	2	2	2	2					
					Aver.(d_{wps})	2.3	2.25	3.5	5	5	5	5	4.5	4	3.5	2.25	2.25	2.25	2.25	2.3					
					Inception																				
					length(cm)	5																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	3.5	3.5	3	3	3	3	3	3	3	3	3	3	3	3					
					Min.	3	2.8	2.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Max.	4	3.5	3.5	3	3	3	3	3	3	3	3	3	3	3	3					
					Min.	3	2.8	2.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5					
					Aver.(d_{wps})	3.5	3.15	3.15	2.8	2.75	2.8	2.8	2.8	2.75	2.75	2.75	2.75	2.75	2.75	2.8					
					Inception																				
					length(cm)	20																			
					Flow patt	No air cavities,weak recirculating vortices,neither nappe nor skimming flow																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	2.8	4.5	5	5.5	5.5	5.5	5	4.5	4	4	4.2	4.4	4.5	4.6	4.8	5	4.8	4.5	4.5	4.5
					Min.	2	4	5	5.5	5	5	4.5	4	4	3.5	3.6	3.8	4	4	4	4	3.8	3.5	3.5	3.5
					Max.	2.8	4.5	5	5.5	5.5	5.5	5	4.5	4	4	4.2	4.4	4.5	4.6	4.8	5	4.8	4.5	4.5	4.5
2	2.95	0.008	0.2	0.04	Min.	2	4	5	5.5	5	5	4.5	4	4	3.5	3.6	3.8	4	4	4	4	3.8	3.5	3.5	3.5
					Aver.(d_{wps})	2.4	4.25	5	5.5	5.25	5.3	4.8	4.3	4	3.75	3.9	4.1	4.25	4.3	4.4	4.5	4.3	4	4	4
					Inception																				
					length(cm)																				
					Flow patt	100% air cavities				50 to 80% air				100% recir.vortices											
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.8	3.5	4.5	5	6	6	5.5	5.5	5.5	4.5	4	3.8	3.5	3.5	3.5					
					Min.	3	3	3.5	4	4.5	4.5	4	4	3.8	3.5	3	3	3	3	3					
					Max.	3.8	3.5	4.5	5	6	6	5.5	5.5	5.5	4.5	4	3.8	3.5	3.5	3.5					
					Min.	3	3	3.5	4	4.5	4.5	4	4	3.8	3.5	3	3	3	3	3					
					Aver.(d_{wps})	3.4	3.25	4	4.5	5.25	5.3	4.8	4.8	4.65	4	3.5	3.4	3.25	3.25	3.3					
					Inception																				
					length(cm)	5																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Manometre reading (x cm)	Disch. (Q) (cum)	Width of spillways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4	4	4	4	4	3	3	3	3	3	3	3	3	3					
					Min.	3.5	3	3	3	3	3	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8					
					Max.	4.5	4	4	4	4	4	3	3	3	3	3	3	3	3	3					
					Min.	3.5	3	3	3	3	3	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8					
					Aver.(d_{wps})	4	3.5	3.5	3.5	3.5	3.5	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9					
					Inception																				
					length(cm)	35																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3	4.5	5	5.5	5.5	5.5	5	4	4	4	4.5	5	5.5	5.5	5.5	5.5	5.5	5	4.5	4.5
					Min.	3	4.5	5	5.5	5.5	5	4.5	3.5	3.5	3.5	4	4	4.5	4.5	4.5	4.5	4.5	4	4	4
					Max.	3	4.5	5	5.5	5.5	5.5	5	4	4	4	4.5	5	5.5	5.5	5.5	5.5	5.5	5	4.5	4.5
3	4.61	0.01	0.2	0.05	Min.	3	4.5	5	5.5	5.5	5	4.5	3.5	3.5	3.5	4	4	4.5	4.5	4.5	4.5	4.5	4	4	4
					Aver.(d_{wps})	3	4.5	5	5.5	5.5	5.3	4.8	3.8	3.75	3.75	4.25	4.5	5	5	5	5	5	4.5	4.25	4.3
					Inception																				
					length(cm)																				
					Flow patt	100% air cav.		60to10% air.			100% recir.vortices														
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.8	3.5	4	5	5.5	5.5	5.5	5.5	5.5	5.5	5	4.5	4	4	4					
					Min.	3.8	3	3.5	4	4.5	4.5	4.5	4.5	4.5	4.5	4	3.8	3.5	3	3					
					Max.	4.8	3.5	4	5	5.5	5.5	5.5	5.5	5.5	5.5	5	4.5	4	4	4					
					Min.	3.8	3	3.5	4	4.5	4.5	4.5	4.5	4.5	4.5	4	3.8	3.5	3	3					
					Aver.(d_{wps})	4.3	3.25	3.75	4.5	5	5	5	5	5	5	4.5	4.15	3.75	3.5	3.5					
					Inception																				
					length(cm)	5																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5.5	5.5	5	4.5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Min.	4.5	4.5	4	3.5	3	3	3	3	3	3	3	3	3	3	3					
					Max.	5.5	5.5	5	4.5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Min.	4.5	4.5	4	3.5	3	3	3	3	3	3	3	3	3	3	3					
					Aver.(d_{wps})	5	5	4.5	4	3.5	3.3	3.3	3.3	3.25	3.25	3.25	3.25	3.25	3.25	3.3					
					Inception																				
					length(cm)	35																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	4.5	5	5.5	4	4	4	4	4	4.5	5	5	5.5	6	5	5	6	6	5.5	5.5
					Min.	3	4.5	5	5.5	3.5	3.5	3.5	3.5	3.5	3	3.5	4	4.5	4.8	4.8	4.8	4.8	4.8	4.5	4.5
					Max.	3.5	4.5	5	5.5	4	4	4	4	4	4.5	5	5	5.5	6	5	5	6	6	5.5	5.5
4	6.63	0.012	0.2	0.06	Min.	3	4.5	5	5.5	3.5	3.5	3.5	3.5	3.5	3	3.5	4	4.5	4.8	4.8	4.8	4.8	4.8	4.5	4.5
					Aver.(d_{wps})	3.25	4.5	5	5.5	3.75	3.8	3.8	3.8	3.75	3.75	4.25	4.5	5	5.4	4.9	4.9	5.4	5.4	5	5
					Inception																				
					length(cm)																				
					Flow patt	100% air	50% air.		100% recir.vortices																
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	4	4.5	5	5.5	6	6	6	6	6	5.8	5.5	5	4	4					
					Min.	4	3.5	4	4.5	4.5	4.5	5	5	5	5	4.5	4	4	3.5	3.5					
					Max.	5	4	4.5	5	5.5	6	6	6	6	6	5.8	5.5	5	4	4					
					Min.	4	3.5	4	4.5	4.5	4.5	5	5	5	5	4.5	4	4	3.5	3.5					
					Aver.(d_{wps})	4.5	3.75	4.25	4.8	5	5.3	5.5	5.5	5.5	5.5	5.15	4.75	4.5	3.75	3.8					
					Inception																				
					length(cm)	5																			
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways $\alpha_1 = 34^0 32'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	5	4.5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Min.	4	4	3.5	3	3	3	3	3	3	3	3	3	3	3	3					
					Max.	6	5	4.5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Min.	4	4	3.5	3	3	3	3	3	3	3	3	3	3	3	3					
					Aver.(d_{wps})	5	4.5	4	3.5	3.25	3.3	3.3	3.3	3.25	3.25	3.25	3.25	3.25	3.25	3.3					
					Inception																				
					length(cm)	25																			
					Flow patt	No air cavities,weak recirculating vortices																			
					Slope of stepped spillways $\alpha_2 = 52^0 14'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	3.5	4.5	5	5.5	5.5	5.5	5.5	5	4.5	5	5.5	6	6	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Min.	3	4.5	5	5.5	5.5	5.5	5	4.5	4	4.5	4.5	5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
					Max.	3.5	4.5	5	5.5	5.5	5.5	5.5	5	4.5	5	5.5	6	6	5.5	5.5	5.5	5.5	5.5	5.5	5.5
5	9.03	0.014	0.2	0.07	Min.	3	4.5	5	5.5	5.5	5.5	5	4.5	4	4.5	4.5	5	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
					Aver.(d_{wps})	3.25	4.5	5	5.5	5.5	5.5	5.3	4.8	4.25	4.75	5	5.5	5.5	5	5	5	5	5	5	5
					Inception																				
					length(cm)																				
					Flow patt	100% air		25% air.		100% recir.vortices															
					Slope of stepped spillways $\alpha_3 = 38^0 50'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5	4	4.5	4.8	5.5	6	6.2	6.5	6.5	6	6	5.8	5	5	5					
					Min.	4	3.5	4	4	4.5	5	5.2	5.5	5	4.5	4.5	4.5	4.5	4.5	4.5					
					Max.	5	4	4.5	4.8	5.5	6	6.2	6.5	6.5	6	6	5.8	5	5	5					
					Min.	4	3.5	4	4	4.5	5	5.2	5.5	5	4.5	4.5	4.5	4.5	4.5	4.5					
					Aver.(d_{wps})	4.5	3.75	4.25	4.4	5	5.5	5.7	6	5.75	5.25	5.25	5.15	4.75	4.75	4.8					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways $\alpha_1 = 34^0 32'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	7	6	5.5	5	4	4	4	4	4	4	4	4	4	4	4					
					Min.	5	5.5	5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Max.	7	6	5.5	5	4	4	4	4	4	4	4	4	4	4	4					
					Min.	5	5.5	5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Aver.(d_{wps})	6	5.75	5.25	4.5	3.75	3.8	3.8	3.8	3.75	3.75	3.75	3.75	3.75	3.75	3.8					
					Inception																				
					length(cm)	25																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways $\alpha_2 = 52^0 14'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	4.5	5	5.5	5.5	5.5	5	5	5	5.5	6	6	6	6	6	6	6	6	6	6
					Min.	3.5	4.5	5	5	5	5	4.5	4.5	4.5	4.5	6	5	5	5	5	5	5	5	5	5
					Max.	4	4.5	5	5.5	5.5	5.5	5	5	5	5.5	6	6	6	6	6	6	6	6	6	6
6	11.8	0.016	0.2	0.08	Min.	3.5	4.5	5	5	5	5	4.5	4.5	4.5	4.5	6	5	5	5	5	5	5	5	5	5
					Aver.(d_{wps})	3.75	4.5	5	5.3	5.25	5.3	4.8	4.8	4.75	5	6	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Inception																				
					length(cm)																				
					Flow patt	100% air		50% air		100% recir.vortices															
					Slope of stepped spillways $\alpha_3 = 38^0 50'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	5.5	4.6	4.5	5	5.5	6	6.5	6.5	6.5	6.5	6.5	6.5	6	6	6					
					Min.	5	4	4	4.5	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5	5	5					
					Max.	5.5	4.6	4.5	5	5.5	6	6.5	6.5	6.5	6.5	6.5	6.5	6	6	6					
					Min.	5	4	4	4.5	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5	5	5					
					Aver.(d_{wps})	5.25	4.3	4.25	4.8	5	5.5	6	6	6	6	6	6	5.5	5.5	5.5					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways $\alpha_1 = 34^0 32'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	8	6	5	4.5	4	4	4	4	4	4	4	4	4	4	4					
					Min.	6	5	4	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Max.	8	6	5	4.5	4	4	4	4	4	4	4	4	4	4	4					
					Min.	6	5	4	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5					
					Aver.(d_{wps})	7	5.5	4.5	4.3	3.75	3.8	3.8	3.8	3.75	3.75	3.75	3.75	3.75	3.75	3.8					
					Inception																				
					length(cm)	30																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways $\alpha_2 = 52^0 14'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4	4.5	5	5.5	5.5	5	5	5	5	5.5	6	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
					Min.	3.5	4.5	5	5	5	4.5	4.5	4.5	4.5	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Max.	4	4.5	5	5.5	5.5	5	5	5	5	5.5	6	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
7	14.92	0.018	0.2	0.09	Min.	3.5	4.5	5	5	5	4.5	4.5	4.5	4.5	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
					Aver.(d_{wps})	3.75	4.5	5	5.3	5.25	4.8	4.8	4.8	4.75	5	5.5	6	6	6	6	6	6	6	6	6
					Inception																				
					length(cm)																				
					Flow patt	100 to 10% air				100% recir.vortices															
					Slope of stepped spillways $\alpha_3 = 38^0 50'$																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	6	5	4.8	5.5	6	6.5	6.5	6.5	6.8	7	6.8	6.5	6.5	6	6					
					Min.	5	4.5	4.2	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.3	5	5	5					
					Max.	6	5	4.8	5.5	6	6.5	6.5	6.5	6.8	7	6.8	6.5	6.5	6	6					
					Min.	5	4.5	4.2	4.5	5	5.5	5.5	5.5	5.5	5.5	5.5	5.3	5	5	5					
					Aver.(d_{wps})	5.5	4.75	4.5	5	5.5	6	6	6	6.15	6.25	6.15	5.9	5.75	5.5	5.5					
					Inception																				
					length(cm)																				
					Flow patt	100% recirculating vortices in all steps																			

SN	Mano metre reading (x cm)	Disch. (Q) (cum)	Width of spillw. ways (b m)	Disch. perunit length (q) cum/m)	Slope of stepped spillways α_1 =34°32'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	10	8	7	6	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	8	6	6	5	4.5	4	4	4	4	4	4	4	4	4	4					
					Max.	10	8	7	6	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	8	6	6	5	4.5	4	4	4	4	4	4	4	4	4	4					
					Aver.(d_{wps})	9	7	6.5	5.5	4.75	4.3	4.3	4.3	4.25	4.25	4.25	4.25	4.25	4.25	4.3					
					Inception																				
					length(cm)	30																			
					Flow patt	No air cavities,strong recirculating vortices																			
					Slope of stepped spillways α_2 =52°14'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	4.5	4.5	5	5.5	5.8	5.5	5	5	5	5.5	6	6	6.5	6.5	6.5	7	7	7	7	7
					Min.	4.2	4.5	4.5	5	5.5	5	4.5	4	4.5	4.5	5	5	5.5	5.5	5.5	6	6	6	6	6
					Max.	4.5	4.5	5	5.5	5.8	5.5	5	5	5	5.5	6	6	6.5	6.5	6.5	7	7	7	7	7
8	18.42	0.02	0.2	0.1	Min.	4.2	4.5	4.5	5	5.5	5	4.5	4	4.5	4.5	5	5	5.5	5.5	5.5	6	6	6	6	6
					Aver.(d_{wps})	4.35	4.5	4.75	5.3	5.65	5.3	4.8	4.5	4.75	5	5.5	5.5	6	6	6	6.5	6.5	6.5	6.5	6.5
					Inception																				
					length(cm)																				
					Flow patt	100 to 25% air			100% recir.vortices																
					Slope of stepped spillways α_3 =38°50'																				
					Step nos.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					Max.	7	6	5.5	5.4	6	6.5	7.5	8	8	8	7.5	6.5	6	6	6					
					Min.	6	5	4.5	4.5	5	5.5	6	6.5	6.5	6	5.5	5.5	5	5	5					
					Max.	7	6	5.5	5.4	6	6.5	7.5	8	8	8	7.5	6.5	6	6	6					
					Min.	6	5	4.5	4.5	5	5.5	6	6.5	6.5	6	5.5	5.5	5	5	5					
					Aver.(d_{wps})	6.5	5.5	5	5	5.5	6	6.8	7.3	7.25	7	6.5	6	5.5	5.5	5.5					
					Inception																				
					length(cm)	5																			
					Flow patt	100% recirculating vortices in all steps																			

3.6.2.14 Calculation of cavitation number:

Equation for cavitation number, $\sigma=(d*\cos\alpha+d*V^2/gR+Pb-Pv)/(V^2/2g)$
Where
d=depth of flow
α=inclination of spillways with horizontal
Pb=atmospheric pressure=76cm of Hg=76/100*13.6=10.33m of water
Pv=vapour pressure of water=0.233m of water
V=velocity of flow
R=radius of curvature
dV^2/gR is +ve for concave&-ve for convex

Important points about an aerator:

1 If cavitation number $\sigma > 1.8$ then no protection against cavitation is required.
2 If cavitation number σ is in between 0.25 to 1.8 then surface treatement is adequate.
3 If cavitation number σ is in between 0.17 to 0.25 then modify design or provide an aerator.
4 If cavitation number σ is in between 0.12 to 0.17 then an aerator must be provided.
5 If cavitation number $\sigma < 0.12$ then an aerator will not be able to eliminate cavitation so design should be changed.must be provided.
6 First aerator should be provided where $\sigma=0.2$ and Froude number is about 6.
7 Other aerator will be provided at a distance 2 times the average velocity in the reach.

Data:

Q =20 lps per 0.20m width of spillways i.e. q = 0.10 m3/s/m
$\alpha_1 = 34°32'$; d1= 0.049m ;V1=2.03m/s.(Knight&McDonold)
$\alpha_2 = 52°14'$;d2 = 0.045m; V2=2.24m/s.(Knight&McDonold)
$\alpha_3 = 38°50'$;d3=0.048m ;V3=2.09m/s.(Knight&McDonold)
Suppose radius of curvature,R = 1.0m.

Equation for **cavitation number,** $\sigma=(d*\cos\alpha+d*V^2/gR+Pb-Pv)/(V^2/2g)$

Calculations of cavitations no.:

d(m)	cosα	V(m/s)	R(m)	V2/gR	V2/2g	σ	Remarks
0.049	0.824	2.03	very big	0.00000	0.21004	2.12921	> 1.8 so no protection against cavitations
0.045	0.824	2.24	1	0.5115	0.25574	2.58579	
0.048	0.824	2.09	1	0.4453	0.22264	2.26151	

3.7 The study flow patterns in the multislope stepped spillways:

(a) For small flow rates: (Qw = 4 to 8 lps per 0.20m width of spillways);

qw = Q/b=4 lps/20 cm=0.004 m3/s/0.2m=0.02 m3/s/m

$dc=(qw^2/g)^{1/3}$=(0.02²/9.81)^0.333=0.034 m.

qw = Q/b=8 lps/20 cm=0.008 m3/s/0.2m=0.04 m3/s/m

$dc=(qw^2/g)^{1/3}$=(0.04²/9.81)^0.333=0.0546 m.

Table-1.

Qw(lps)	qw(Qw/0.2) m3/s/m	α (degree)	h(cm)	l(cm)	dc/h	h/l	0.05<h/l <1.7
4	0.02	34°32'	3.33	4.84	1.043	0.68	Ok
8	0.04				1.655		
4	0.02	52°14'	5	3.87	0.69	1.29	Ok
8	0.04				1.09		
4	0.02	38°50'	3.33	4.14	1.042	0.80	Ok
8	0.04				1.64		

Table-2

Spillways slopes	Upper limit of nappe flow regimes dc/h=0.89-0.4 *h/l (Chanson 2001)	Lower limit of skimming flow regimes dc/h=1.2-0.325 *h/l (Chanson 2001)	Onset of skimming flow dc/h=0.91-0.14 *tan α (Boes And Hager 2003)	Flow regimes (NA, TRA, SK) (From table- 1)
34°32'	0.62	0.98	0.81	SK
52°14'	0.373	0.78	0.73	SK
38°50'	0.57	0.96	0.80	SK

i.e. in small flow rates for α=34°32' (q=0.02 to 0.04 m3/s/m) the flow over the steps were observed undular in phase with the step geometry but the flow regime was found to be skimming flow because all the steps have recirculating vortices. Aeration in the step corners was observed immediately U/S of the inception point of air entrainment. Inception length was increased when the flow rate increased. For the flow rate less than q=0.02m3/s/m the flow was observed a nappe flow regime, where the flow was bouncing from one step to other. After the inception point, more or less the flow depths were found to be uniform.

For slope α=50°14', the flow was different from the first slope. At the junction point of slopes (1st and 2nd slope) of the spillways, the flow seemed to be sprayed and followed a convex curve and a trajectory path, under which the steps from the first to few steps (1^{st} to 6^{th}) to the D/S there was no water in the niches of steps i.e. full of air cavities. The sizes of air cavities were full at first and decreasing when we go D/S of the channel. From the point where the trajectory of flow hits the step, the aeration took place and strong recirculating vortices were existed. After the point from where the recirculating vortices created, the flow was more or less uniform. The spraying of water droplets started from the step just D/S of the junction point and hit the steps D/S of the channel at different locations at the bottom of channel and the side walls according to its residual energy collected from the first slope of the flow.

For slope α=38°50', the nature of flow was nearly same as of 2^{nd} slope, and only the difference was at the junction point of 2^{nd} and 3^{rd} slopes where the slope changed to smaller than former. At this junction point the flow was of concave nature of curve and after the potential of the residual energy the flow follow the trajectory path D/S of the steps. Under the trajectory flow, the steps had air cavities filled with 25 to 0% from first to 2^{nd} step, and after it the flow was recirculating in the niches of steps i.e. skimming flow regime. The aeration started just after the tip of step from where the change of the slope started. The sprayed water followed the trajectory path of flow with the bigger depths at rising point and smaller depths at falling point. Most of the flow followed uniform depth after the inception point (which was comparatively smaller in concave flow).

(b) **For higher flow rates:** (Qw = 20 lps per 0.20m width of spillways);

qw = Q/b=20 lps/20 cm=0.02 m3/s/0.2m=0.10 m3/s/m

$dc=(qw^2/g)^{1/3}=(0.10^2/9.81)$^0.333=0.10 m.

Table-1.

Qw(lps)	qw(Qw/0.2) m3/s/m	α (degree)	h(cm)	l(cm)	dc/h	h/l	0.05<h/l <1.7
20	0.10	34°32'	3.33	4.84	3.02	0.68	Ok
		52°14'	5	3.87	2.0	1.29	Ok
		38°50'	3.33	4.14	3.003	0.80	Ok

Table-2

Spillways slopes	Upper limit of nappe flow regimes dc/h=0.89-0.4 *h/l (Chanson 2001)	Lower limit of skimming flow regimes dc/h=1.2-0.325 *h/l (Chanson 2001)	Onset of skimming flow dc/h=0.91-0.14 *tan α (Boes And Hager 2003)	Flow regimes (NA, TRA, SK) (From table-1)
34°32'	0.62	0.98	0.81	SK
52°14'	0.373	0.78	0.73	SK
38°50'	0.57	0.96	0.80	SK

i.e. in high flow rates, for slope α=34°32' (q=0.1m3/s/m) the flow was smooth and glassy on the upper steps and no free aeration was observed. The air entrainment started from the inception point steps. The flow depths in the upper steps were gradual from bigger to smaller and was minimum at just U/S of inception point. The flow depths after the inception point were nearly uniform. Full recirculating vortices were found in all steps after the inception point. Before inception point invisible recirculation vortices were observed.
For slope α=50°14' the flow at the junction point of the change of slope of spillways was of convex nature and spraying type of flow was observed. The spray of droplets followed the trajectory path and the flow depths were varying along length of spillway as the trajectory path of flow i.e. depths over first few steps were smaller and then bigger in mid steps and smaller at the last steps. First few steps were having air cavities. The full recirculating vortices started from the point from where few of trajectory flow hit the steps, which was the point of uniform flow with nearly constant depths. The aeration generally seemed started from the first step from where the trajectory flow started.

For slope α=38°50' the flow was of concave nature at the junction point of 2nd and 3rd slopes (α=50°14'and 38°50') and sprayed in the trajectory path to the D/S of the spillways. The inception point was short i.e. up to 2nd step. The aeration started from the inception point. The flow depths were varying from smaller at first two to three steps to larger at the mid steps and smaller in the later parts of the steps of the channel because the flow was of trajectory nature. The recirculating vortices were seen in all steps. So the flow was skimming flow regime. See figs (graphs and drawings) in Annex-1 & 2.

CHAPTER- 4

DISCUSSION OF RESULTS AND CONCLUSIONS

Chapter-4
Discussion of results and conclusions

4.1 Discussion and results:

The flow patterns of the multislope/monoslope stepped spillways with or without suppressor plates are given in section 3.6.2.7 tables, 3.7,in graphs (Annex-B), in AutoCAD drawings & photographs (Annex-C) and enrgy dissipation rates by Tatewar & Ingle (1996) and Knight & McDonold (1979) in the multislope and monoslope stepped spillways were found to be 87.4% and 89.9% respectively for the flow rate of 20 lps (or unit flow rate q = 0.10 m3/s/s). And similarly by Chanson (1994) the rate of energy dissipation were found to be 85.3% and 85.85% respectively for the same flow rate.

Among the circular and elliptical suppressor plates used in experiments, the elliptical suppressor plate gave good result in uniformity of flow with smaller flow of depths after placement of it at the junction points. It means after placement of suppressor plate the flow depth decreases and obviously the concentration of air in the flow also decreases.

Results in tables:

Calculation of H_{max}, H_{loss}, H_{res}, d_{90w} and V_w:

Result:

α	h	l	ΔH/Hmax	Hmax	Hloss	Hres	dw(m)	V(m/s)
34.533	0.033	0.048	0.5719	0.65	0.372	0.2787	0.049	2.03
52.233	0.05	0.039	0.5456	1.549	1.026	0.523	0.045	2.24
38.833	0.033	0.041	0.514	0.545	0.229	0.316	0.048	2.09

Calculation of flow regimes:

Table:1 (Theoretical)

q (m3/s)	Slope (α)	Step height (h)m	Step length (l)m	h/l	dc(m)	dc/h	dc/h (onsct)			Flow regimes
							Chanson		Boes & Hager	
							NA-TRA	TRA-SK		
0.02	34o32'	0.033	0.0484	0.682	0.034	**1.043**	0.617	0.978	0.815	SK
0.02	52o14'	0.05	0.0387	1.292	0.034	**0.689**	0.373	0.780	0.729	TRA
0.02	38o50'	0.0333	0.0414	0.804	0.034	**1.034**	0.568	0.939	0.797	SK
0.03	34o32'	0.033	0.0484	0.682	0.045	**1.367**	0.617	0.978	0.815	SK
0.03	52o14'	0.05	0.0387	1.292	0.045	**0.902**	0.373	0.780	0.729	SK
0.03	38o50'	0.0333	0.0414	0.804	0.045	**1.355**	0.568	0.939	0.797	SK
0.04	34o32'	0.033	0.0484	0.682	0.055	**1.656**	0.617	0.978	0.815	SK
0.04	52o14'	0.05	0.0387	1.292	0.055	**1.093**	0.373	0.780	0.729	SK
0.04	38o50'	0.0333	0.0414	0.804	0.055	**1.641**	0.568	0.939	0.797	SK
0.05	34o32'	0.033	0.0484	0.682	0.063	**1.922**	0.617	0.978	0.815	SK
0.05	52o14'	0.05	0.0387	1.292	0.063	**1.268**	0.373	0.780	0.729	SK
0.05	38o50'	0.0333	0.0414	0.804	0.063	**1.904**	0.568	0.939	0.797	SK

0.06	34o32'	0.033	0.0484	0.682	0.072	**2.170**	0.617	0.978	0.815	SK
0.06	52o14'	0.05	0.0387	1.292	0.072	**1.432**	0.373	0.780	0.729	SK
0.06	38o50'	0.0333	0.0414	0.804	0.072	**2.151**	0.568	0.939	0.797	SK
0.07	34o32'	0.033	0.0484	0.682	0.079	**2.405**	0.617	0.978	0.815	SK
0.07	52o14'	0.05	0.0387	1.292	0.079	**1.587**	0.373	0.780	0.729	SK
0.07	38o50'	0.0333	0.0414	0.804	0.079	**2.383**	0.568	0.939	0.797	SK
0.08	34o32'	0.033	0.0484	0.682	0.087	**2.629**	0.617	0.978	0.815	SK
0.08	52o14'	0.05	0.0387	1.292	0.087	**1.735**	0.373	0.780	0.729	SK
0.08	38o50'	0.0333	0.0414	0.804	0.087	**2.605**	0.568	0.939	0.797	SK
0.09	34o32'	0.033	0.0484	0.682	0.094	**2.844**	0.617	0.978	0.815	SK
0.09	52o14'	0.05	0.0387	1.292	0.094	**1.877**	0.373	0.780	0.729	SK
0.09	38o50'	0.0333	0.0414	0.804	0.094	**2.818**	0.568	0.939	0.797	SK
0.1	34o32'	0.033	0.0484	0.682	0.101	**3.050**	0.617	0.978	0.815	SK
0.1	52o14'	0.05	0.0387	1.292	0.101	**2.013**	0.373	0.780	0.729	SK
0.1	38o50'	0.0333	0.0414	0.804	0.101	**3.023**	0.568	0.939	0.797	SK

Calculations of cavitations no.:

d(m)	cosα	V(m/s)	R(m)	V2/gR	V2/2g	σ	Remarks
0.049	0.824	2.03	very big	0.00000	0.21004	2.12921	> 1.8 so no protection against cavitations
0.045	0.824	2.24	1	0.5115	0.25574	2.58579	
0.048	0.824	2.09	1	0.4453	0.22264	2.26151	

4.2 Conclusions:

1.Energy dissipation capacity of spillways and energy dissipaters is a key element to minimize the erosion potential of the flow d/s of a dam and thus to ensure its stability against failure during flood. Stepped spillways allow to continuously dissipate a considerable amount of the kinetic energy such that the downstream stilling basin where the residual energy is dissipated by hydraulic jump can be largely reduced in dimension compared to a basin at the toe of a conventional smooth chute. Also the cavitations risk along the spillways decreases significantly due to smaller flow velocities and the large air entrainment rate because the macro-roughness of the steps significantly reduces flow velocities and leads to flow aeration along the spillways.

2.Now-a-days stepped spillways has been designed for increasing dam height and design discharges due to good experience gained with the Roller Compacted Concrete (RCC) construction methods. This raises the question on the application limit of the stepped cascades. Up to the date unit discharges do not exceed q = 25 to 30 m3/s/m (Minor 2000) which is far below the maximum discharge rates of q = 200 to 250 m3/s/m (Volkart 1984) for smooth chutes. This limitation comes from the fact that the inception point of air entrainment moves downstream with increasing unit discharges leaving a longer spillways stretch length without the air bubbles counter acting cavitations damage at the concrete surface

3.Keeping in mind the shortcomings mentioned above a systematic study on spillway aeration on stepped spillways, as a measure against the inception of cavitations erosion

for high unit discharges should be undertaken. For conventional spillways, where the air entrainment takes place significantly further downstream compared to stepped chutes, the placement of aerators to artificially aerate the spillways invert locally has proved to be an effective measure against cavitations damages. **The application to this principle to stepped spillways is therefore a research topic of great interest.**

4. Multislope stepped spillways have more than one longitudinal channel slopes with different step height (or step geometries). In the first channel slope $\alpha_1 = 34^0 32'$ of the experimental set up, the flow patterns were same as in single slope (mono slope) stepped spillways and in other channel slopes d/s of it the flow patterns were different from it. The second channel slope $\alpha_2 = 50^0 14'$, which is steeper than first slope, and the third channel slope $\alpha_3 = 38^0 50'$ which is milder than second slope, had different flow patterns: i.e. the convex flow and trajectory flow depths and the concave flow and trajectory flow depths respectively.

5. At the first junction point of the channel slopes α_1 and α_2 the flow was of convex nature and the flow past it through a trajectory path d/s of the channel with the slope α_2. The flow at the second junction point of the channel of slopes α_2 and α_3 was of concave nature and similarly in slope α_3 the flow past through a trajectory path d/s of the channel with the slope α_3. At the lower unit discharge rates (3 to 4 lps/0.2m i.e. 0.015 to 0.02 m3/s/m) the flow pattern followed transition and skimming flow regimes pattern where as at higher flow rates than these rates (6 to 20 lps/0.2m i.e. 0.03 to 0.10m3/s/m) the flow were all skimming flow regimes with recirculating vortices. At the convex and concave flow regions first-six to first-two steps were having air cavities with bigger sizes at upper ones and decreasing the cavity sizes to d/s steps.

6. After the placement of suppressor plates at the junction points of slopes the flow followed uniform depth throughout the channel d/s of it. The placement height of the suppressor plate was fixed as the depth of flow at the toe of respective slopes. Hence the suppressor plates were found to be a good key structural element to reduce the flow depths in the spillways, which help in reducing the sidewall height of the spillways. Among the circular and elliptical suppressor plates used in experiments, the elliptical suppressor plate (P=135mm) gave good result in uniformity of flow with smaller flow of depths after placement of it at the junction points. It means after placement of suppressor plate the flow depth decreases and obviously the concentration of air in the flow also decreases.

7. The energy dissipation rate by Tatewar & Ingle (1996) and Knight & McDonold (1979) in the multislope and monoslope stepped spillways were found to be 87.4% and 89.9% respectively for the flow rate of 20 lps (or unit flow rate q = 0.10 m3/s/s). And similarly by Chanson (1994) the rate of energy dissipation were found to be 85.3% and 85.85% respectively for the same flow rate.

8. Multislope stepped spillways with the final or last channel slope steeper than the second last slope dissipated more head or energy compared to spillways channels with the milder slope than the second slope..

REFERENCES

References

Boes & Hager (2003 Sept.) "Two phase flow characteristics of stepped spillways" ASCE, JOHE, Vol. 129 No. 9.

Boes & Hager (2003 Sept.) "Hydraulic design of stepped spillways" ASCE, JOHE, Vol. 129 No. 9.

Chamani & Rajaratnam (1994 Feb.) "Jet flow on stepped spillways" ASCE, JOHE, Vol.120 No. 2

Chamani & Rajaratnam (1999 Sept.) "Onset of skimming flow on stepped spillways" ASCE, JOHE, Vol.125 No. 9

Chamani & Rajaratnam (1999 April.) "Characteristics of skimming flow over stepped spillways" ASCE, JOHE, Vol.125 No. 4

Chanson (2001) "Hydraulic design of stepped spillways and downstream energy dissipaters" University of Queens land, Australia.

Chanson (2001) "A transition flow regime on stepped spillways the facts" University of Queensland, Australia.

Chanson (1994) "Hydraulics of stepped cascades, channels, weirs & spillways" University of Queensland, Australia.

Detlef aigner (2000) "Hydraulic design of pooled step cascades" Technische Universitact Dresden, 01309 Germany.

James, Ball (1976) "Cavitations from surface irregularities in high velocities" ASCE, JOHD, Vol.102 No. HY 9.

Marinis, Fratino & Piccini (2000) "Flow regimes on stepped spillways" Italy casino

Minor&Hager (2000) "Hydraulics of stepped spillways"

N.Sharma, Prof.WRDTC, IIT, Roorkee (2003) "Preliminary draft of standard on design of stepped spillways"

Ohmoto, Nagaya, Nariai &Yakita (1995) "Flow characteristics of skimming flow in stepped steep open channel" Kumanoto University Japan.

Shahani,P.B. Surveying part II, UOR, Roorkee, 1966.

Appendix-A

Hydraulic design of stepped chutes (spillways)

6.1 Chanson (1994):

(i) Nappe flow regimes: Design steps;

1.Calculate dc/h from given data with the formula:

$$dc = \sqrt[3]{\frac{qw^2}{g}}$$; where dc is the critical depth.

2.Calculate (dc/h)char with the relation;

$$(\frac{dc}{h})char = 0.0916(\frac{h}{l})^{-1.276}$$, where h/l=tanα.

3.Calculate db flow depth at the brink of step.

4.Calculate nappe thickness at the impact with the receiving pool by the relation,

$$\frac{di}{h} = 0.687(\frac{dc}{h})^{1.483}$$

5.Calculate impact velocity of the nappe, by;

$$\frac{vi}{vc} = 1.455(\frac{dc}{h})^{-0.483}$$

6.Calculate jet angle of the impinging nappe with,

$$\tan\theta = 0.838(\frac{dc}{h})^{-0.586}$$

7.Calculate flow depth (conjugate) upstream of hydraulic jump with the relation;

$$\frac{d1}{h} = 0.54(\frac{dc}{h})^{1.275}$$

8.Find Fraude no. at the start of hydraulic jump;

$$Fr = \frac{q}{\sqrt{gd1^3}}$$

9.Find conjugate depth d2;

$$\frac{d2}{d1} = \frac{1}{2}(\sqrt{1+8Fr^2} - 1)$$

10.Find flow depth in pool beneath the nappe,

$$\frac{dp}{h} = (\frac{dc}{h})^{0.66}$$

11.Calculate length of drop with,

$$\frac{Ld}{h} = 4.3(\frac{dc}{h})^{0.81}$$

12.Find out length of jump or roller length;

$$\frac{Lj}{d1} = 8[(\frac{dc}{d1})^{\frac{3}{2}} - 1.5]$$

13.Rate of energy dissipation can be calculated by the formula;

$$\frac{\Delta H}{H\max} = 1 - [\frac{0.54(\frac{dc}{h})^{0.275} + \frac{3.43}{2}(\frac{dc}{h})^{-0.55}}{\frac{3}{2} + \frac{Hdam}{dc}}$$ for ungated chute.

14.Nappe ventilation at each step can be found out by the relation;

$$\frac{Qair^{nappe}}{Qw} = 0.19(\frac{h - dp}{dp})^{0.95}$$ for 3 < Fr <10

$$\frac{Qair^{nappe}}{Qw} = 0.21(\frac{h - dp}{dp})^{1.03}$$ for 13 < Fr <15

15.By Kogga (1982);

$Ve = 2.58\theta - 0.3$ for d=4.6mm and $\Pi/7.2 < \theta < \Pi/2.8$

$Ve = 1.73\theta - 0.73$ for d=1.2mm and $\Pi/3 < \theta < \Pi/2$

16.Nappe Fraude no. at the impact;

$$Fr = \frac{(V - Ve)}{\sqrt{gd}}$$ where d is the jet thickness or dia.

17.Plunging jet entrainment at each step;

$$\frac{Qair^{jet}}{Qw} = K4\frac{Fr^2}{(\sin\theta)^{1.2}}$$ where K4 is proportionality constant= 0.0055 for

$$\frac{Vi}{\sqrt{gd1}} < 5.5$$

18.Air entrainment at hydraulic jump at each step;

$$\frac{Qair^{Hj}}{Qw} = 0.018(Fr - 1)^{1.245}$$ where $Fr = \frac{qw}{\sqrt{gd1^3}}$

(ii) Skimming flow regime: Design steps;

1.Calculate dimension less critical depth by;

$$\frac{dc}{h} = \frac{\sqrt{\frac{qw^2}{g}}}{h}$$

2.Skimming flow occurs for discharge larger than a critical value,

$$\frac{(dc)onset}{h} = 1.057 - 0.465\frac{h}{l}$$

It is deduced for h/l ranging from 0.2 to 0.125 (i.e. $11^{\circ}<a<52^{\circ}$)

3.Location of the point of inception point;

$$\frac{Li}{Ks} = 9.719(\sin\alpha)^{0.0796} Fr^{0.713}$$ where Ks=hCosα and α= slope angle,

$$Fr = \frac{qw}{\sqrt{g\sin\alpha(h\cos\alpha)^3}}$$

4.Flow depth at the point of inception;

$$\frac{di}{Ks} = \frac{0.4034}{(\sin\alpha)^{0.04}} Fr^{0.592}$$

5.Average equilibrium air concentration Ce;

$$Ce = 0.9\sin\alpha$$

6.Uniform aerated flow depth;

$$\frac{do}{dc} = \sqrt{\frac{fe}{8\sin\alpha}}$$ f=1.0 for non aerated friction factor and aerated friction factor fe;

$$\frac{fe}{f} = 0.5[1+\tanh(0.628\frac{0.514-Ce}{Ce(1-Ce)})]$$ where $\tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$

7.Characteristic depth Y90 where C=90%;

$$\frac{Y90}{dc} = \sqrt{\frac{fe}{8(1-Ce)^3\sin\alpha}}$$

8.Mean flow velocity;

$$(Uw)o = \frac{qw}{do}$$

6.2 Boes and Hager (2003):

Skimming flow: Design steps

1.Selection of spillways width:

To avoid converging spillway training walls which lead to the creation of shock waves, a chute width equal to the d/s river width is chosen.
Therefore chose width = b
Find unit discharge, qw = Qd/b
Find critical depth $dc = \sqrt[3]{\frac{qw^2}{g}}$

2.Selection of step height and flow regime:

If RCC lift is given then take step height, h=2*lift height. Because it facilitates spillways construction on one hand and ensure a large energy dissipation rate on the other.
Onset of skimming flow;

$$\frac{dc}{h} = 0.91 - 0.14\tan\alpha$$

3.Inception of air entrainment: Length of inception point or backwater distance;

$$Li = \frac{5.9(dc)^{\frac{6}{5}}}{(\sin\alpha)^{\frac{7}{5}} h^{\frac{1}{5}}}$$

4.Inception flow depth for 26°<α<55°

Find air mixed depth;

$$\frac{dmi}{h} = 0.4Fr^{0.60} \text{ where } Fr = \frac{qw}{\sqrt{g\sin\alpha h^3}}$$

Find two phase air mixed flow velocity at inception point;

$$Vmi = \frac{qw}{dmi}$$

Find depth averaged inception air concentration;

$$\overline{Ci} = 1.2 * 10^{-3}(240 - \alpha)$$

Find inception clear water depth;

$$dwi = dmi(1 - \overline{Ci})$$

Find clear water velocity;

$$Vwi = \frac{qw}{dwi}$$

This value should be just below the critical velocity for the inception of cavitations in unaerated stepped chute flow.
5.Attainment of uniform flow:

Vertical distance required for uniform flow to be attained;

$$\frac{Hdam,u}{dc} = 24(\sin\alpha)^{\frac{2}{3}}$$

6.Uniform flow depths: If the spillway is sufficiently long for uniform flow to be established, the uniform equivalent clear water depth would be;

$$\frac{dw,u}{dc} = 0.215(\sin\alpha)^{\frac{-1}{3}}$$

and uniform characteristic mixture depth;

$$\frac{d90u}{h} = 0.5Fr^{(0.1\tan\alpha + 0.5)}$$

and uniform depth averaged air concentration,

$$\overline{Cu} = 1 - \frac{dw,u}{d90,u}$$

7.Energy dissipation:

Residual head at any section along a stepped spillway regardless of uniform or non-uniform condition can be expressed by;

$Hres = dw\cos\alpha + Ec\frac{qw^2}{2g(dw)^2}$ where Ec is energy correction coefficient=1.1.

Rate of energy dissipation; $\frac{Hres}{H\max} = \exp[(-0.045(\frac{K}{Dhw})^{0.1}(\sin\alpha)^{-0.8})\frac{Hdam}{dc}]$

for Hdam/dc < 15 to 20.

And $\frac{Hres}{H\max} = \frac{F}{\frac{Hdam}{dc} + F}$ with $F = (\frac{fh}{8\sin\alpha})^{\frac{1}{3}}\cos\alpha + \frac{Ec}{2}(\frac{fh}{8\sin\alpha})^{\frac{-2}{3}}$

for Hdam/dc>15 to 20.

Where Hmax=Hdam+1.5 dc

Dh,w=Hydraulic diameter=4Rhw=$\frac{4b(dwu)}{(b+2(dwu))}$

Ec=1.1

fh=friction factor=$[0.5 - 0.42\sin(2\alpha)](\frac{K}{Dhw})^{0.2}$

K= h $\cos\alpha$

8.Training wall design:

Training wall height, $hd = \eta(d90,u)$ where η is factor of safety=1.2 for concrete dam and 1.5 for emergency spillways.

6.3 Tatewar & Ingle (1996) and Knight & Mc Donold (1979):

Skimming flow design steps. See section 2.12 (Energy dissipation)

Appendix-B

Graphs:

Tables of calculations and plotting of graphs of:

1.Flow depth $d_{90}(d_w)$ verses distance x graphs

2. Flow depth d_{90} (d_w) verses Fr graphs

3.H_{res}/H_{max} verses H_{spill}/d_c graphs

4. Flow depth $d_{90}(d_w)$ verses velocity V_w graphs

Graphs: Without circular suppressor plate

(1) d_{w90} vs x graph:

Sn	α	cosα	q_w (m^3/s)	Step no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	34o32	0.82	0.1	x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
				dw90cosa	9	8.6	8.25	7	5.4	5.3	5	4.9	4.8	4.8	4.8	4.8	4.8	4.8	4.8					
				(d_{w90})cm	11	10	10	8.5	6.5	6.4	6.07	5.9	5.8	5.8	5.8	5.8	5.8	5.8	5.8					
	52o14	0.61		x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
				dw90cosa	5.2	6.8	8.13	9.5	10	12	11.9	13	13	14	14	13	13	12	12	11	11	9.8	9.1	9.1
				(d_{w90})cm	8.5	7.5	13.3	15.5	17	19	19.4	21	21	22	22	21	20	20	20	18	18	16	15	15
	38o50	0.78		x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
				dw90cosa	7.4	6.6	6.25	7	8.9	9.1	10.3	10	11	11	11	11	11	10	10					
				(d_{w90})cm	9.47	8.5	8.02	8.99	11.4	11.7	13.2	13.2	14.4	14.3	14	14	14.1	13	13					

Sn	α	cosα	q_w (m3/s)	Step no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	34o32	0.82	0.09	x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
				dw90cosa	8	8	6.25	6	4.8	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
				(d_{w90})cm	9.7	9.7	7.58	7.28	5.8	5.5	5.46	5.5	5.5	5.5	5.8	5.8	5.8	5.8	5.8					
	52o14	0.61		x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
				dw90cosa	4.9	6.8	8.13	9.5	9.9	11	11.6	13	13	14	14	14	12	12	12	12	11	10	10	10
				(d_{w90})cm	8	11	13.3	15.5	16	18	19	21	21	22	22	22	20	20	20	19	18	17	16	15
	38o50	0.78		x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
				dw90cosa	6.8	5.9	5.63	7	8.6	9.8	10.4	11	11	12	12	11	10	10	10					
				(d_{w90})cm	8.66	7.5	7.22	8.99	11.1	12.5	13.3	13.5	14.4	15.1	15	14	13.2	13	13					

Sn	α	cosα	q_w (m3/s)	Step no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
3	34o32	0.82	0.08	x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
				dw90cosa	7.9	7.3	6.25	5.5	5.5	4.5	4.5	4.5	4	4	4	4.3	4.4	4.4	4.3					
				(d_{w90})cm	9.6	8.8	7.58	6.67	6.7	5.5	5.46	5.5	4.9	4.9	5.8	5.8	5.8	5.8	5.8					
	52o14	0.61		x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
				dw90cosa	4.6	6.3	7.75	9.13	9.9	11	11.6	12	14	14	13	13	11	11	11	11	9.8	8.8	8.5	8.4
				(d_{w90})cm	7.5	10	12.6	14.9	16	18	19	20	21	22	22	20	18	18	20	18	18	14	14	14
	38o50	0.78		x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
				dw90cosa	6.8	5.4	5.13	6.25	7.9	8.1	9.88	11	11	12	11	9.8	9	9	9					
				(d_{w90})cm	8.66	6.9	6.58	8.02	10.1	10.4	12.7	13.5	14	14.8	13	14	11.6	12	12					

Sn	α	cosα	q_w (m3/s)	Step no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
4	34o32	0.82	0.07	x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
				dw90cosa	5.4	5	5	5	4	4	4	4	4	4.2	4.2	4.2	4.2	4.2	4.2					
				(d_{w90})cm	6.5	6.1	6.07	6.07	4.9	4.9	4.85	4.9	4.9	5	5.8	5.8	5.8	5.8	5.8					
	52o14	0.61		x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
				dw90cosa	4.4	6.3	7.95	8.88	9.9	11	11.4	12	13	13	13	12	11	10	9.3	9	9	8.1	7.5	7.5
				(d_{w90})cm	7.1	10	13	14.5	16	17	18.6	19	21	21	22	19	19	17	15	15	15	13	12	12
	38o50	0.78		x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
				dw90cosa	5.5	4.6	4.63	6	7.4	8.1	8.5	9.3	9.3	8.5	8.5	8.3	7.4	6.6	6					
				(d_{w90})cm	7.06	5.9	5.94	7.7	9.47	10.4	10.9	11.9	11.9	10.9	11	11	9.47	8.5	7.7					

Sn	α	cosα	q_w (m3/s)	Step no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
				x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
	34o32	0.82		dw90cosa	5.5	5.5	4.5	4.5	4.5	4.5	3.5	3.5	3.5	3.5	3.5	3.7	3.9	3.8	4.1					
				(d_{w90})cm	6.7	6.7	5.46	5.46	5.5	5.5	4.25	4.2	4.2	4.2	5.8	5.8	5.8	5.8	5.8					
				x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
5	52o14	0.61	0.06	dw90cosa	4.5	5.9	7.5	8.75	9.9	10	10	10	11	11	11	10	9	8.3	7.8	8	7.5	6.5	6	5.8
				(d_{w90})cm	7.3	9.6	12.2	14.3	16	16	16.3	16	21	18	22	16	15	13	20	13	18	11	9.8	9.4
				x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
	38o50	0.78		dw90cosa	5.5	4.5	4.65	5.38	6.3	8.3	8	8.6	9.3	9.5	7	6.3	6.3	5.9	5.9					
				(d_{w90})cm	7.06	5.8	5.97	6.9	8.02	10.6	10.3	11.1	11.9	12.2	9	14	8.02	7.5	13					

Sn	α	cosα	q_w (m3/s)	Step no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
				x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
	34o32	0.82		dw90cosa	3.8	3.8	3.75	2.9	2.9	2.9	2.9	2.8	2.9	2.9	3.3	3.4	3.4	3.4	3.4					
				(d_{w90})cm	4.6	4.6	4.55	3.52	3.5	3.5	3.52	3.3	3.5	3.5	5.8	5.8	5.8	5.8	5.8					
				x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
6	52o14	0.61	0.05	dw90cosa	3.5	5	6	6.75	7.8	7.8	8	8.3	5.5	8.6	7.5	6.8	6	5.5	5.3	5.3	5.3	5	4.8	4.8
				(d_{w90})cm	5.7	8.2	9.79	11	13	13	13.1	13	9	14	12	11	9.8	9	8.6	8.6	8.6	8.2	7.7	7.9
				x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
	38o50	0.78		dw90cosa	4.4	3.4	4.25	5.25	6	6.3	6.53	7.1	6.8	6.4	6.3	6.1	5.4	5	5					
				(d_{w90})cm	5.62	4.3	5.46	6.74	7.7	8.02	8.38	9.15	8.7	8.22	8	14	6.9	6.4	6.4					

(2) d_w vs Fr graph:

Sn	q_w (m3/s)	α	sinα	dw (m)	Fr
1	0.05	34.5	0.57	0.033	3.54
	0.05	52.2	0.79	0.029	3.64
	0.05	38.8	0.63	0.032	3.52
2	0.06	34.5	0.57	0.036	3.72
	0.06	52.2	0.79	0.033	3.60
	0.06	38.8	0.63	0.035	3.70
3	0.07	34.5	0.57	0.04	3.71
	0.07	52.2	0.79	0.036	3.68
	0.07	38.8	0.63	0.039	3.66
4	0.08	34.5	0.57	0.043	3.8
	0.08	52.2	0.79	0.039	3.73
	0.08	38.8	0.63	0.042	3.75
5	0.09	34.5	0.57	0.046	3.87
	0.09	52.2	0.79	0.042	3.76
	0.09	38.8	0.63	0.045	3.80
6	0.1	34.5	0.57	0.049	3.91
	0.1	52.2	0.79	0.045	3.76
	0.1	38.8	0.63	0.048	3.83

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
		0.05		d_{w90}cm	4.6	4.6	4.6	3.5	3.5	3.5	3.5	3.5	3.5	3.5	5.8	5.8	5.8	5.8	5.8					
				d_{w90}cm/h	139	139	139	106	106	106	106	106	106	106	176	176	176	176	176					
1	52o14'		0.05	x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	5.7	8.2	9.8	11	13	13	13	13	11	14	12	11	9.8	9	9	9	9	8.2	7.7	7.9
				d_{w90}cm/h	114	164	196	220	260	260	260	260	220	280	240	220	196	180	180	180	180	164	154	158
	38o50'		0.03	x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	5.6	4.3	5.5	6.7	6.7	8	8.4	9.2	8.7	8.2	8	8	7	6.4	6.4					
				d_{w90}cm/h	170	130	167	203	203	242	255	279	264	248	242	242	212	194	194					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
		0.06		d_{w90}cm	6.7	6.7	5.46	5.46	5.5	5.5	4.25	4.2	4.2	4.2	5.8	5.8	5.8	5.8	5.8					
				d_{w90}cm/h	202	202	165	165	165	165	129	129	129	129	176	176	176	176	176					
2	52o14'		0.05	x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	5.7	8.2	9.8	11	13	13	13	13	11	14	12	11	9.8	9	9	9	9	8.2	7.7	7.9
				d_{w90}cm/h	114	164	196	220	260	260	260	260	220	280	240	220	196	180	180	180	180	164	154	158
	38o50'		0.03	x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	7.1	5.8	5.97	6.9	8	11	10.3	11	12	12	9	14	8	7.5	13					
				d_{w90}cm/h	214	175	181	209	243	321	311	336	360	370	272	424	243	229	388					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
		0.07		d_{w90}cm	6.5	6.1	6.07	6.07	4.9	4.9	4.85	4.9	4.9	5	5.8	5.8	5.8	5.8	5.8					
				d_{w90}cm/h	198	184	184	184	147	147	147	147	147	153	176	176	176	176	176					
3	52o14'		0.05	x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	7.14	10	13	14.5	16.1	17.3	18.6	19.4	21	21.4	22	19	18.6	17	15	14.7	14.7	13.3	12.2	12
				d_{w90}cm/h	143	204	259	290	322	347	371	387	420	428	440	383	371	330	302	294	294	265	245	245
	38o50'		0.03	x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	7.1	5.9	5.94	7.7	9.5	10	10.9	12	12	11	11	11	9.5	8.5	7.7					
				d_{w90}cm/h	214	180	180	233	287	314	331	360	360	331	331	321	287	258	233					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
		0.08		d_{w90}cm	9.6	8.8	7.58	6.67	6.7	5.5	5.46	5.5	4.9	4.9	5.8	5.8	5.8	5.8	5.8					
				d_{w90}cm/h	290	267	230	202	202	165	165	165	147	147	176	176	176	176	176					
4	52o14'		0.05	x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	7.46	10	12.6	14.9	16.1	17.9	19	19.6	21	22.4	22	20	18.4	18	20	17.9	18	14.3	13.9	14
				d_{w90}cm/h	149	204	253	298	322	359	379	392	420	449	440	408	367	367	400	359	360	285	277	273
	38o50'		0.03	x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	8.7	6.9	6.58	8.02	10	10	12.7	13	14	15	13	14	12	12	12					
				d_{w90}cm/h	263	209	199	243	306	316	384	408	423	447	408	424	350	350	364					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
		0.09		d_{w90}cm	9.7	9.7	7.58	7.28	5.8	5.5	5.46	5.5	5.5	5.5	5.8	5.8	5.8	5.8	5.8					
				d_{w90}cm/h	294	294	230	221	175	165	165	165	165	165	176	176	176	176	176					
5	52o14'		0.05	x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	7.95	11	13.3	15.5	16.1	17.9	19	20.8	21	22.4	22	22	19.6	20	20	18.8	18	16.7	16.3	15
				d_{w90}cm/h	159	220	265	310	322	359	379	416	420	449	440	449	392	392	400	375	360	334	326	300
	38o50'		0.03	x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	8.7	7.5	7.22	8.99	11	13	13.3	13	14	15	15	14	13	13	13					
				d_{w90}cm/h	263	229	219	272	336	379	404	408	438	457	457	424	399	389	388					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	11.7	17.6	23.4	29.3	35.1	41	46.9	52.7	59	64	70.3	76	82					
		0.1		d_{w90}cm	11	10	10	8.5	6.5	6.4	6.07	5.9	5.8	5.8	5.8	5.8	5.8	5.8	5.8					
				d_{w90}cm/h	331	317	303	257	198	193	184	179	175	175	176	176	176	176	176					
6	52o14'		0.05	x(cm)	5.9	12	18.5	24.9	31	38	43.5	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	8.48	7.5	13.3	15.5	16.7	19	19.4	20.8	21	22.4	22	21	20.4	20	20	18.4	18	15.9	14.9	15
				d_{w90}cm/h	170	150	265	310	334	379	387	416	420	449	440	424	408	400	400	367	360	318	298	300
	38o50'		0.03	x(cm)	6.32	12	16.9	22.3	27.6	32.9	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	9.5	8.5	8.02	8.99	11	12	13.2	13	14	14	14	14	14	13	13					
				d_{w90}cm/h	287	258	243	272	345	355	399	399	438	433	428	424	428	389	388					

(3) H_{res}/H_{max} vs H_{spill}/d_c graph :

Data:

q_w=0.02cum/0.2m=0.1cum/m

Equations to be solved:

Tatewar & Ingle (1996) &Knight & Mc Donald(1979) Methods

$z^{0.1}/ng^{0.5}=0.25+19\log(\lambda/l)+5.75\log(z^{0.6}/k)$ ... ...(1)

$z=qn/(\sin a)^{0.5}$ ... ... (2)

$y=\{qn/(\sin a)^{0.5}\}^{0.6}$ ... ... (.3)

$v=q/y$ ... ... (4)

$k=h*\cos a$ ... ... (5)

$\lambda=(h^2+l^2)^{0.5}$ ... ... (6)

$E_c=H_{spill}+1.5d_c$... ... ...(7)

$E_t=d_w+u_o^2/2g$ ... ... (8)

$\Delta E=E_c-E_t$... ... ...(9)

Calculations:

Critical depth (dc)=$(q_w^2/g)^{1/3}$

q_w	**d_c (m)**		**H_{spill}**
0.1	0.10		2
h	l	**λ (m)**	
0.033	0.0414	0.053	
a	sina	cosa	**k(m)**
38.83	0.627	0.779	0.026

Solving Manning's n from eq.(1)

n	z	λ/l	LHS
0.05	0.00632	1.2788	3.84801
{z^0.6/k}			log(l/l)
1.862			0.10681
log{z^0.6/k}			RHS
0.27			3.83237

Put different values of n & check whether LHS=RHS

n	LHS	RHS
0.04	4.7038	3.498
0.05	**3.848**	**3.832**

Hence value of n is 0.05

Therefore equvalent water depth, $d_w = \{q_w n/\sin a^{0.5}\}^{0.6}$

$d_{w\,(m)}$

0.048

Uniform velocity, u_w =qw/dw

$u_{w\,(m/s)}$

2.09

Change in energy between crest and toe of spillways:DE=Ec-Et

Ec =Hspill+1.5dc	**Ec(m)**
	2.151
Et $=d_w+u_w^2/2g$	**Et(m)**
	0.270
	ΔE(m)
	1.881

Energy dissipated=ΔE/Ec*100 = 87.4 %

Residual head =Et =0.27m

Sn	q (m3/s)	Hres (m	Hmax (m	Hspill(m)	dc(m)	H_{res}/H_{max}	H_{spill}/dc
1	0.1	0.27	2.15	2	0.1	0.13	15.93
2	0.09	0.25	2.14	2	0.09	0.12	17.12
3	0.08	0.23	2.13	2	0.09	0.11	18.52
4	0.07	0.21	2.12	2	0.08	0.10	20.19
5	0.06	0.18	2.11	2	0.07	0.09	23.44
6	0.05	0.16	2.1	2	0.06	0.08	26.25

Without circular suppressor plate:

x(cm)	dw90(Q=20lps)	x(cm)	dw90(Q=14lps)	x(cm)	dw90(Q=10lps)
0	11	0	7	0	5
6	10	6	6	6	5
12	10	12	6	12	5
18	9	18	6	18	4
23	7	23	5	23	4
29	6	29	5	29	4
35	6	35	5	35	4
41	6	41	5	41	4
47	6	47	5	47	4
53	6	53	5	53	4
59	6	59	6	59	6
64	6	64	6	64	6
70	6	70	6	70	6
76	6	76	6	76	6
82	6	82	6	82	6
88	9	88	7	88	6
94	8	94	10	94	8
101	13	101	13	101	10
107	16	107	15	107	11
113	17	113	16	113	13
120	19	120	17	120	13
126	19	126	19	126	13
132	21	132	19	132	13
138	21	138	21	138	11
145	22	145	22	145	12
151	22	151	22	151	12
157	21	157	19	157	11
164	20	164	19	164	10
170	20	170	17	170	9
176	20	176	15	176	9
183	18	183	15	183	9
189	18	189	15	189	9
195	16	195	13	195	8
202	15	202	12	202	8
208	15	208	12	208	8
214	10	214	7	214	6
220	9	220	6	220	4
225	8	225	6	225	6
230	9	230	8	230	7
236	11	236	10	236	7
241	12	241	10	241	8
246	13	246	11	246	8
251	13	251	12	251	9
257	14	257	12	257	9
262	14	262	11	262	8
267	14	267	11	267	8
273	14	273	11	273	8
278	14	278	10	278	7
283	13	283	9	283	6
289	13	289	8	289	6

Hres/Hr	Hspill/dc
0.13	15.93
0.12	17.12
0.11	18.52
0.10	20.19
0.09	23.44
0.08	26.25

With circular suppressor:

x(cm)	dw90(Q=20lps)	x(cm)	dw90(Q=14lps)	x(cm)	dw90(Q=10lps)
0	9	0	6	0	4
6	9	6	5	6	4
12	8	12	5	12	3
18	7	18	5	18	3
23	6	23	4	23	3
29	6	29	4	29	3
35	6	35	4	35	3
41	5	41	4	41	3
47	5	47	4	47	3
53	5	53	4	53	3
59	5	59	4	59	3
64	5	64	4	64	3
70	5	70	4	70	3
76	5	76	4	76	3
82	5	82	4	82	3
88	5	88	4	88	3
94	5	94	5	94	4
101	5	101	5	101	5
107	6	107	6	107	6
113	6	113	6	113	6
120	6	120	6	120	6
126	6	126	6	126	6
132	6	132	6	132	6
138	6	138	6	138	6
145	6	145	6	145	6
151	6	151	6	151	6
157	6	157	6	157	6
164	6	164	6	164	6
170	6	170	6	170	6
176	6	176	6	176	6
183	6	183	6	183	5
189	6	189	6	189	5
195	6	195	6	195	5
202	6	202	6	202	5
208	6	208	6	208	4
214	6	214	5	214	4
220	6	220	4	220	5
225	6	225	5	225	5
230	6	230	6	230	6

236	7		236	6		236	6
241	8		241	6		241	6
246	8		246	7		246	6
251	8		251	7		251	6
257	9		257	7		257	6
262	9		262	7		262	6
267	9		267	7		267	5
273	9		273	6		273	5
278	8		278	6		278	5
283	8		283	6		283	5
289	8		289	6		289	5

Graphs (With circular suppressor):

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.033	x(cm)	0	5.9	12	17.6	23	29	35	41	47	53	59	64	70	76	82					
		0.05		d_{w90}cm	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3					
				d_{w90}cm/h	121	121	91	91	91	91	91	91	91	91	91	91	91	91	91					
1	52o14'		0.05	x(cm)	5.9	12	19	25	31	38	44	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	3	4	5	6	6	6	6	6	6	6	6	6	6	6	6	5	5	5	5	5
				d_{w90}cm/h	60	80	100	120	120	120	120	120	120	120	120	120	120	120	120	100	100	100	100	100
	38o50'		0.033	x(cm)	6.3	12	17	22.3	28	33	38	44	49	54	59	65	70	75	81	—				
				d_{w90}cm	4	4	5	5	6	6	6	6	6	6	5	5	5	5	5					
				d_{w90}cm/h	121	121	152	152	182	182	182	182	182	182	152	152	152	152	152					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.033	x(cm)	0	5.9	12	17.6	23	29	35	41	47	53	59	64	70	76	82					
		0.07		d_{w90}cm	6	5	5	5	4	4	4	4	4	4	4	4	4	4	4					
				d_{w90}cm/h	182	152	152	152	121	121	121	121	121	121	121	121	121	121	121					
3	52o14'		0.05	x(cm)	5.9	12	19	25	31	38	44	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	4	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
				d_{w90}cm/h	80	100	100	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
	38o50'		0.033	x(cm)	6.3	12	17	22.3	28	33	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	5	4	5	6	6	6	7	7	7	7	7	6	6	6	6					
				d_{w90}cm/h	152	121	152	182	182	182	212	212	212	212	212	182	182	182	182					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.033	x(cm)	0	5.9	12	17.6	23	29	35	41	47	53	59	64	70	76	82					
		0.1		d_{w90}cm	9	9	8	7	6	6	6	5	5	5	5	5	5	5	5					
				d_{w90}cm/h	273	273	242	212	182	182	182	152	152	152	152	152	152	152	152					
6	52o14'		0.05	x(cm)	5.9	12	19	25	31	38	44	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
			–	d_{w90}cm/h	100	100	100	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
	38o50'		0.033	x(cm)	6.3	12	17	22.3	28	33	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	7	6	6	6	6	7	8	8	8	9	9	9	8	8	8					
				d_{w90}cm/h	212	182	182	182	182	212	242	242	242	273	273	273	242	242	242					

Graphs: Average flow depth d_w verses average velocity of flow Vw and flow rates q_w:

Table of Calculations:

Table 1

Q (m3/s)	q (m3/s/m)	Slope (o)	h (m)	l/h	V_w (m/s)	d_w(m)
0.006	0.03	34°32'	0.033	1.455	1.25	0.024
		52°14'	0.05	0.774	1.38	0.022
		38°50'	0.033	1.255	1.29	0.023
0.008	0.04	34°32'	0.033	1.455	1.4	0.028
		52°14'	0.05	0.774	1.55	0.026
		38°50'	0.033	1.255	1.45	0.028
0.01	0.05	34°32'	0.033	1.455	1.54	0.033
		52°14'	0.05	0.774	1.7	0.029
		38°50'	0.033	1.255	1.58	0.032
0.012	0.06	34°32'	0.033	1.455	1.65	0.036
		52°14'	0.05	0.774	1.82	0.033
		38°50'	0.033	1.255	1.7	0.035
0.014	0.07	34°32'	0.033	1.455	1.76	0.04
		52°14'	0.05	0.774	1.94	0.036
		38°50'	0.033	1.255	1.81	0.039
0.016	0.08	34°32'	0.033	1.455	1.85	0.043
		52°14'	0.05	0.774	2.05	0.039
		38°50'	0.033	1.255	1.91	0.042
0.018	0.09	34°32'	0.033	1.455	1.94	0.046
		52°14'	0.05	0.774	2.15	0.042
		38°50'	0.033	1.255	2	0.045
0.02	0.1	34°32'	0.033	1.455	2.03	0.049
		52°14'	0.05	0.774	2.24	0.045
		38°50'	0.033	1.255	2.09	0.048

Table 2

Q (m3/s)	q (m3/s/m)	Slope (o)	h (m)	l/h	V_w (m/s)	d_w(m)
0.006	0.03	34°32'	0.033	1.455	1.25	0.024
0.008	0.04	34°32'	0.033	1.455	1.4	0.028
0.01	0.05	34°32'	0.033	1.455	1.54	0.033
0.012	0.06	34°32'	0.033	1.455	1.65	0.036
0.014	0.07	34°32'	0.033	1.455	1.76	0.04
0.016	0.08	34°32'	0.033	1.455	1.85	0.043
0.018	0.09	34°32'	0.033	1.455	1.94	0.046
0.02	0.1	34°32'	0.033	1.455	2.03	0.049

Table 3

Q (m3/s)	q (m3/s/m)	Slope (o)	h (m)	l/h	V_w (m/s)	d_w(m)
0.006	0.03	52°14'	0.05	0.774	1.38	0.022
0.008	0.04	52°14'	0.05	0.774	1.55	0.026
0.01	0.05	52°14'	0.05	0.774	1.7	0.029
0.012	0.06	52°14'	0.05	0.774	1.82	0.033
0.014	0.07	52°14'	0.05	0.774	1.94	0.036
0.016	0.08	52°14'	0.05	0.774	2.05	0.039
0.018	0.09	52°14'	0.05	0.774	2.15	0.042
0.02	0.1	52°14'	0.05	0.774	2.24	0.045

Table 4

Q (m3/s)	q (m3/s/m)	Slope (o)	h (m)	l/h	V_w (m/s)	d_w(m)
0.006	0.03	38°50'	0.033	1.255	1.29	0.023
0.008	0.04	38°50'	0.033	1.255	1.45	0.028
0.01	0.05	38°50'	0.033	1.255	1.58	0.032
0.012	0.06	38°50'	0.033	1.255	1.7	0.035
0.014	0.07	38°50'	0.033	1.255	1.81	0.039
0.016	0.08	38°50'	0.033	1.255	1.91	0.042
0.018	0.09	38°50'	0.033	1.255	2	0.045
0.02	0.1	38°50'	0.033	1.255	2.09	0.048

Graphs (With elliptical suppressor plate, P=135mm):

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	12	18	23	29	35	41	47	53	59	64	70	76	82					
		0.05		d_{w90}cm	4	4	3	3	3	2	2	2	2	2	2	2	2	2	2					
1	52o14'		0.05	x(cm)	6	12	19	25	31	38	44	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	2	4	4	4	4	3	3	3	3	3	4	4	4	4	3	3	3	3	3	3
	38o50'		0.03	x(cm)	6	12	17	22	28	33	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	3	3	4	4	4	4	4	4	4	3	3	3	3	3	3					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	12	18	23	29	35	41	47	53	59	64	70	76	82					
		0.07		d_{w90}cm	6	5	5	5	4	4	4	4	4	4	4	4	4	4	4					
2	52o14'		0.05	x(cm)	6	12	19	25	31	38	44	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	3	3	4	5	4	4	4	4	4	5	5	5	5	5	4	4	4	4	4	4
	38o50'		0.03	x(cm)	6	12	17	22	28	33	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	4	3	4	4	5	5	5	5	5	4	4	4	4	4	4					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	12	18	23	29	35	41	47	53	59	64	70	76	82					
		0.1		d_{w90}cm	9	9	8	7	6	6	6	5	5	5	5	5	5	5	5					
3	52o14'		0.05	x(cm)	6	12	19	25	31	38	44	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6	6
	38o50'		0.03	x(cm)	6	12	17	22	28	33	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	5	5	5	5	5	6	6	6	6	6	6	5	5	5	5					

Graphs (With elliptical suppressor plate, P=90mm):

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	12	18	23	29	35	41	47	53	59	64	70	76	82					
		0.05		d_{w90}cm	5	4	4	4	3	3	3	3	3	3	3	3	3	3	3					
1	52o14'		0.05	x(cm)	6	12	19	25	31	38	44	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	4	4
	38o50'		0.03	x(cm)	6	12	17	22	28	33	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	4	3	4	5	5	6	6	6	5	5	4	4	4	4	4					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	12	18	23	29	35	41	47	53	59	64	70	76	82					
		0.07		d_{w90}cm	6	6	5	5	4	4	4	4	4	4	4	4	4	4	4					
2	52o14'		0.05	x(cm)	6	12	19	25	31	38	44	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	38o50'		0.03	x(cm)	6	12	17	22	28	33	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	5	4	4	5	6	6	6	6	6	6	5	5	5	5	5					

Sn	α	q_w m3/s	h(m)	Steps	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	34o32'		0.03	x(cm)	0	5.9	12	18	23	29	35	41	47	53	59	64	70	76	82					
		0.1		d_{w90}cm	8	8	7	6	6	5	5	5	5	5	5	5	5	5	5					
3	52o14'		0.05	x(cm)	6	12	19	25	31	38	44	50	56	63	69	75	82	88	94	101	107	113	120	126
				d_{w90}cm	5	5	5	5	5	5	5	5	7	7	7	7	7	7	7	7	7	7	7	7
	38o50'		0.03	x(cm)	6	12	17	22	28	33	38	44	49	54	59	65	70	75	81					
				d_{w90}cm	7	6	5	5	5	6	6	8	8	8	8	8	8	7	7					

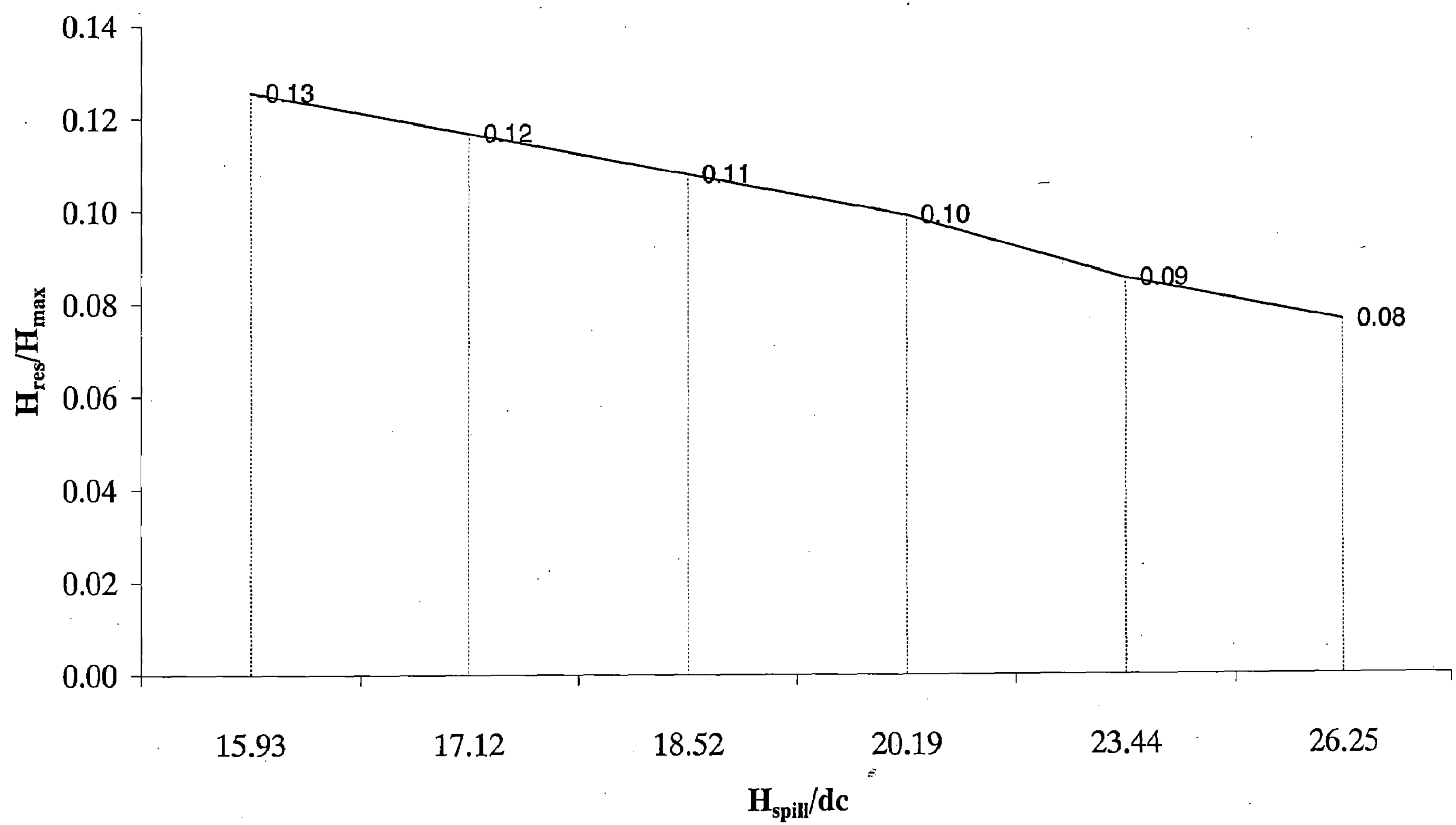
With elliptical suppressor plate P=135mm:

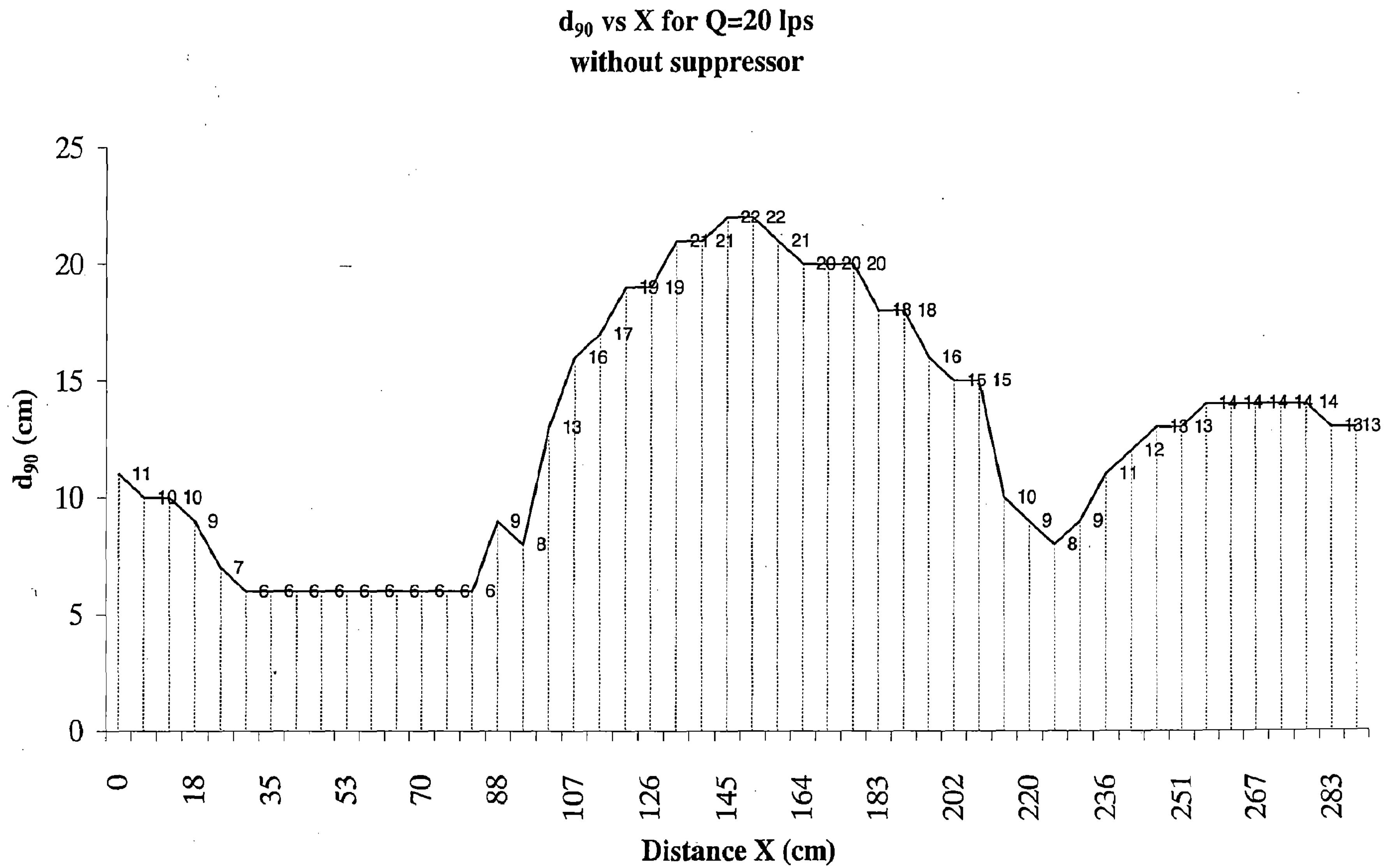
x(cm)	dw90(Q=20lps)	x(cm)	dw90(Q=14lps)	x(cm)	dw90(Q=10lps)
0	9	0	6	0	4
6	9	6	5	6	4
12	8	12	5	12	3
18	7	18	5	18	3
23	6	23	4	23	3
29	6	29	4	29	2
35	6	35	4	35	2
41	5	41	4	41	2
47	5	47	4	47	2
53	5	53	4	53	2
59	5	59	4	59	2
64	5	64	4	64	2
70	5	70	4	70	2
76	5	76	4	76	2
82	5	82	4	82	2
88	5	88	3	88	2
94	5	94	3	94	4
101	5	101	4	101	4
107	5	107	4	107	4
113	5	113	4	113	4
120	5	120	4	120	3
126	5	126	4	126	3
132	5	132	4	132	3
138	5	138	4	138	3
145	5	145	5	145	3
151	5	151	5	151	4
157	5	157	5	157	4
164	5	164	5	164	4
170	5	170	5	170	4
176	5	176	4	176	3
183	5	183	4	183	3
189	5	189	4	189	3
195	5	195	4	195	3
202	5	202	4	202	3
208	5	208	4	208	3
214	5	214	4	214	3
220	5	220	3	220	3
225	5	225	4	225	4
230	5	230	4	230	4
236	5	236	5	236	4
241	5	241	5	241	4
246	5	246	5	246	4
251	5	251	5	251	4
257	5	257	5	257	4
262	6	262	4	262	3
267	6	267	4	267	3
273	6	273	4	273	3
278	6	278	4	278	3
283	6	283	4	283	3
289	6	289	4	289	3

With elliptical suppressor plate P=90mm:

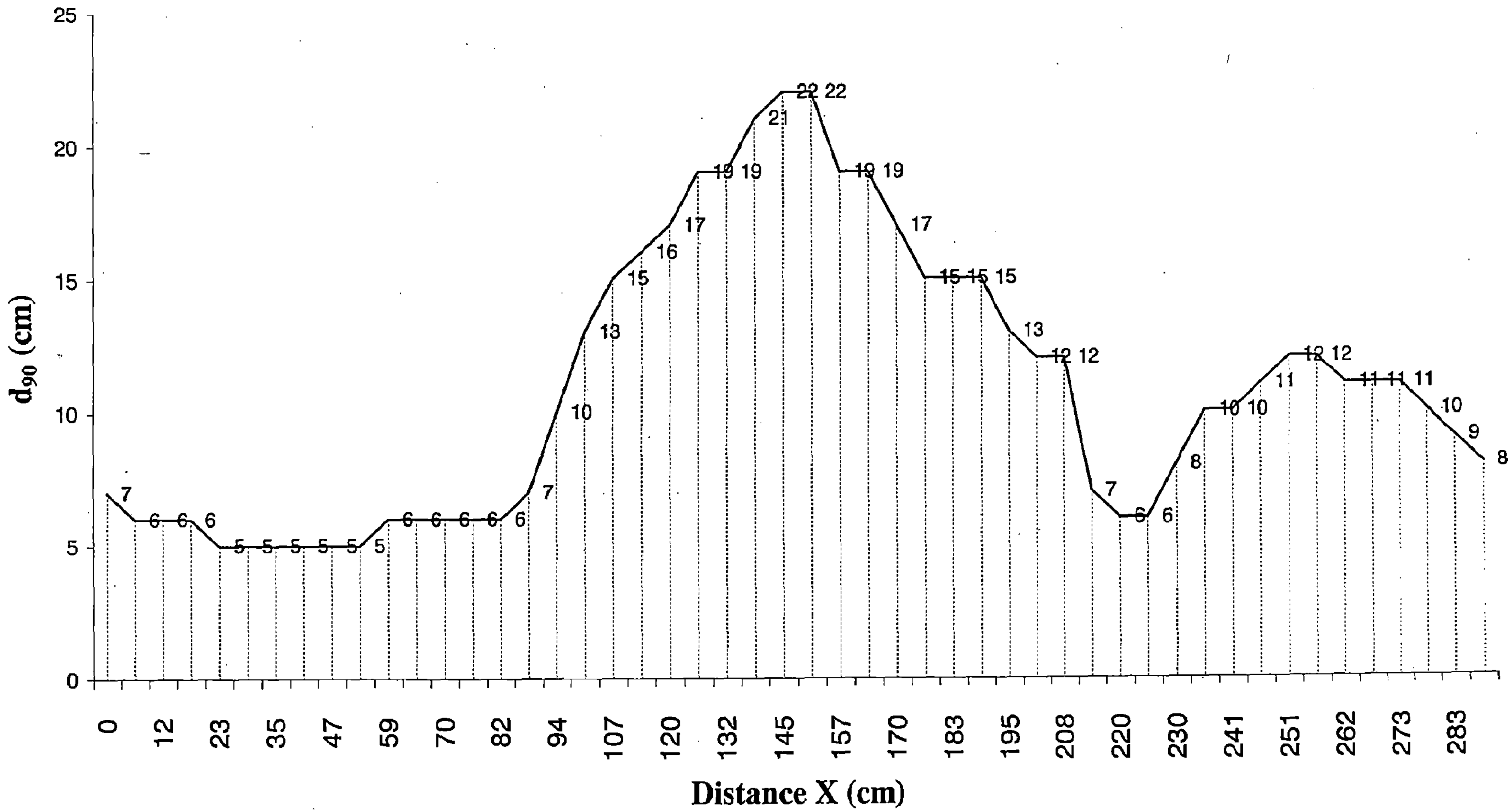
x(cm)	dw90(Q=20lps)		x(cm)	dw90(Q=14lps)		x(cm)	dw90(Q=10lps)
0	8		0	6		0	5
6	8		6	6		6	4
12	7		12	5		12	4
18	6		18	5		18	4
23	6		23	4		23	3
29	5		29	4		29	3
35	5		35	4		35	3
41	5		41	4		41	3
47	5		47	4		47	3
53	5		53	4		53	3
59	5		59	4		59	3
64	5		64	4		64	3
70	5		70	4		70	3
76	5		76	4		76	3
82	5		82	4		82	3
88	5		88	4		88	3
94	5		94	5		94	5
101	5		101	5		101	5
107	5		107	5		107	5
113	5		113	5		113	5
120	5		120	5		120	5
126	5		126	5		126	5
132	5		132	5		132	5
138	7		138	5		138	5
145	7		145	5		145	5
151	7		151	5		151	5
157	7		157	5		157	5
164	7		164	5		164	5
170	7		170	5		170	5
176	7		176	5		176	5
183	7		183	5		183	4
189	7		189	5		189	4
195	7		195	5		195	4
202	7		202	5		202	4
208	7		208	5		208	4
214	7		214	5		214	4
220	6		220	4		220	3
225	5		225	4		225	4
230	5		230	5		230	5
236	5		236	6		236	5
241	6		241	6		241	6
246	6		246	6		246	6
251	8		251	6		251	6
257	8		257	6		257	5
262	8		262	6		262	5
267	8		267	5		267	4
273	8		273	5		273	4
278	8		278	5		278	4
283	7		283	5		283	4
289	7		289	5		289	4

H_{res}/H_{max} vs H_{spill}/dc graph

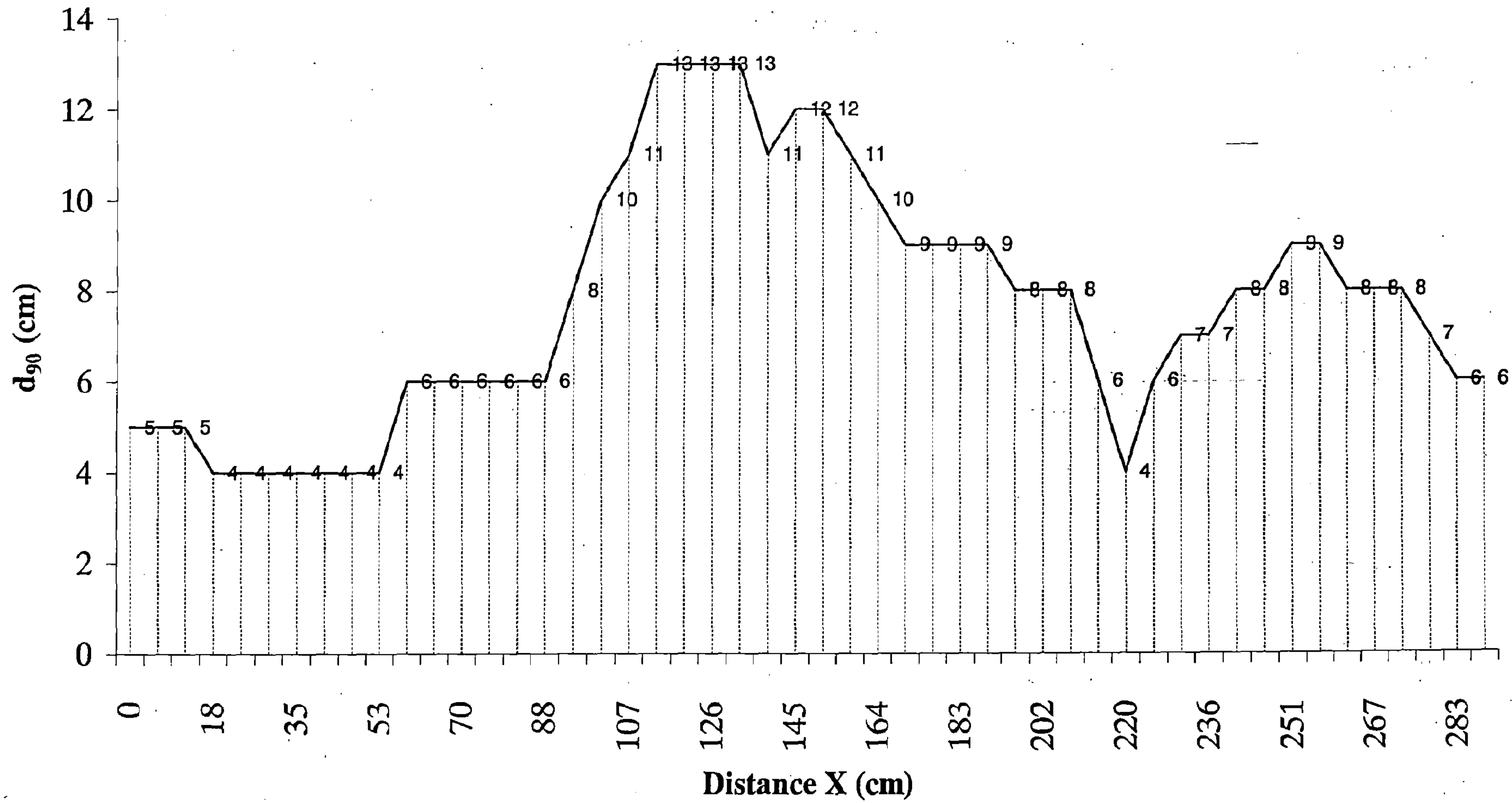



d$_{90}$ vs X for Q=20 lps
without suppressor
d$_{90}$ (cm)
Distance X (cm)
0
5
10
15
20
25
0
18
35
53
70
88
107
126
145
164
183
202
220
236
251
267
283

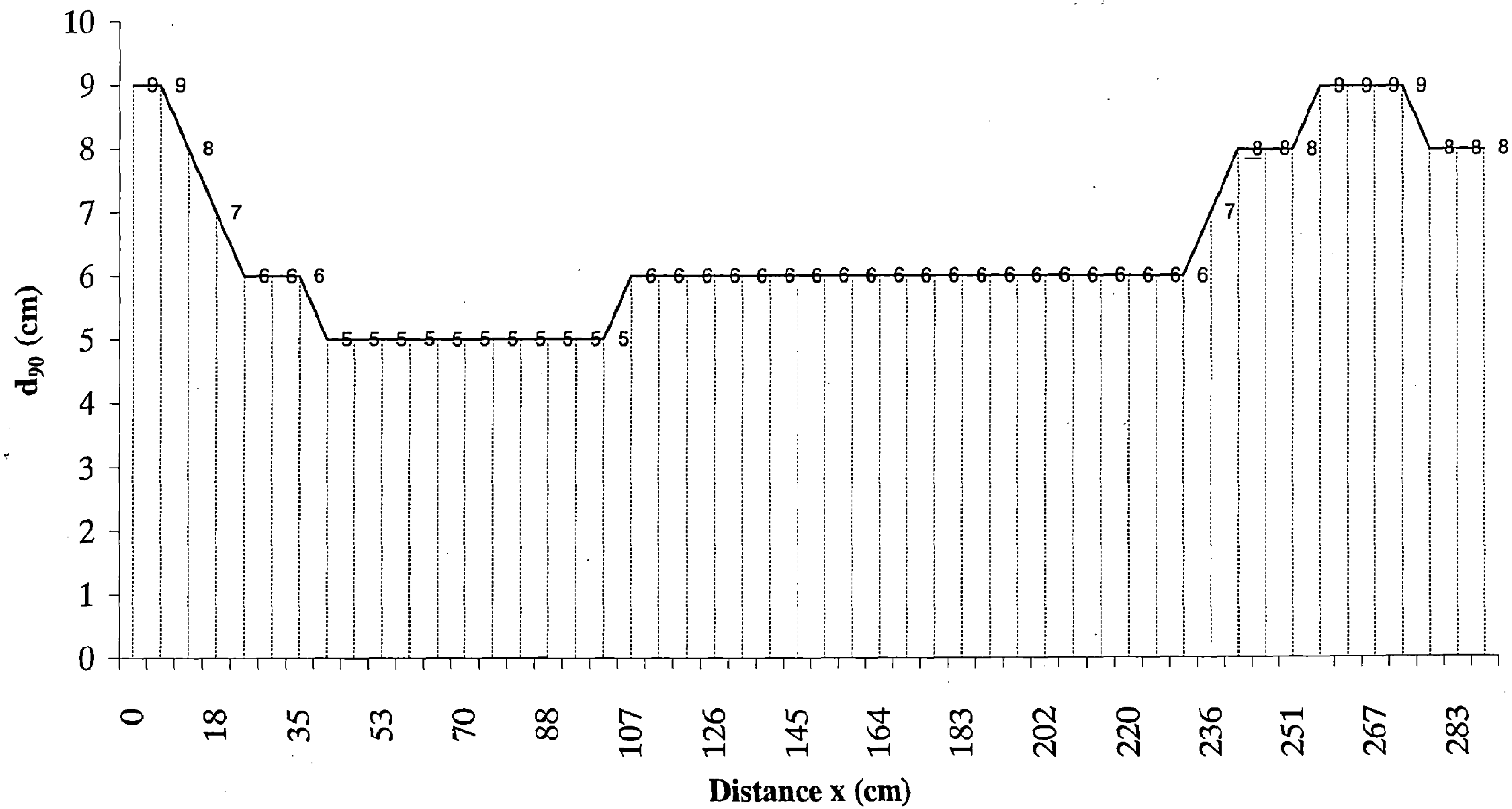
d_{90} vs X for Q=14 lps without suppressor



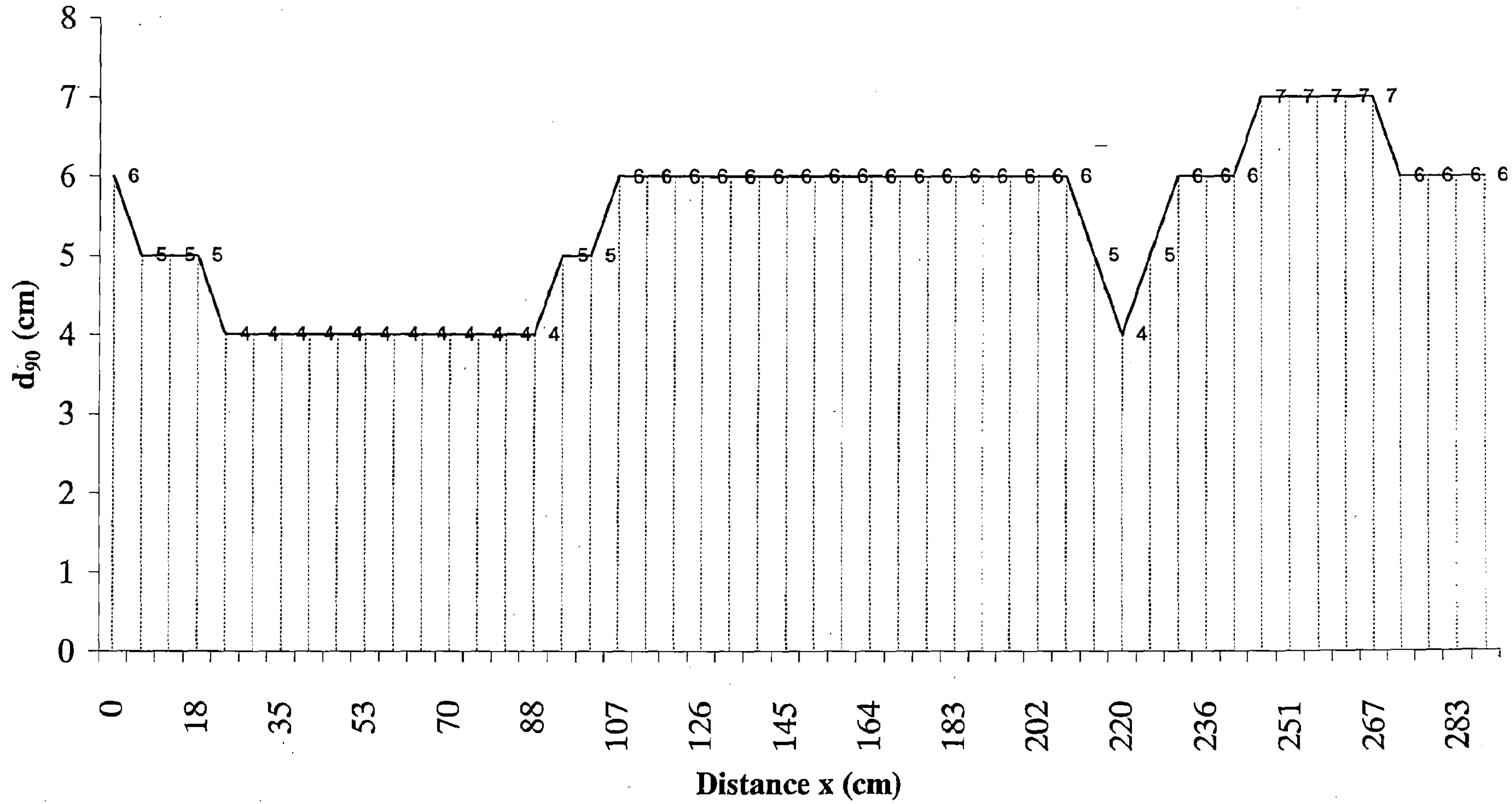
d_{90} vs X for Q=10 lps without suppressor



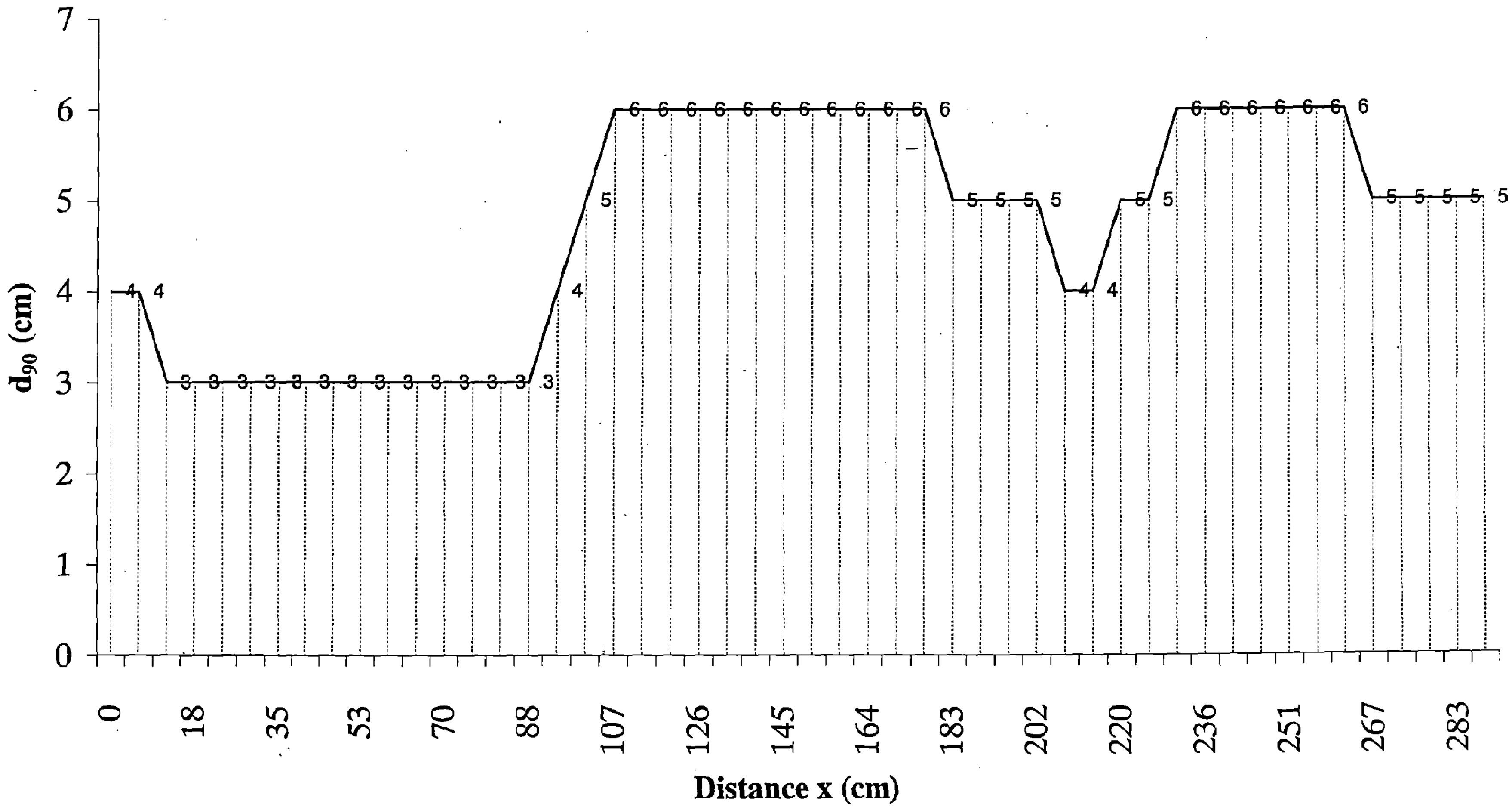
d_{90} vs x for Q=20 lps
with circu.suppressor



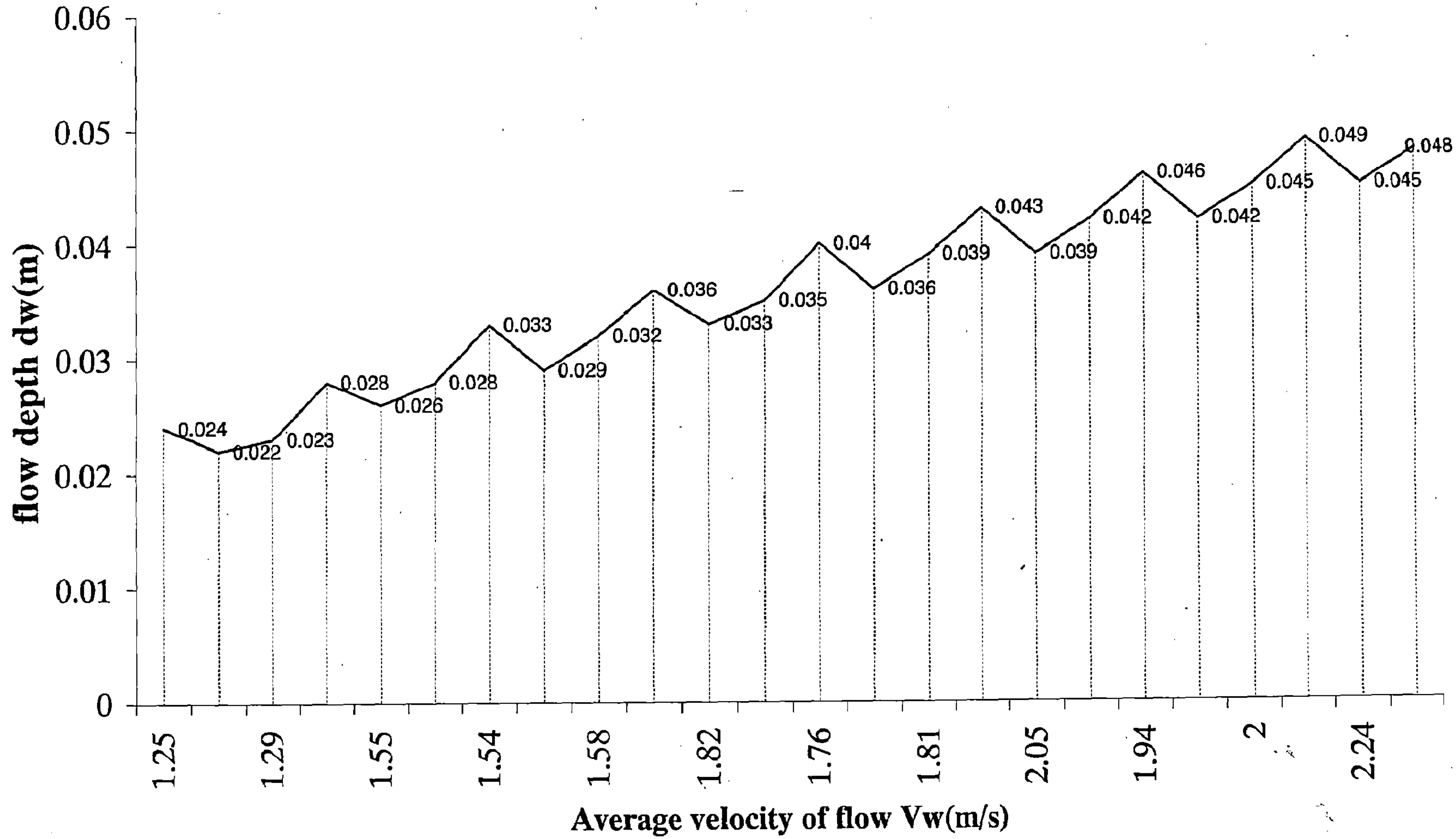
d_{90} vs x for Q=14 lps with circu.suppressor

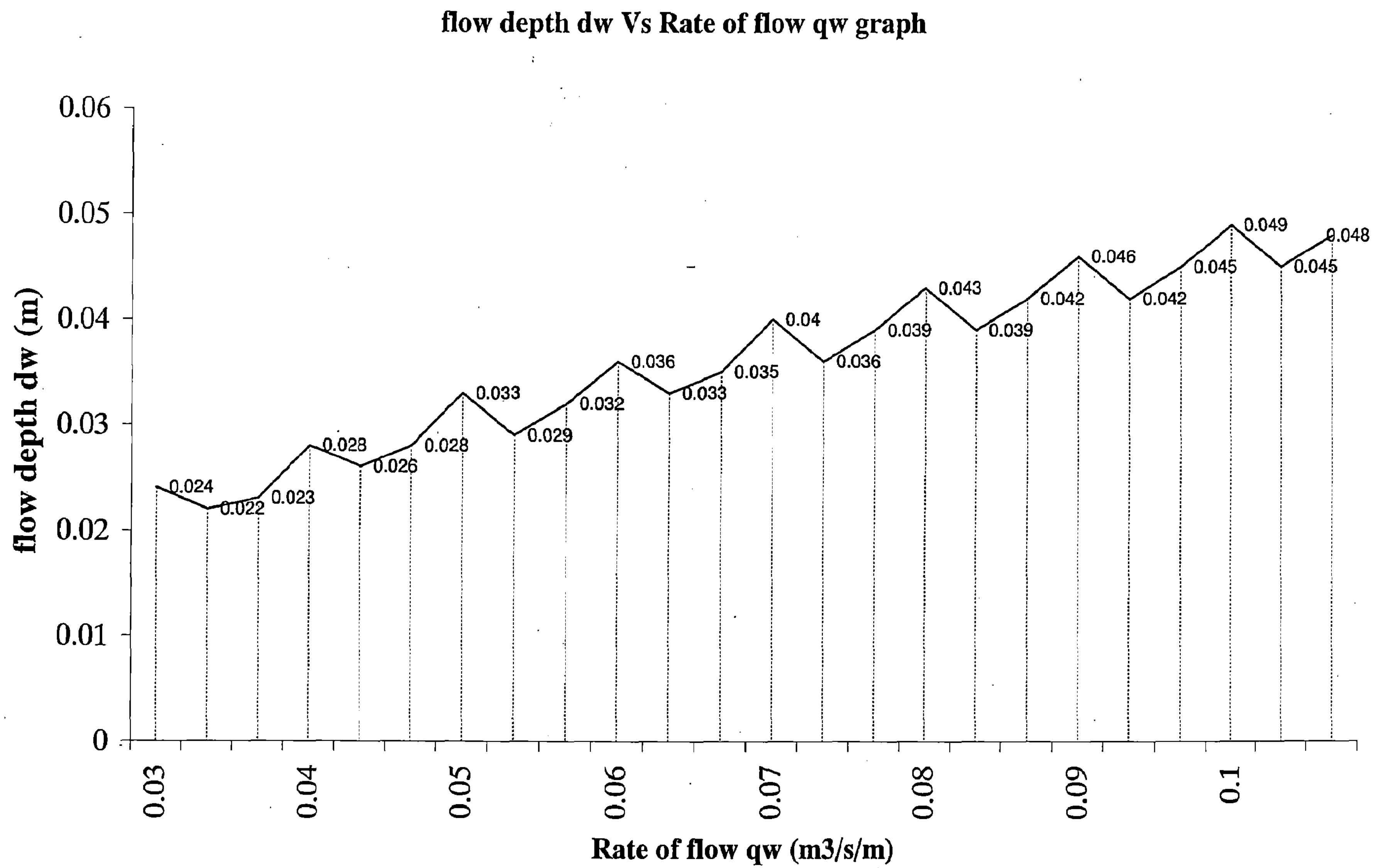


d_{90} vs x for Q=10 lps
with circu.suppressor

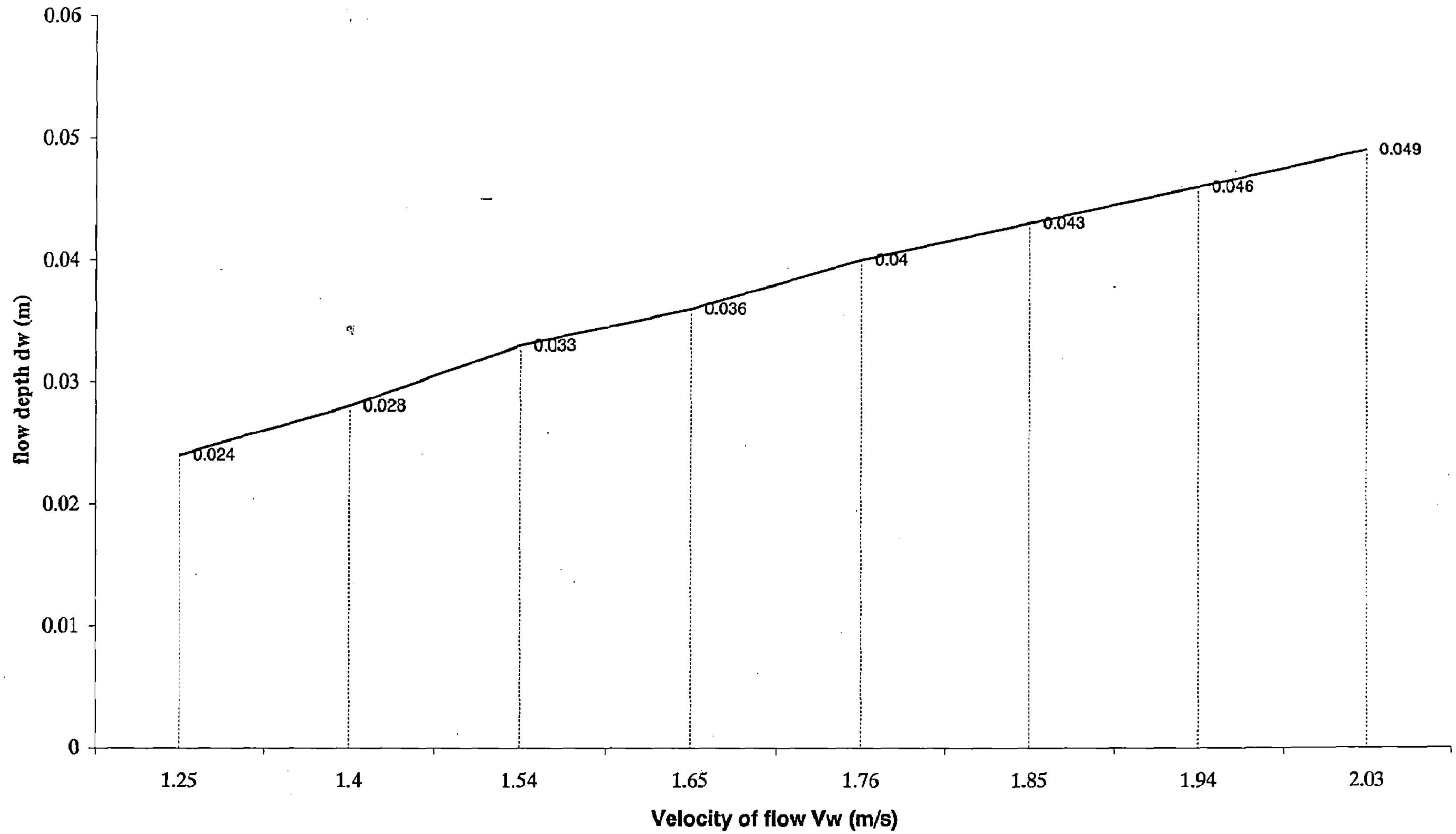


flow depth dw (m) Vs Average velocity Vw (m/s) graph

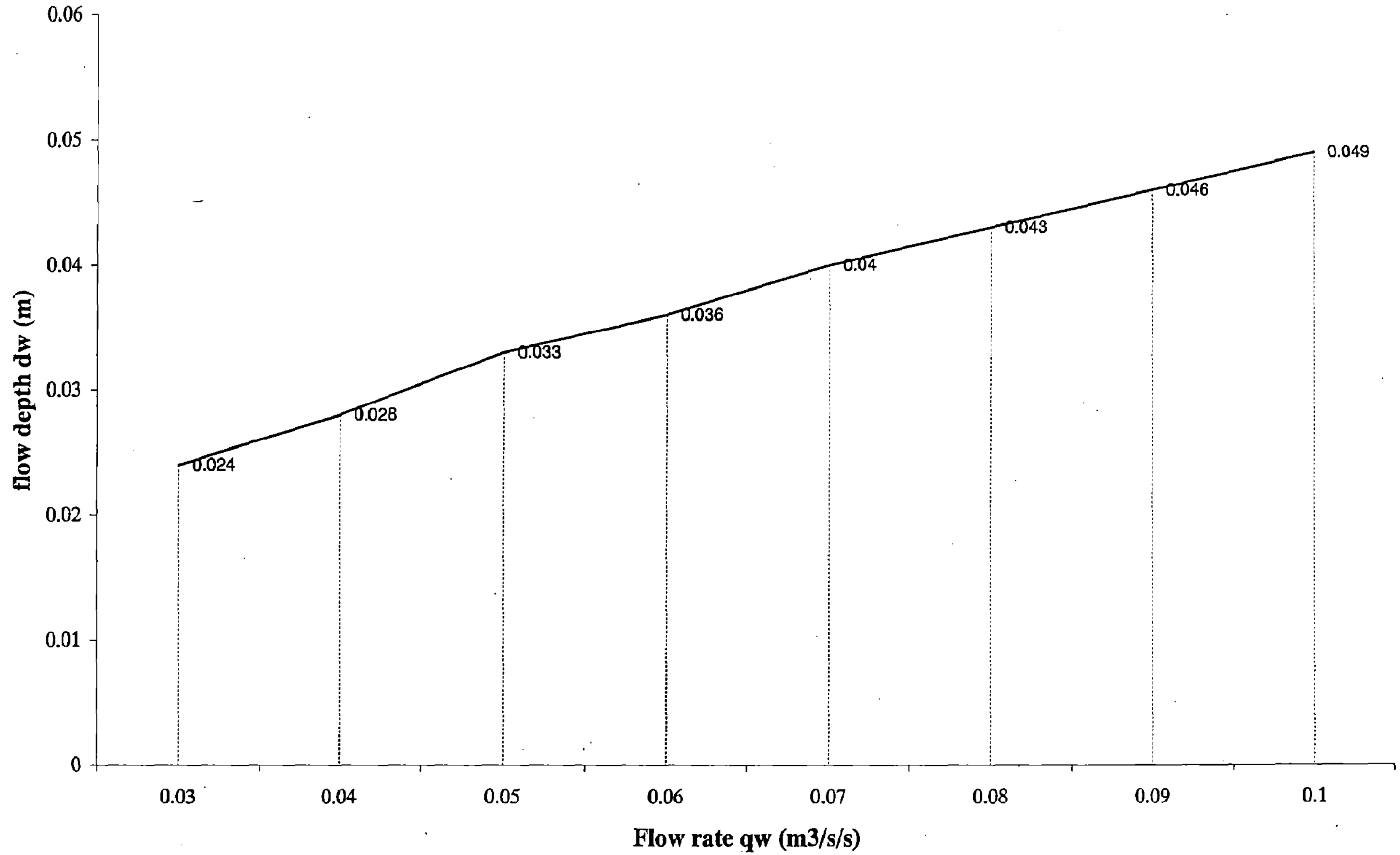



flow depth dw Vs Rate of flow qw graph
flow depth dw (m)
0.06
0.05
0.04
0.03
0.02
0.01
0
0.024
0.022
0.023
0.028
0.026
0.028
0.033
0.029
0.032
0.036
0.033
0.035
0.04
0.036
0.039
0.043
0.039
0.042
0.046
0.042
0.045
0.049
0.045
0.048
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Rate of flow qw (m3/s/m)

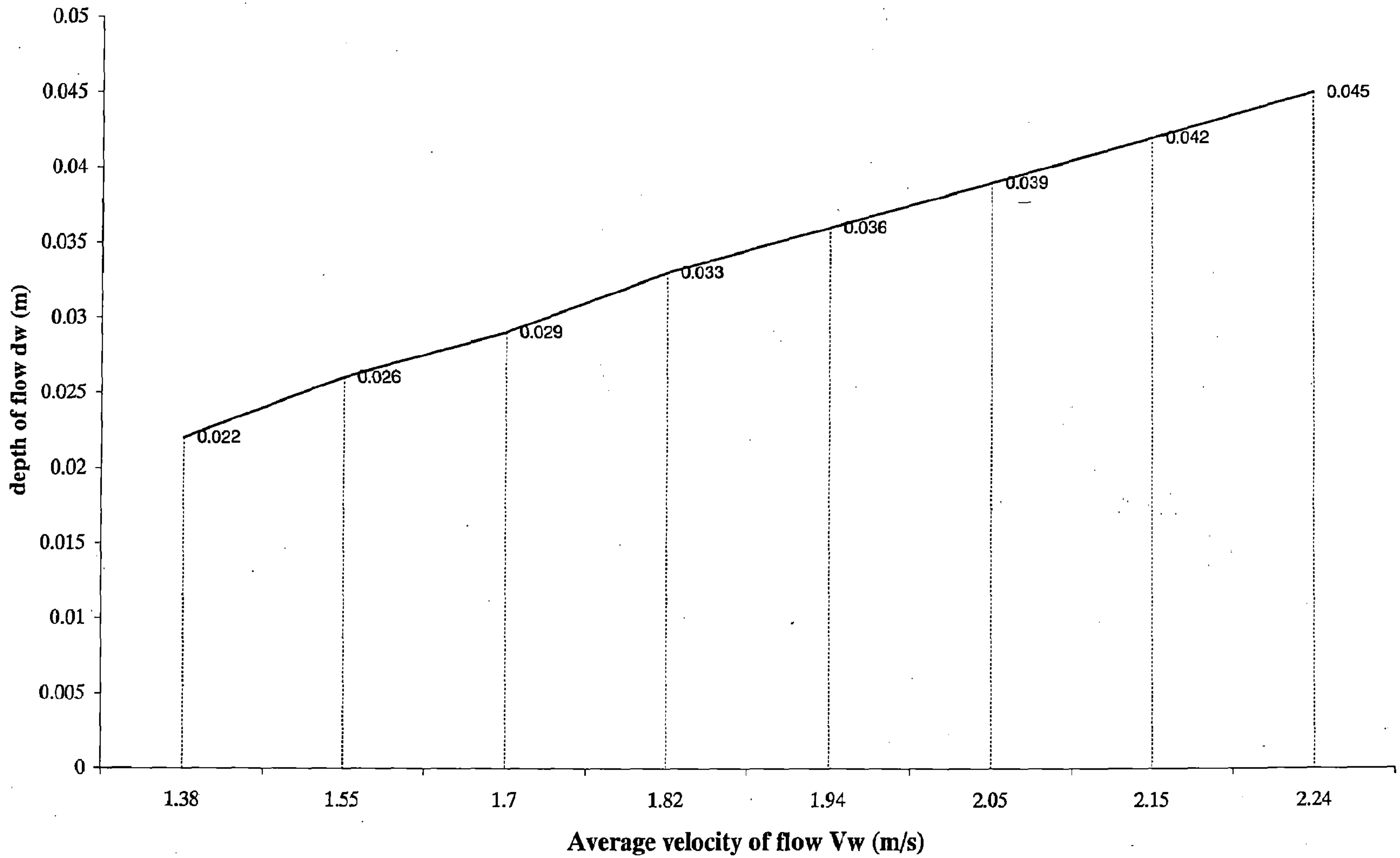
dw verses Vw graph for slope $34^{0}32'$

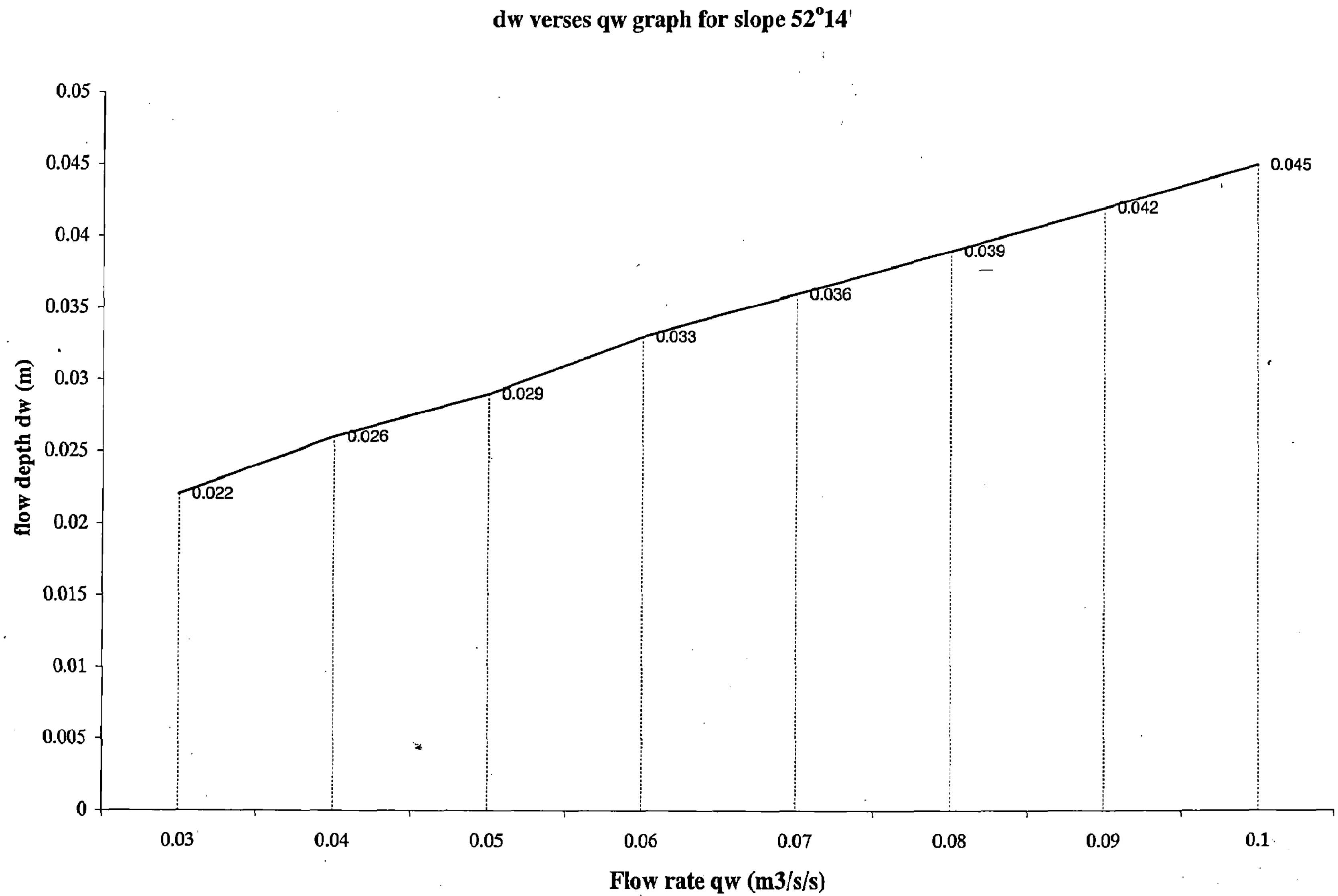


dw verses qw graph for slope 34°32'

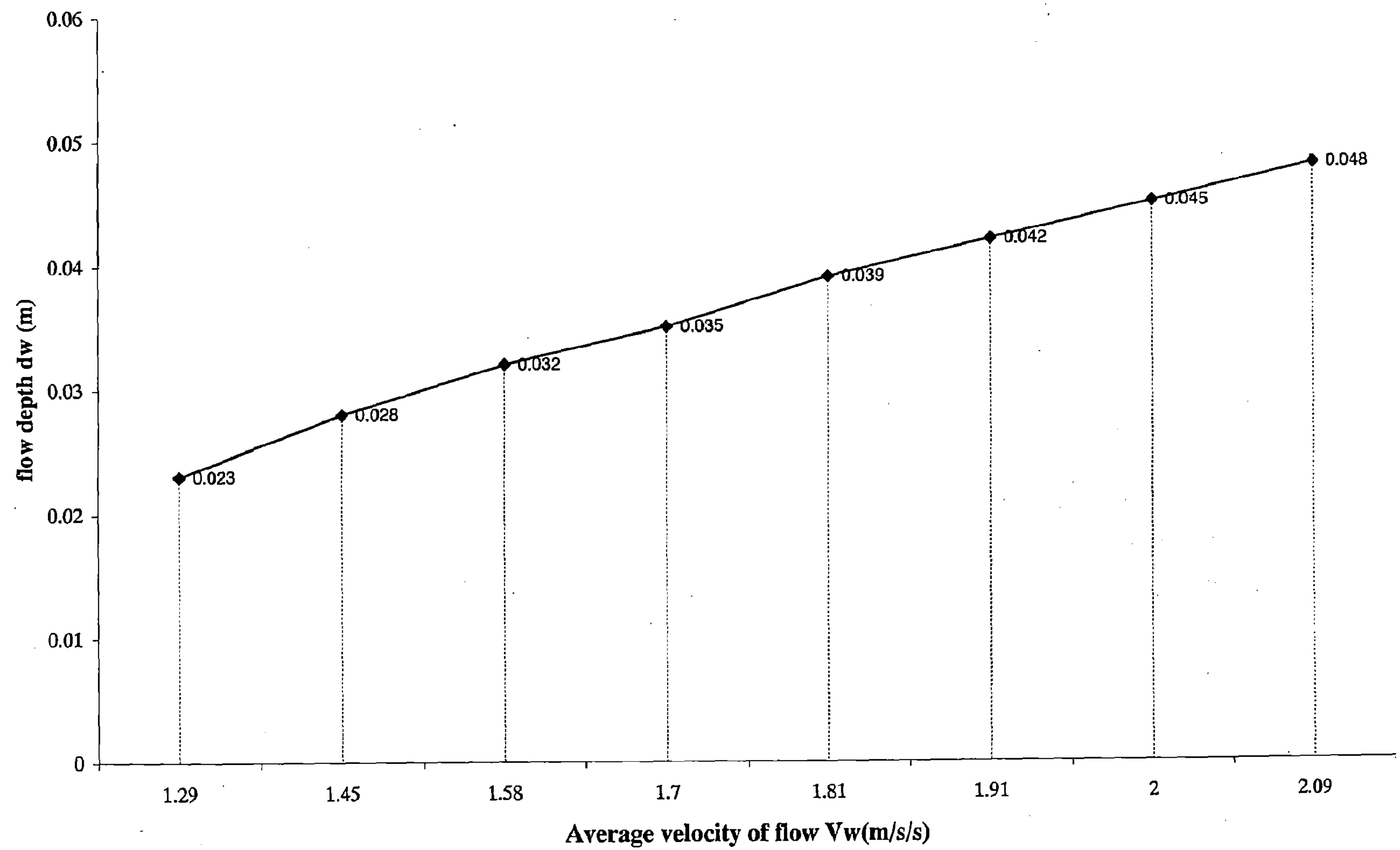


dw verses Vw graph for slope 52°14'

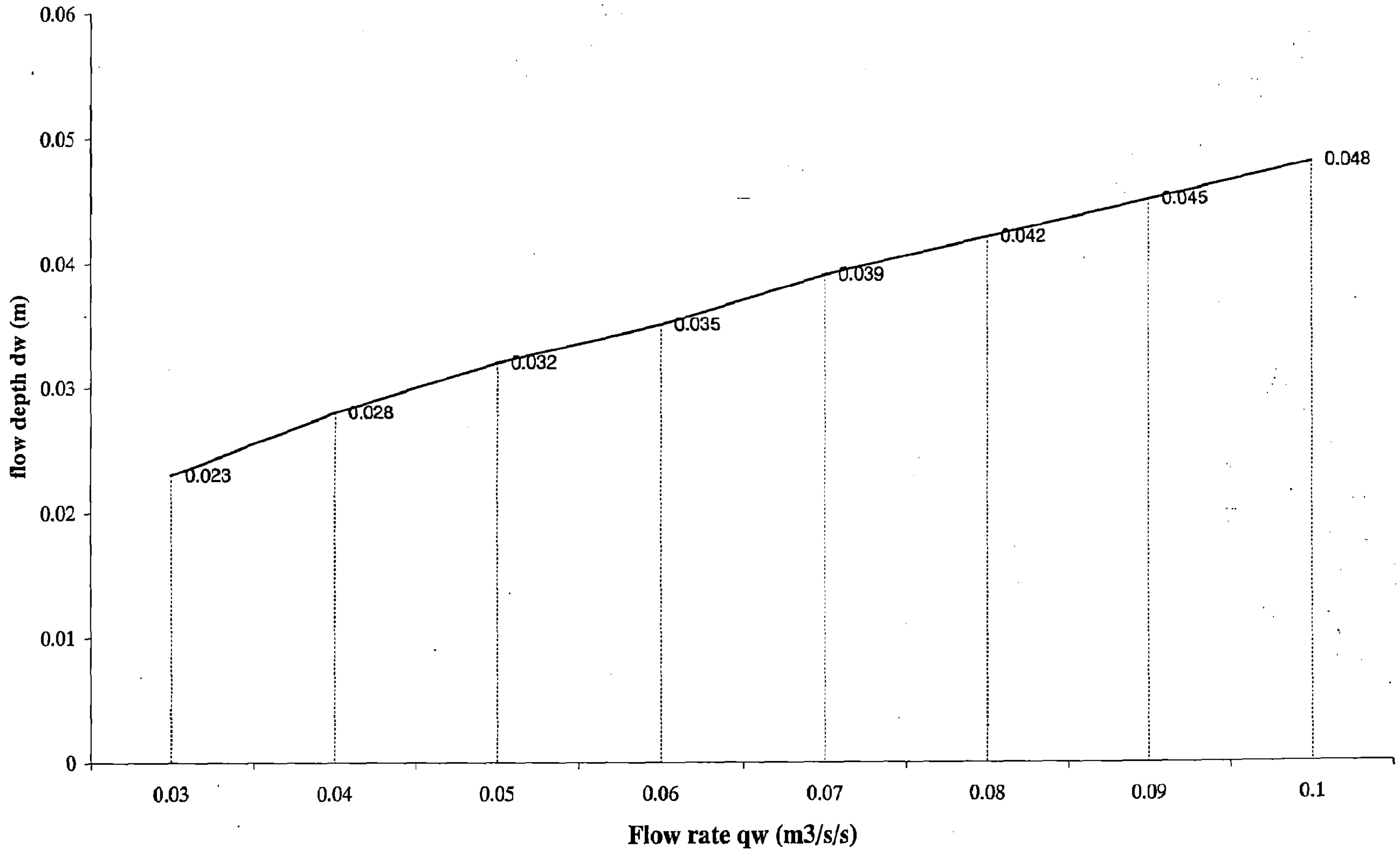



dw verses qw graph for slope 52°14'
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
flow depth dw (m)
0.022
0.026
0.029
0.033
0.036
0.039
0.042
0.045
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Flow rate qw (m3/s/s)

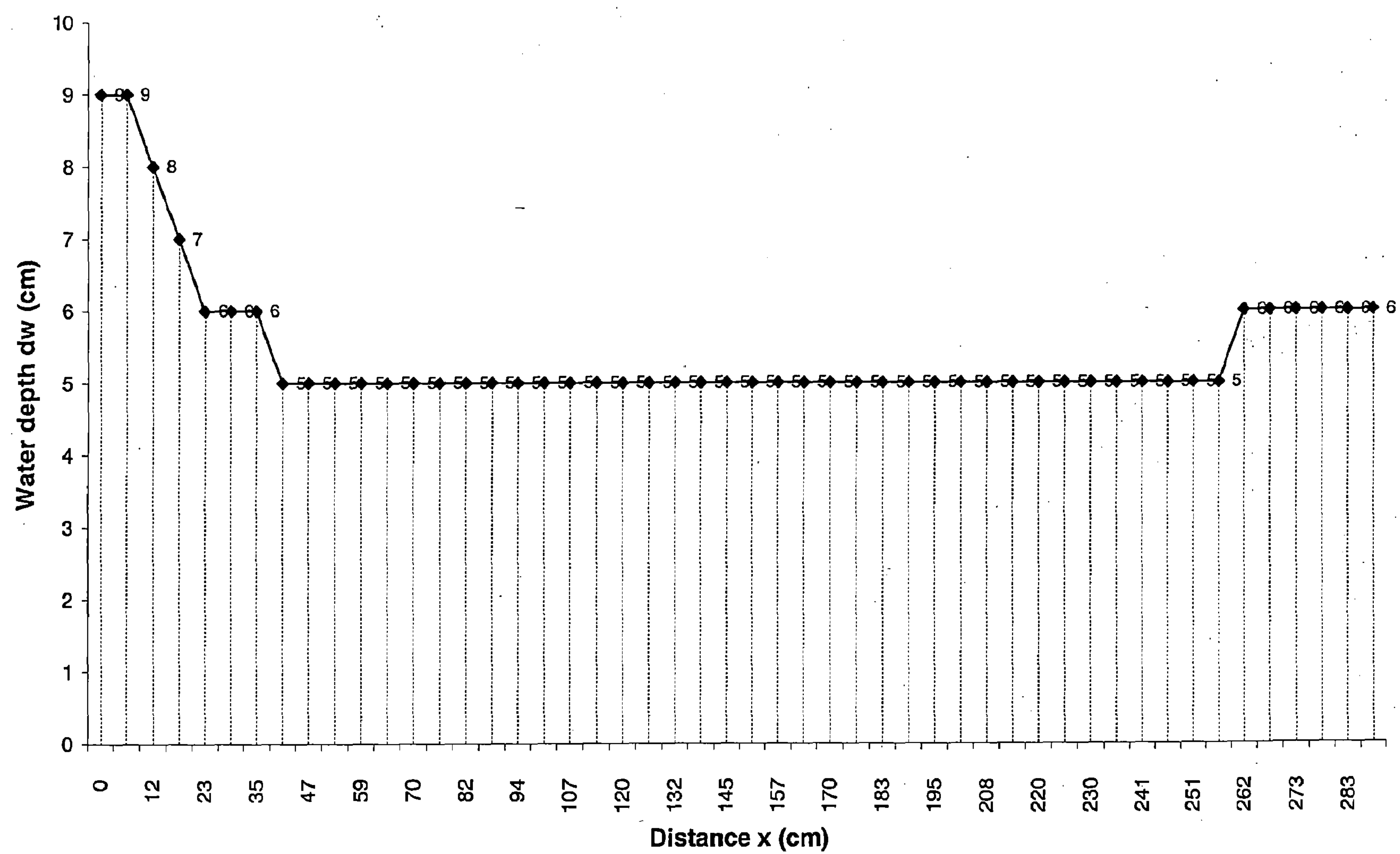
dw verses Vw graph for slope 38°50'



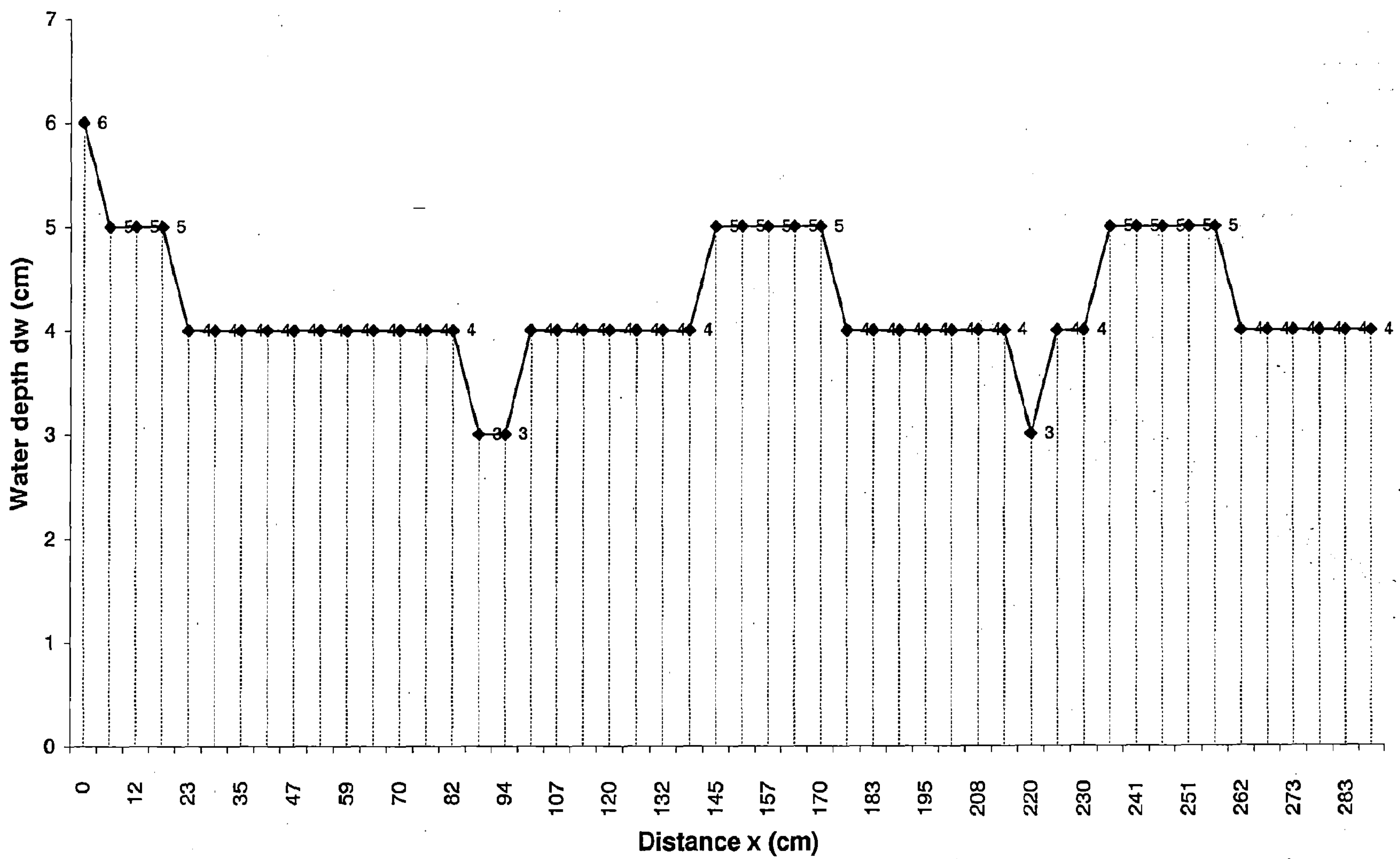
dw verses qw graph for slope 38°50'



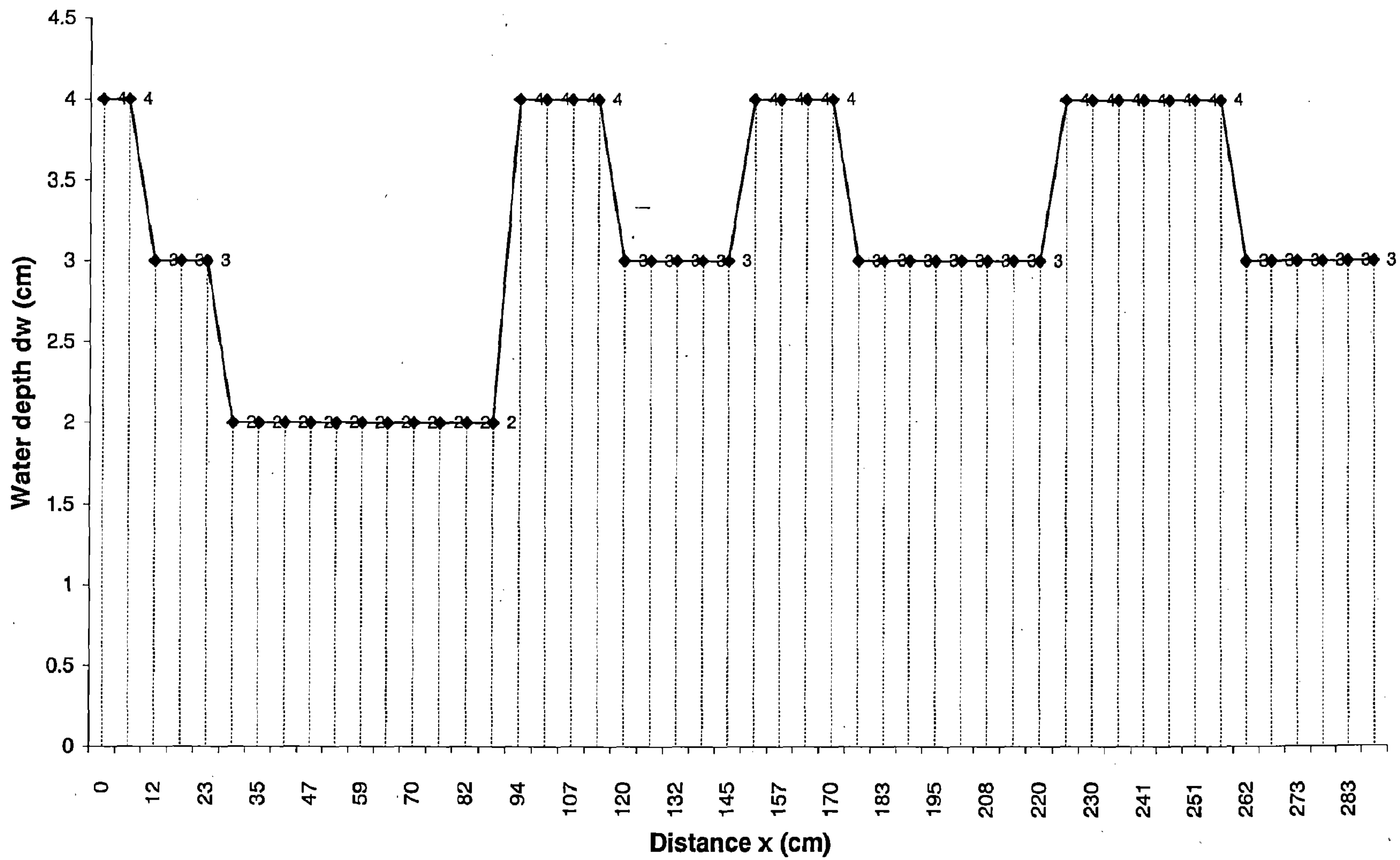
dw vs x graph of 20 lps for elliptical suppressor P=135mm



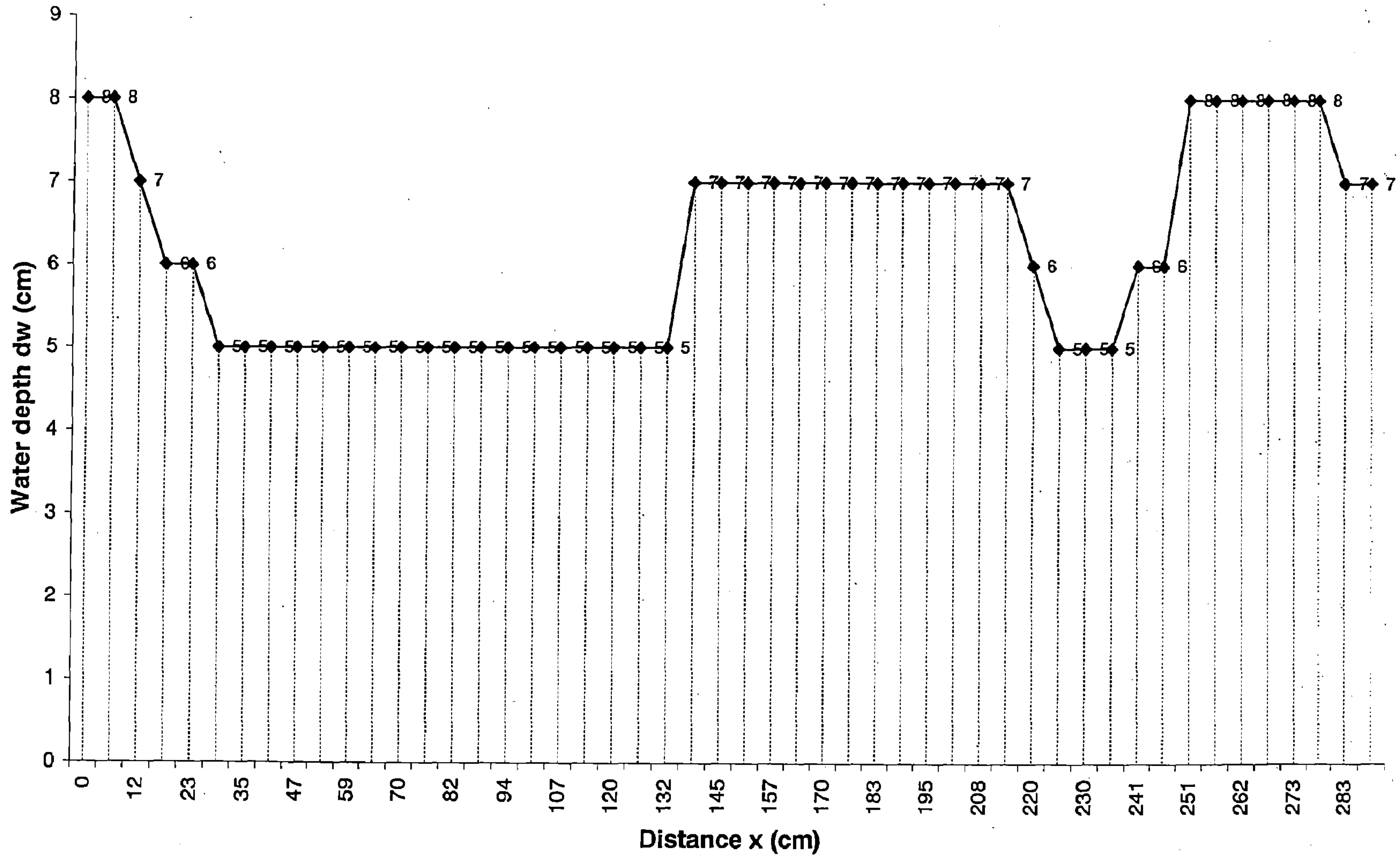
dw vs x graph of 14 lps for elliptical suppressor plate P=135mm



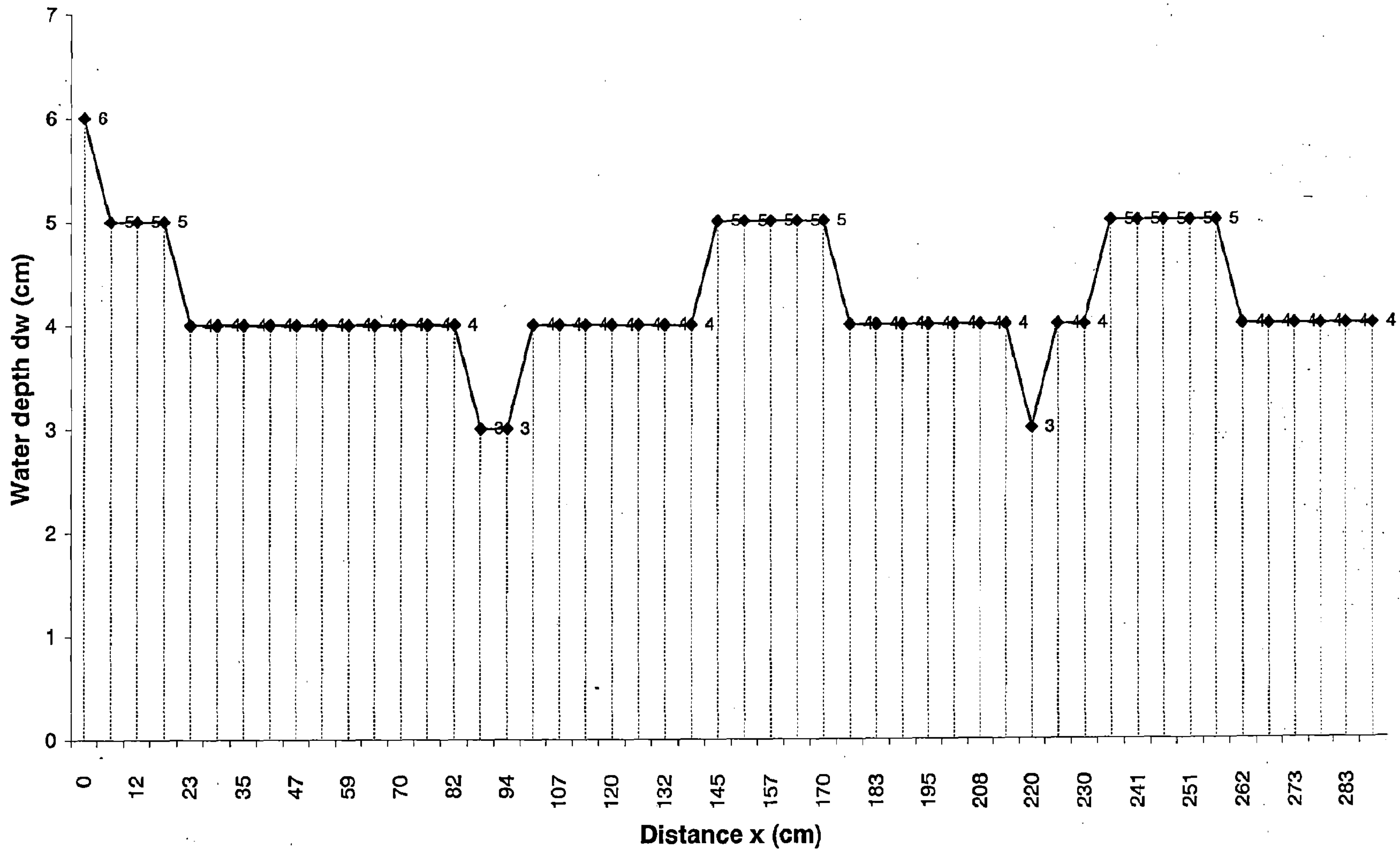
dw vs x graph of 10 lps for elliptical suppressor plate P=135mm



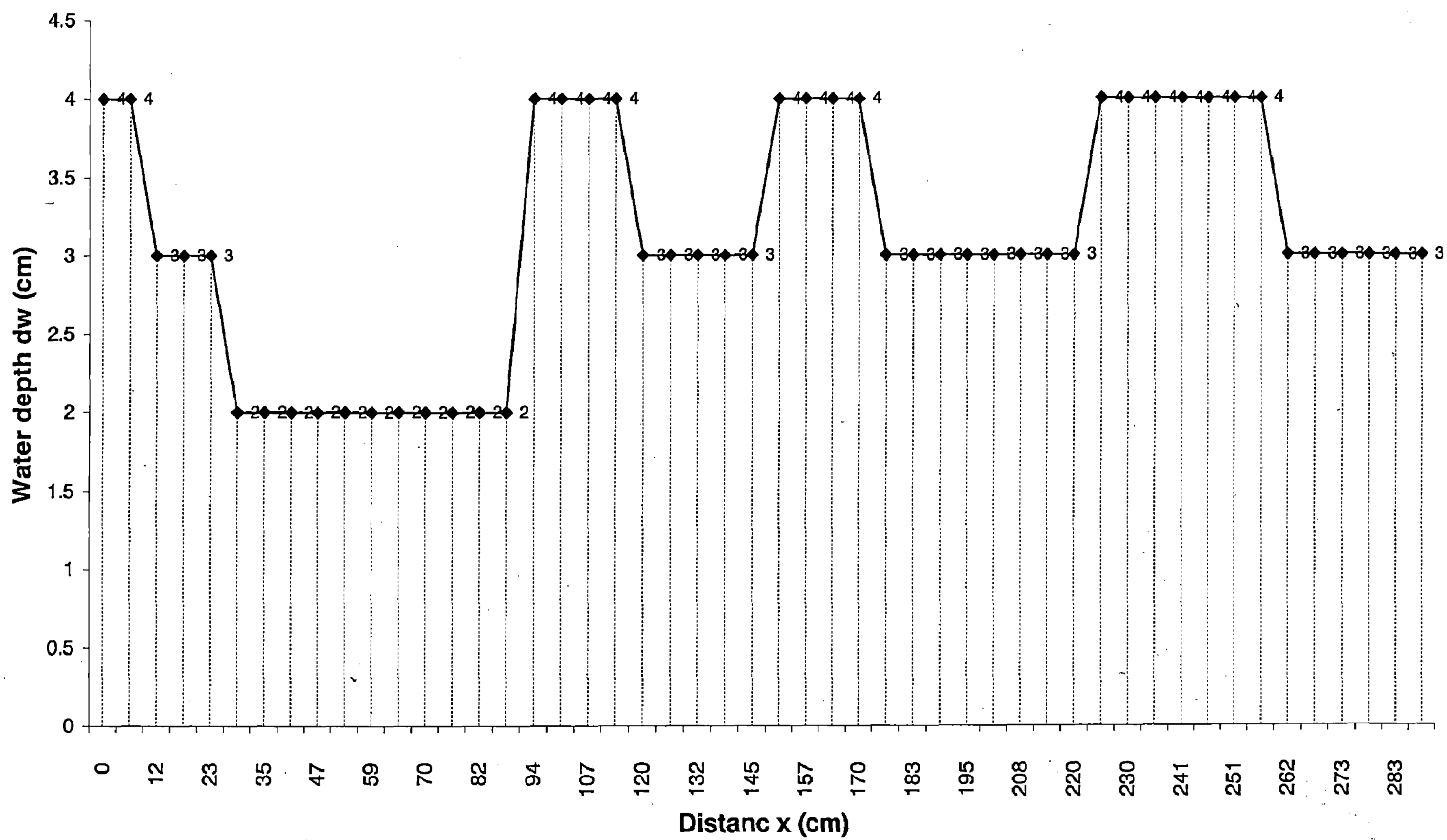
dw vs x graph of 20 lps for elliptical suppressor plate P=90mm



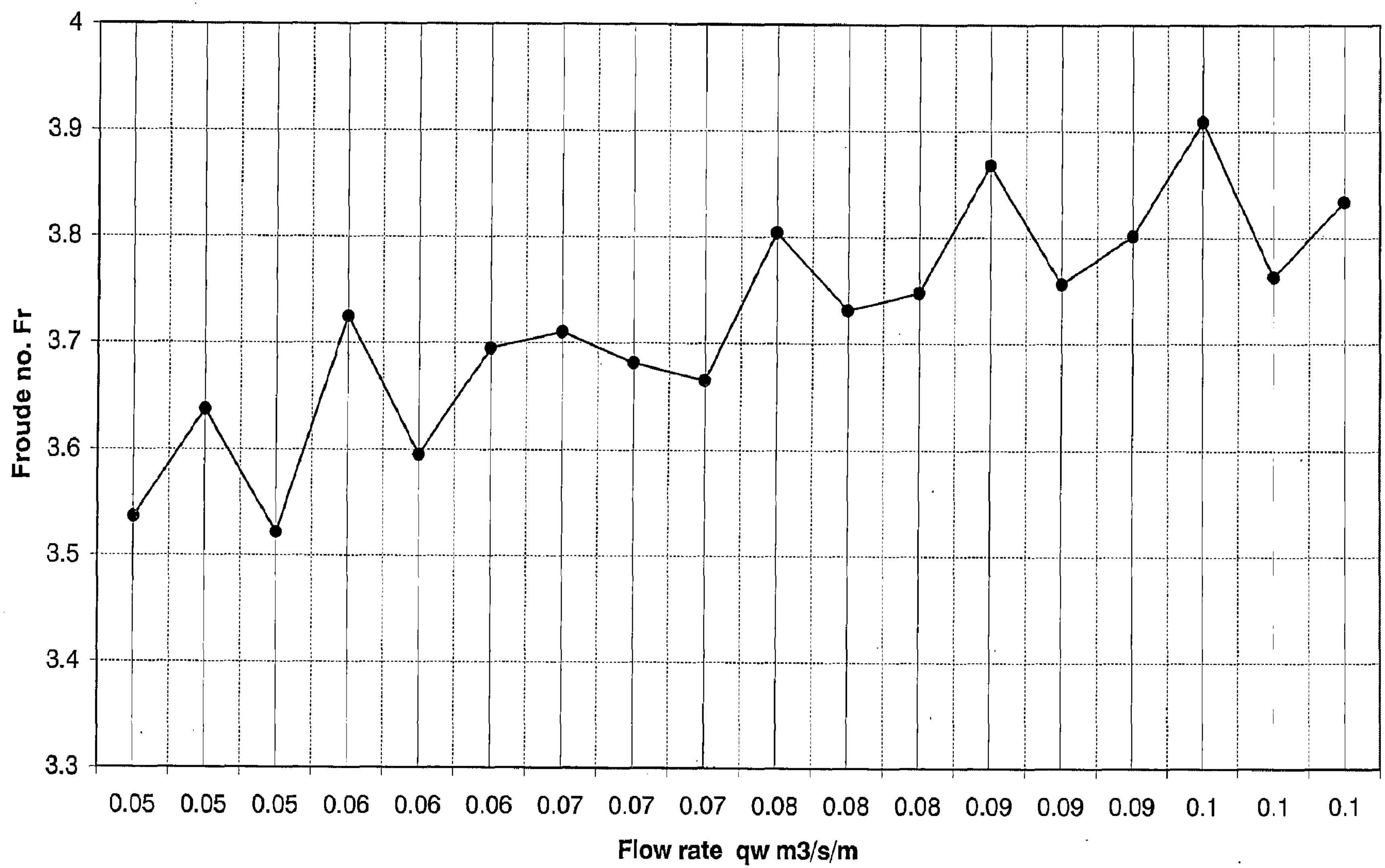
dw vs x graph of 14 lps for elliptical suppressor plate P=90mm



dw vs x graph for 10 lps for elliptical suppressor plate P=90mm



qw vs Fr graph



Appendix-C

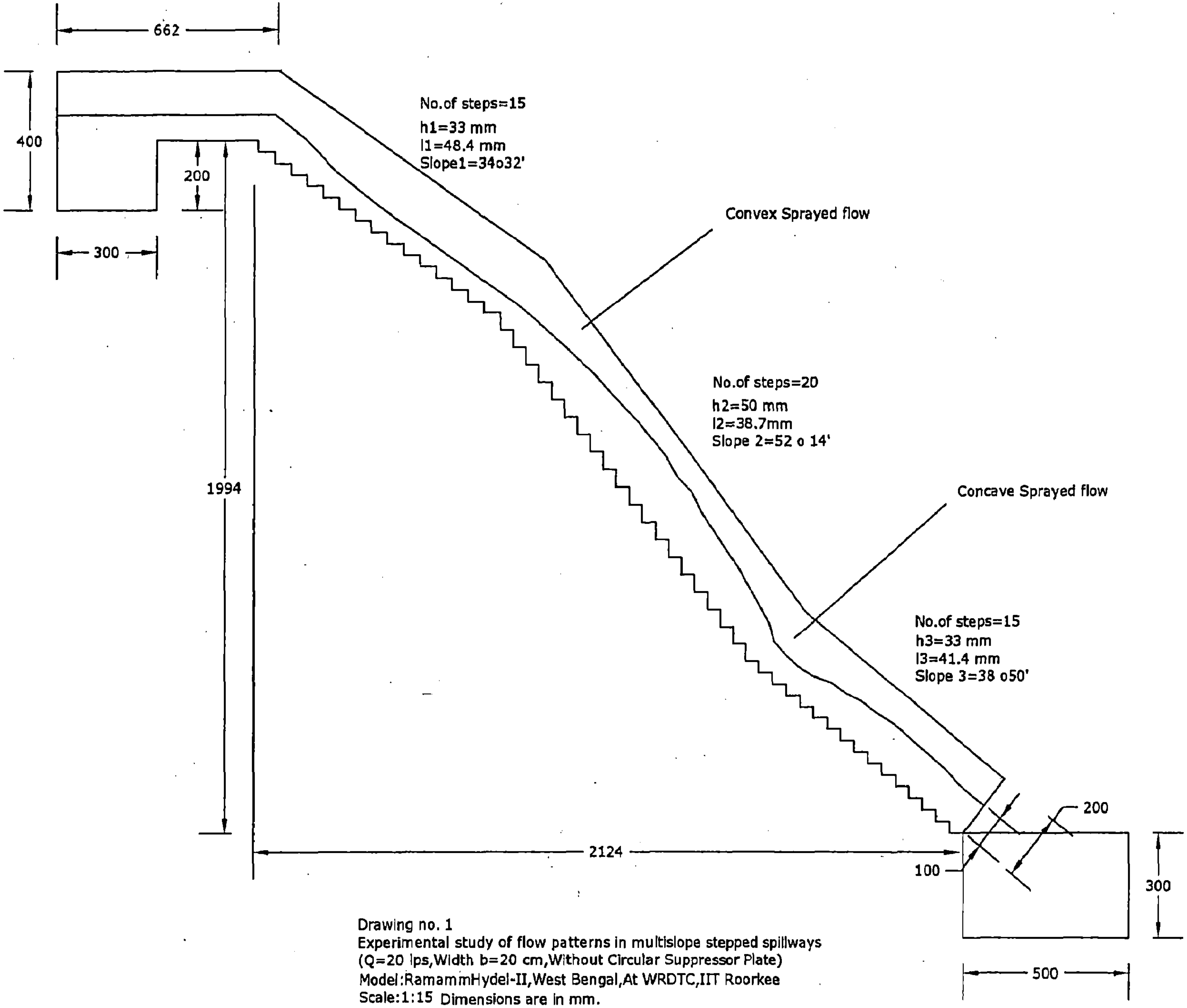
Drawings and Photographs:

(a) AutoCAD drawings:

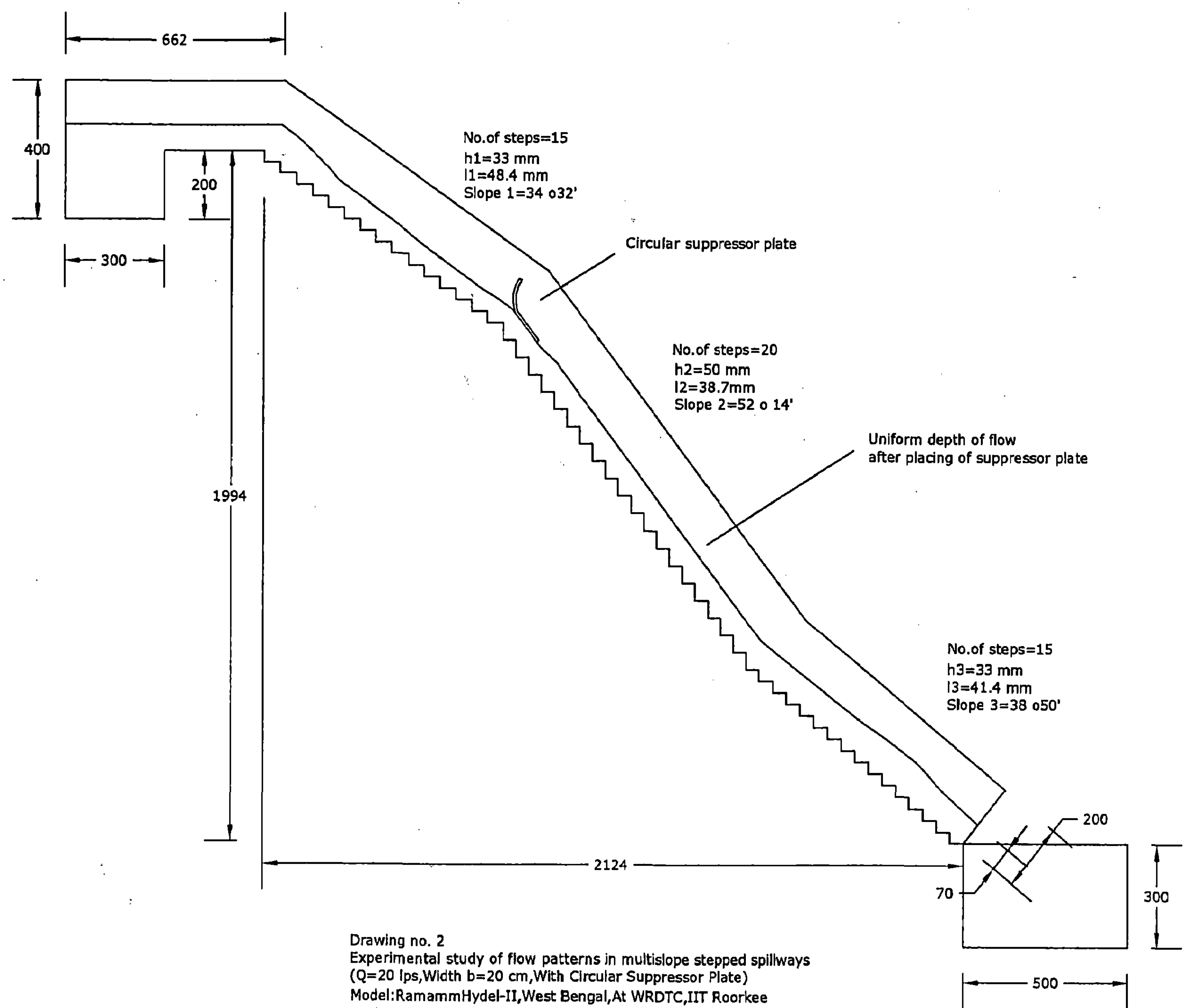
Drawings of flow patterns in multislope and monoslope stepped spillways model (width =20cm) for different discharges ranging from 6 to 20 lps.

(b) Photographs:

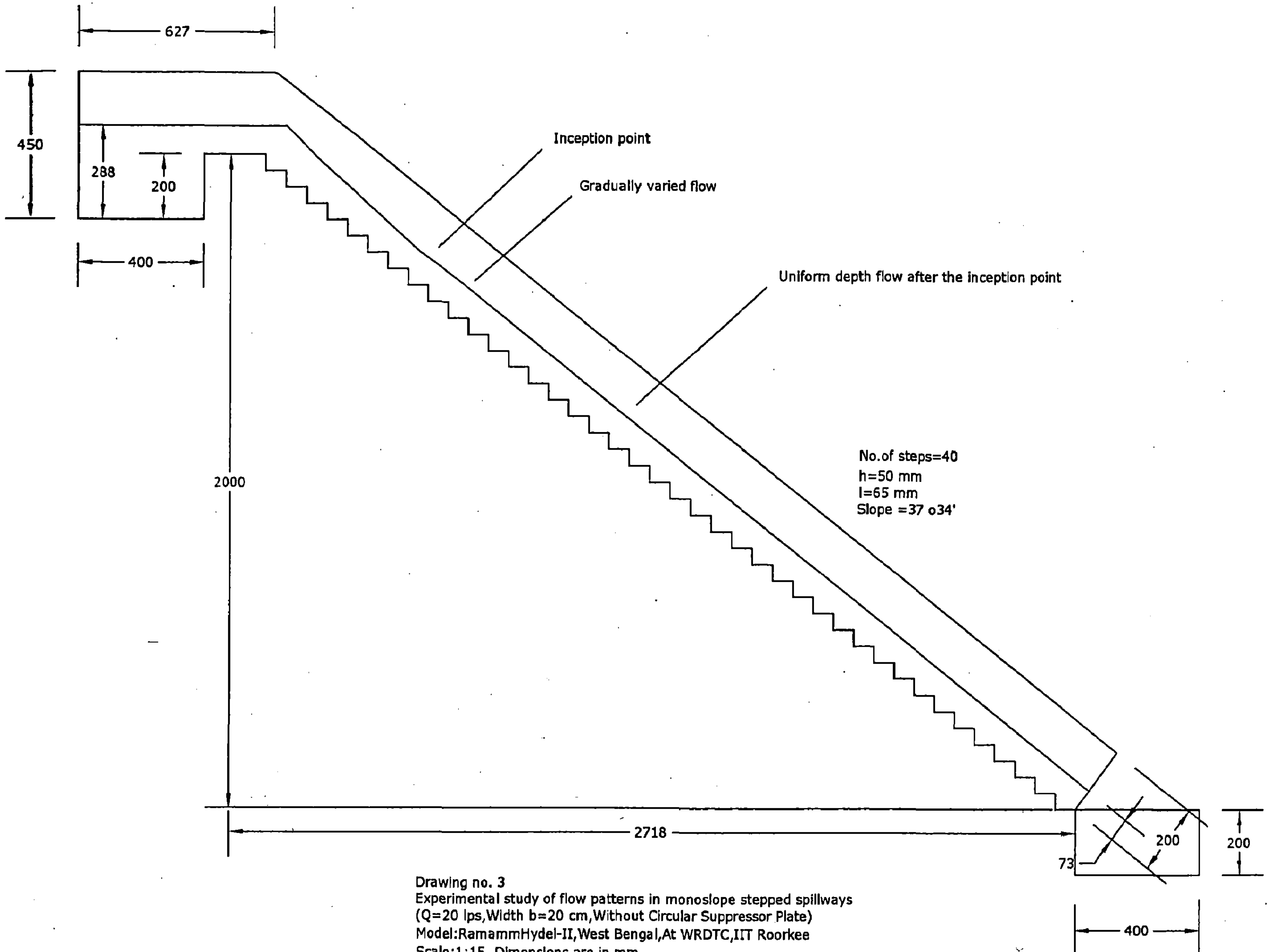
Photographs of flow patterns in the experimental set-ups with different discharges ranging from 6 to 20 lps.



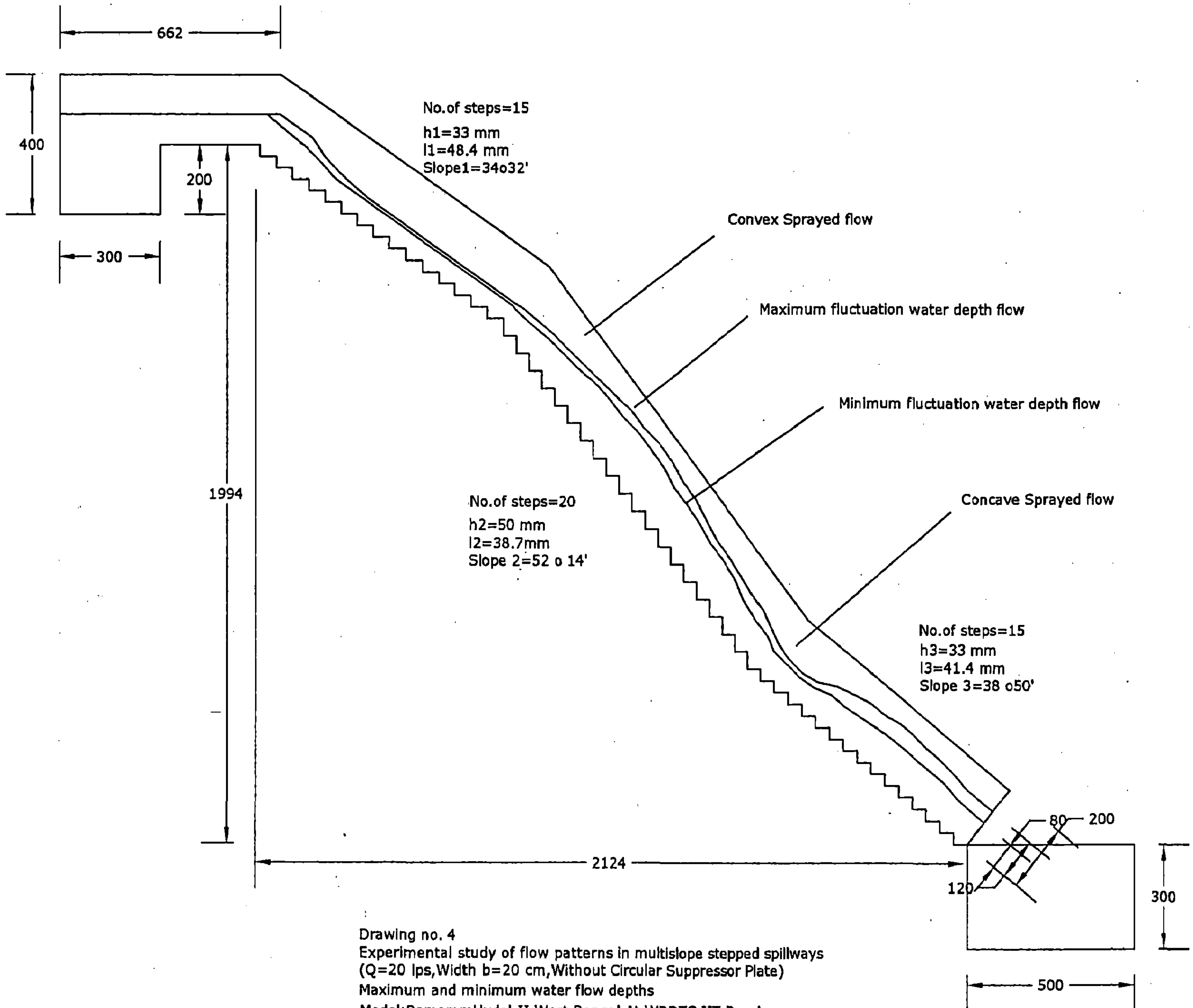
Drawing no. 1
Experimental study of flow patterns in multislope stepped spillways
(Q=20 lps,Width b=20 cm,Without Circular Suppressor Plate)
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm.



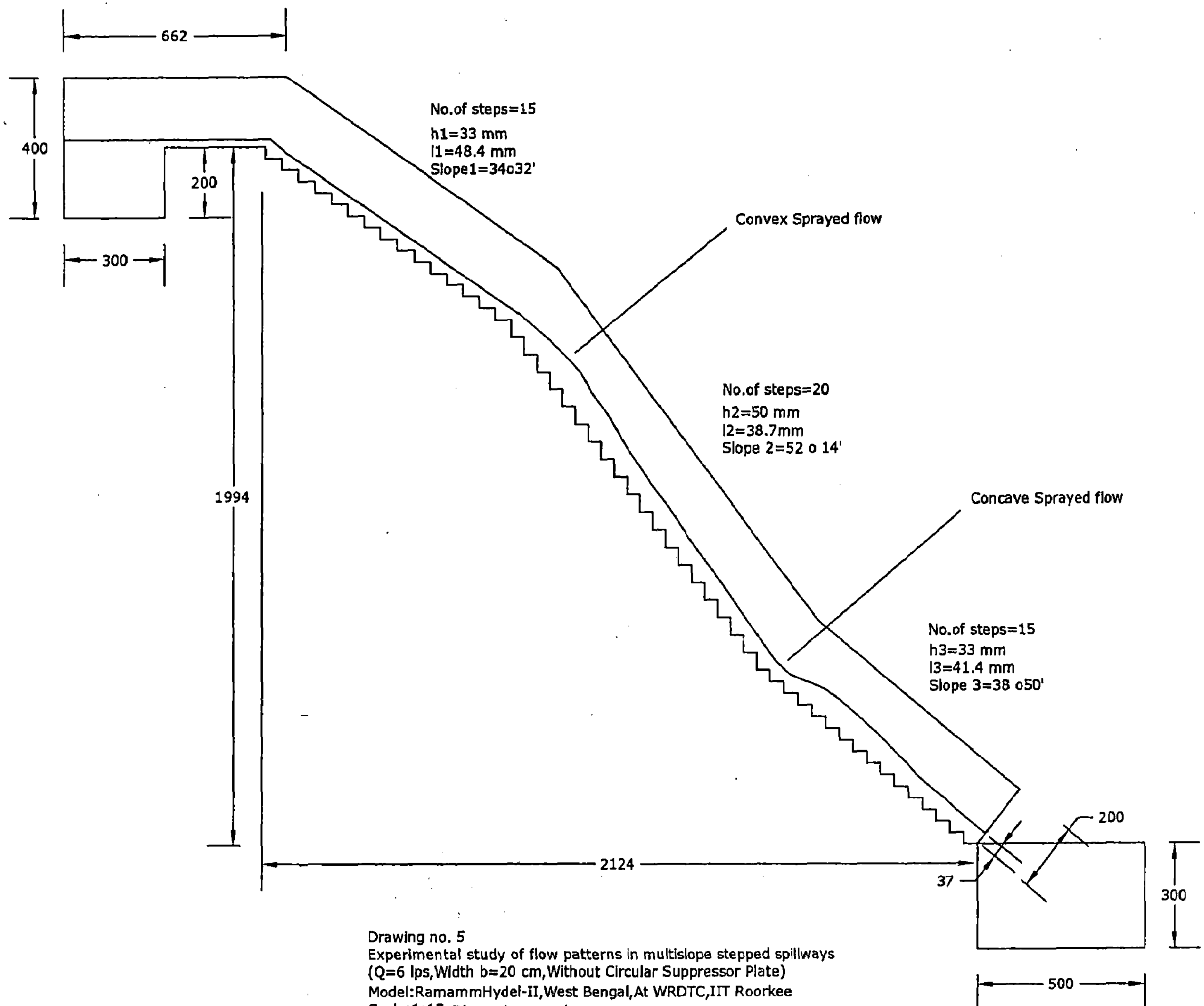
Drawing no. 2
Experimental study of flow patterns in multislope stepped spillways
(Q=20 lps,Width b=20 cm,With Circular Suppressor Plate)
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



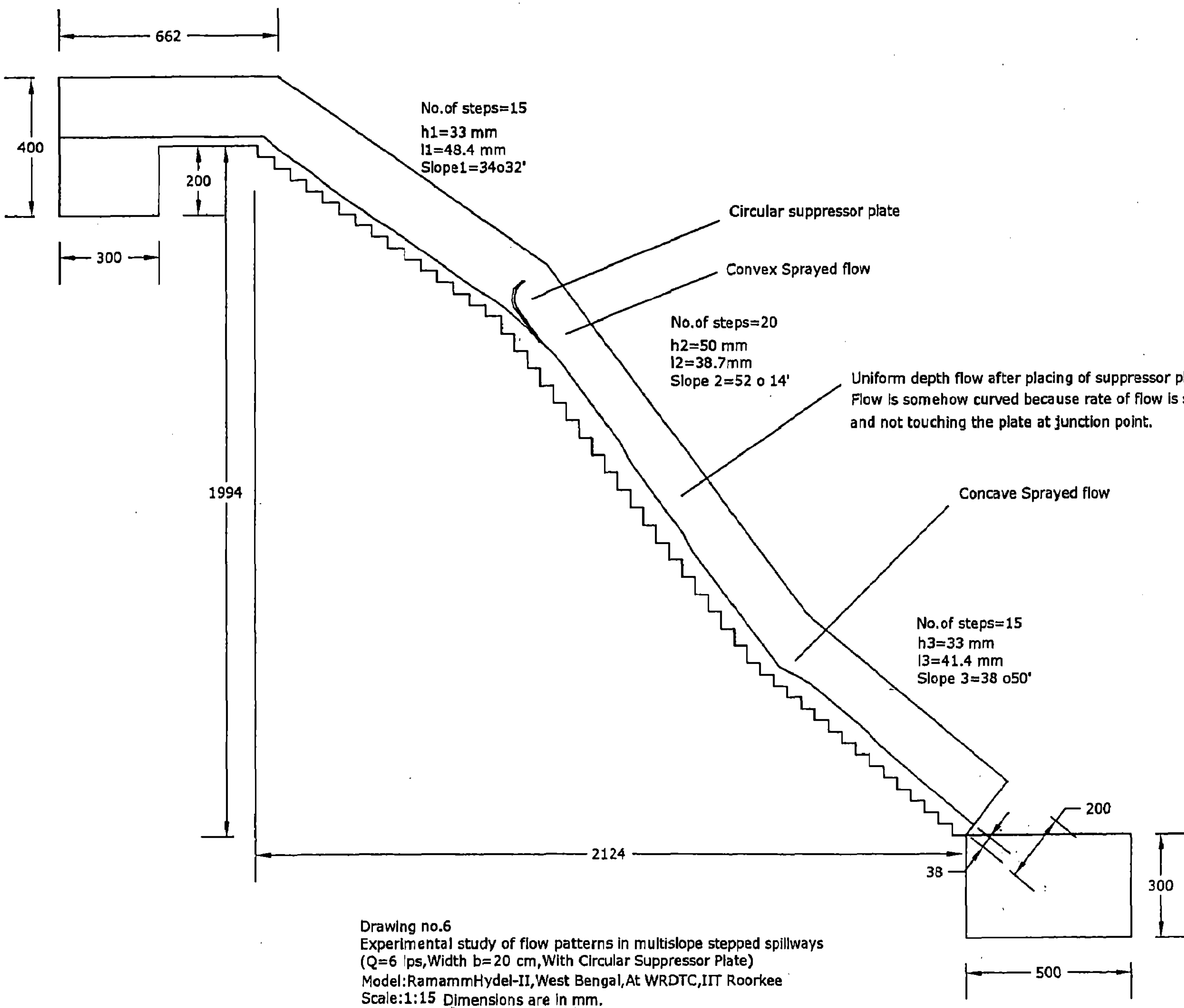
Drawing no. 3
Experimental study of flow patterns in monoslope stepped spillways
(Q=20 lps,Width b=20 cm,Without Circular Suppressor Plate)
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



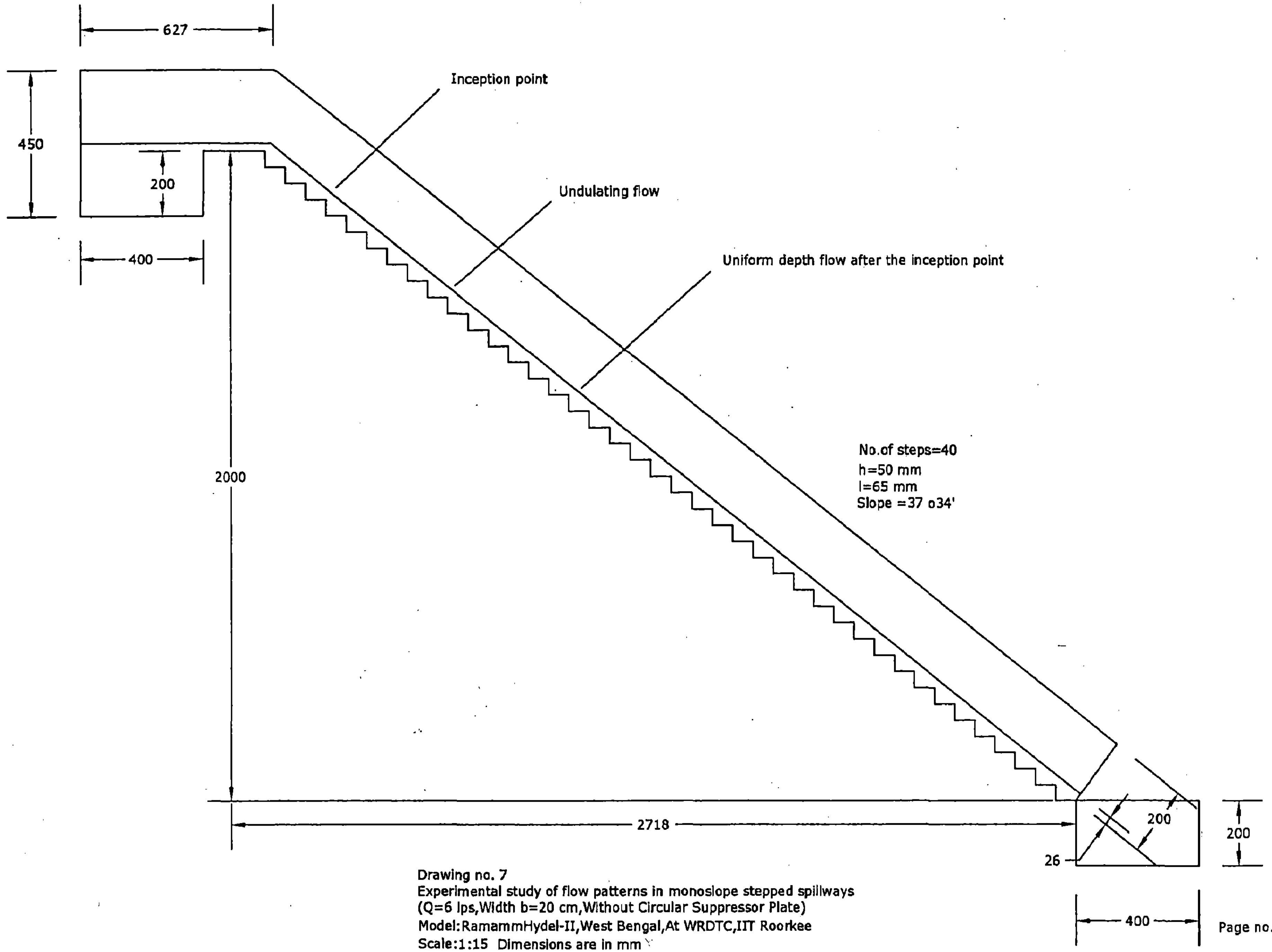
Drawing no. 4
Experimental study of flow patterns in multislope stepped spillways
(Q=20 lps,Width b=20 cm,Without Circular Suppressor Plate)
Maximum and minimum water flow depths
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm.



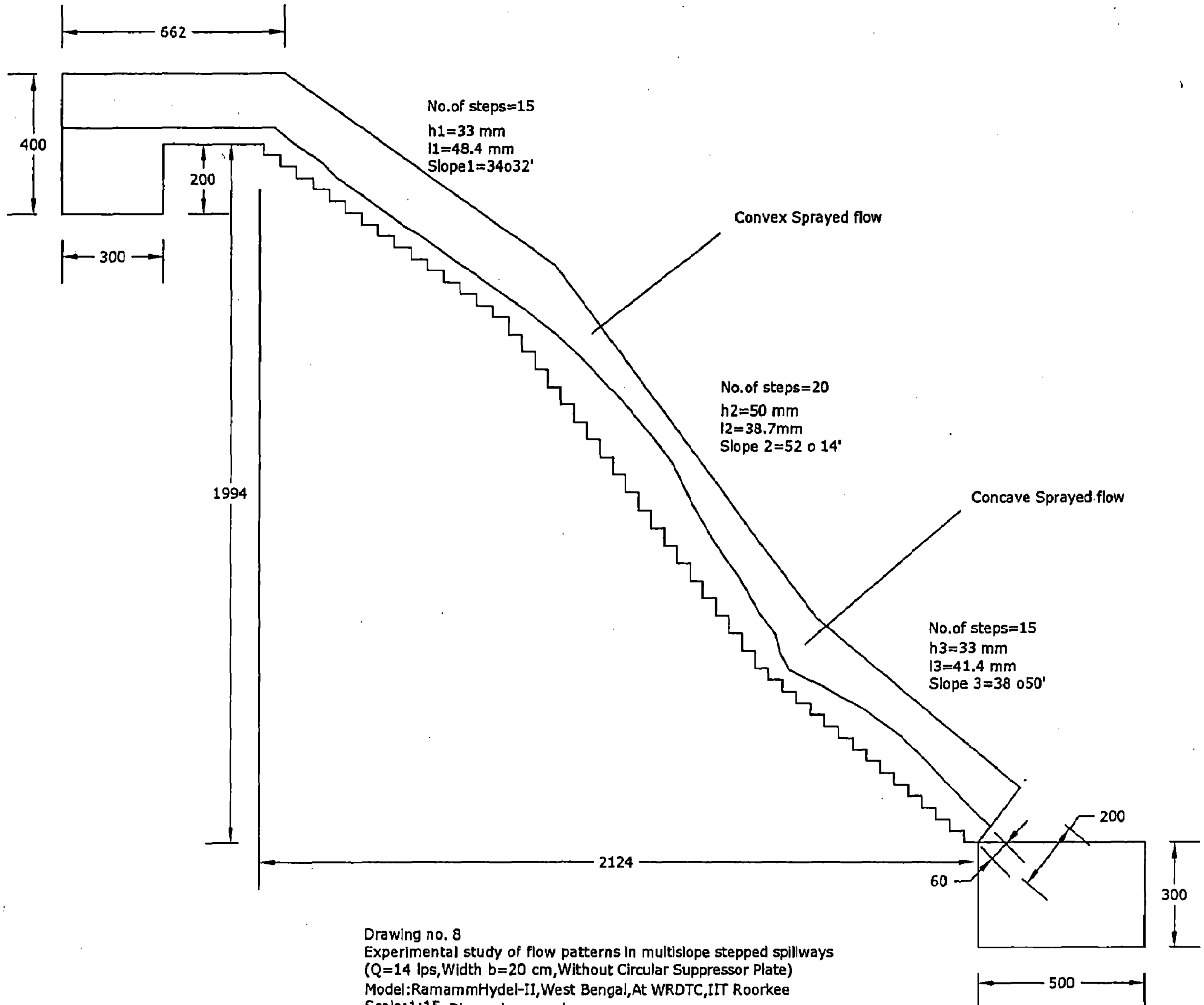
Drawing no. 5
Experimental study of flow patterns in multislope stepped spillways
(Q=6 lps,Width b=20 cm,Without Circular Suppressor Plate)
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm.



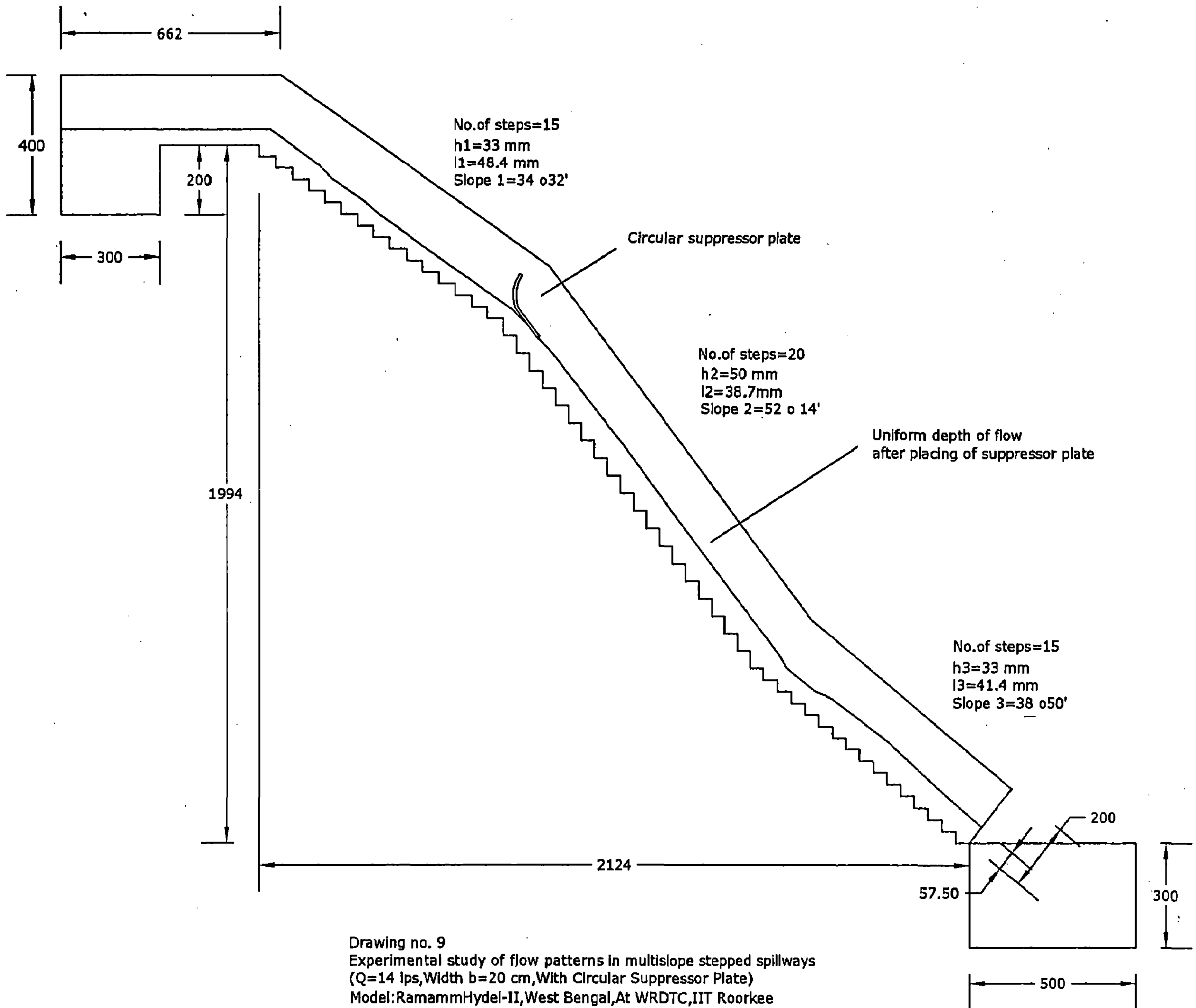
Drawing no.6
Experimental study of flow patterns in multislope stepped spillways
(Q=6 lps,Width b=20 cm,With Circular Suppressor Plate)
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm.



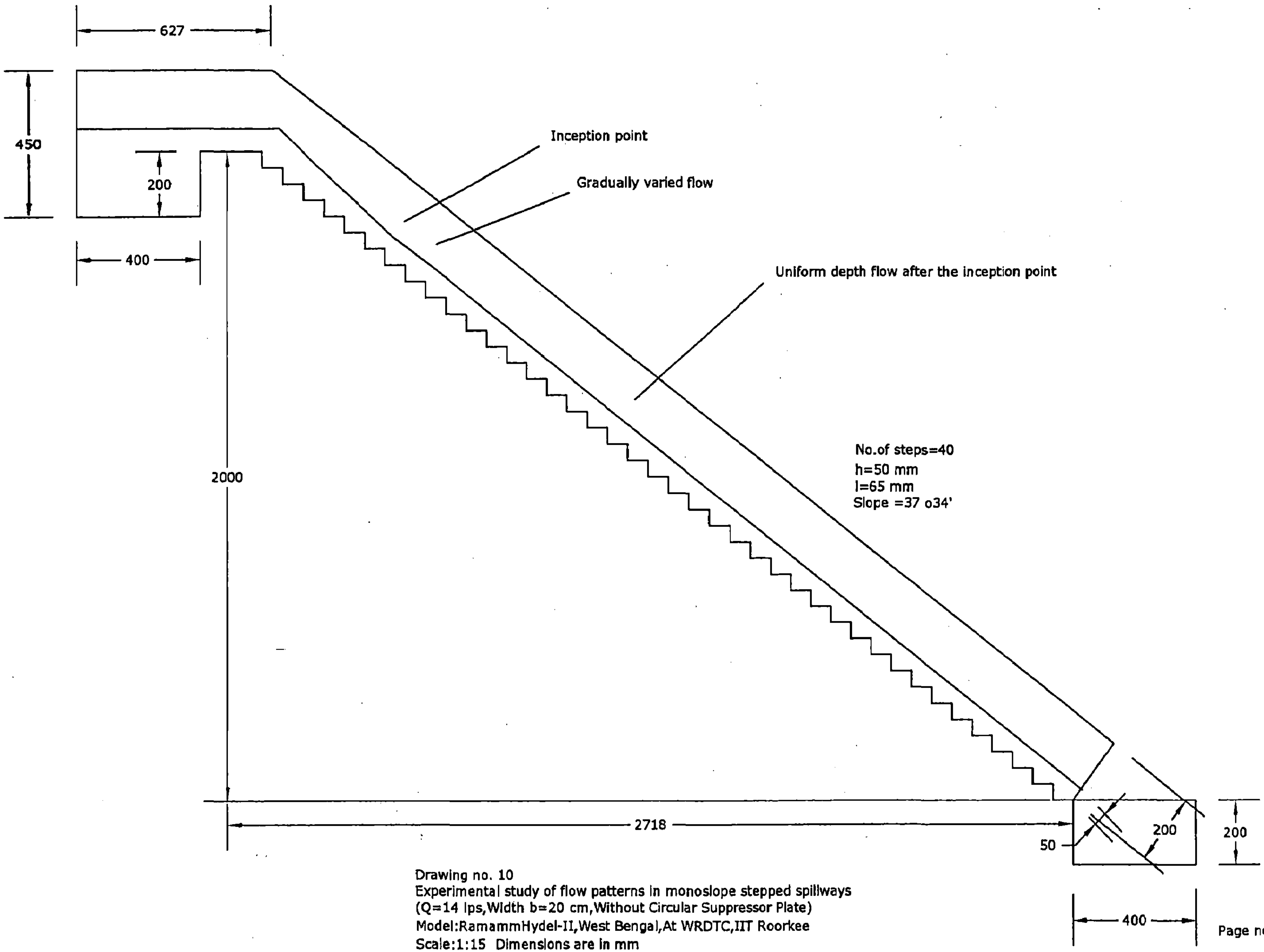
Drawing no. 7
Experimental study of flow patterns in monoslope stepped spillways
(Q=6 lps,Width b=20 cm,Without Circular Suppressor Plate)
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



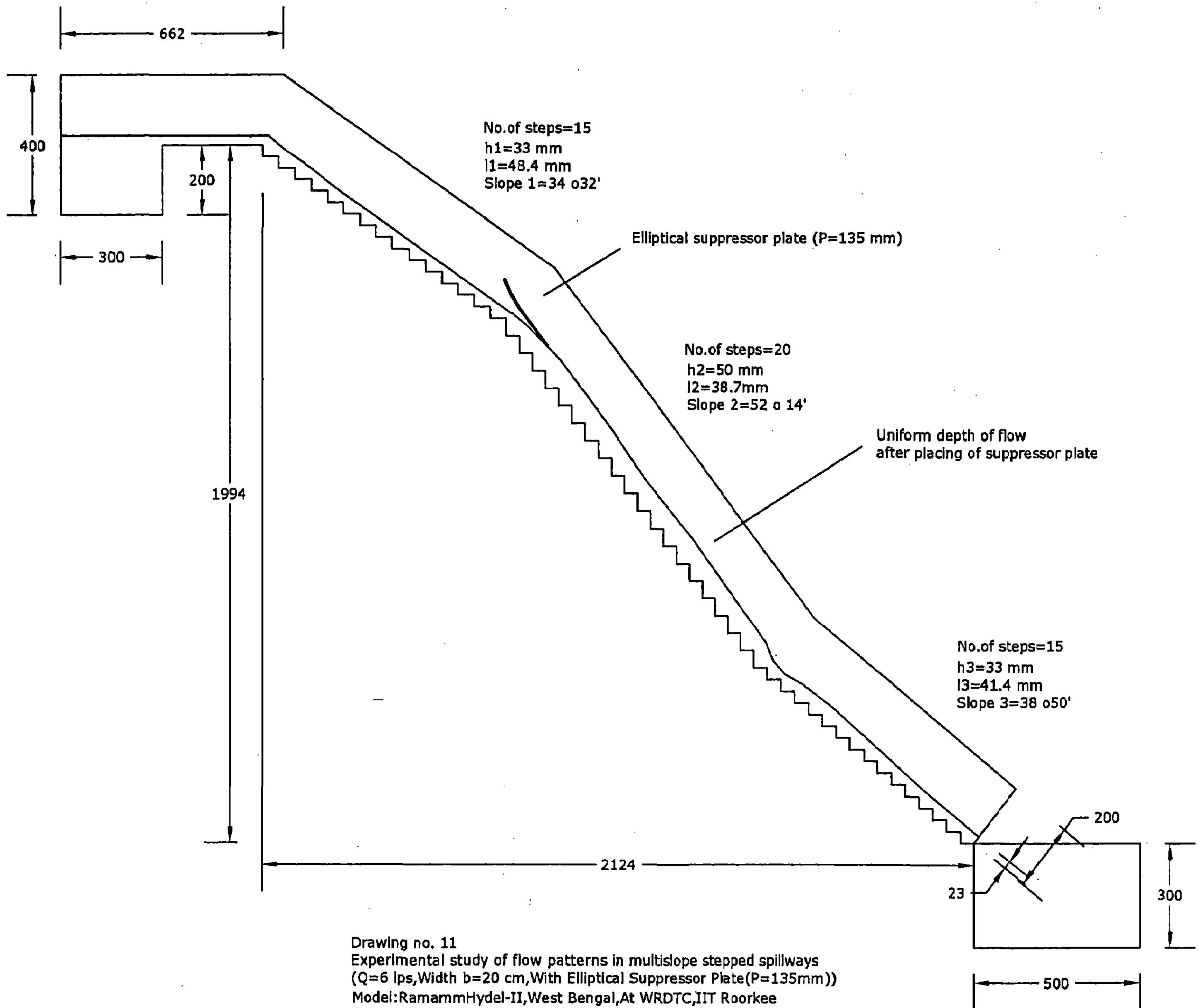
Drawing no. 8
Experimental study of flow patterns in multislope stepped spillways
(Q=14 lps,Width b=20 cm,Without Circular Suppressor Plate)
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm.



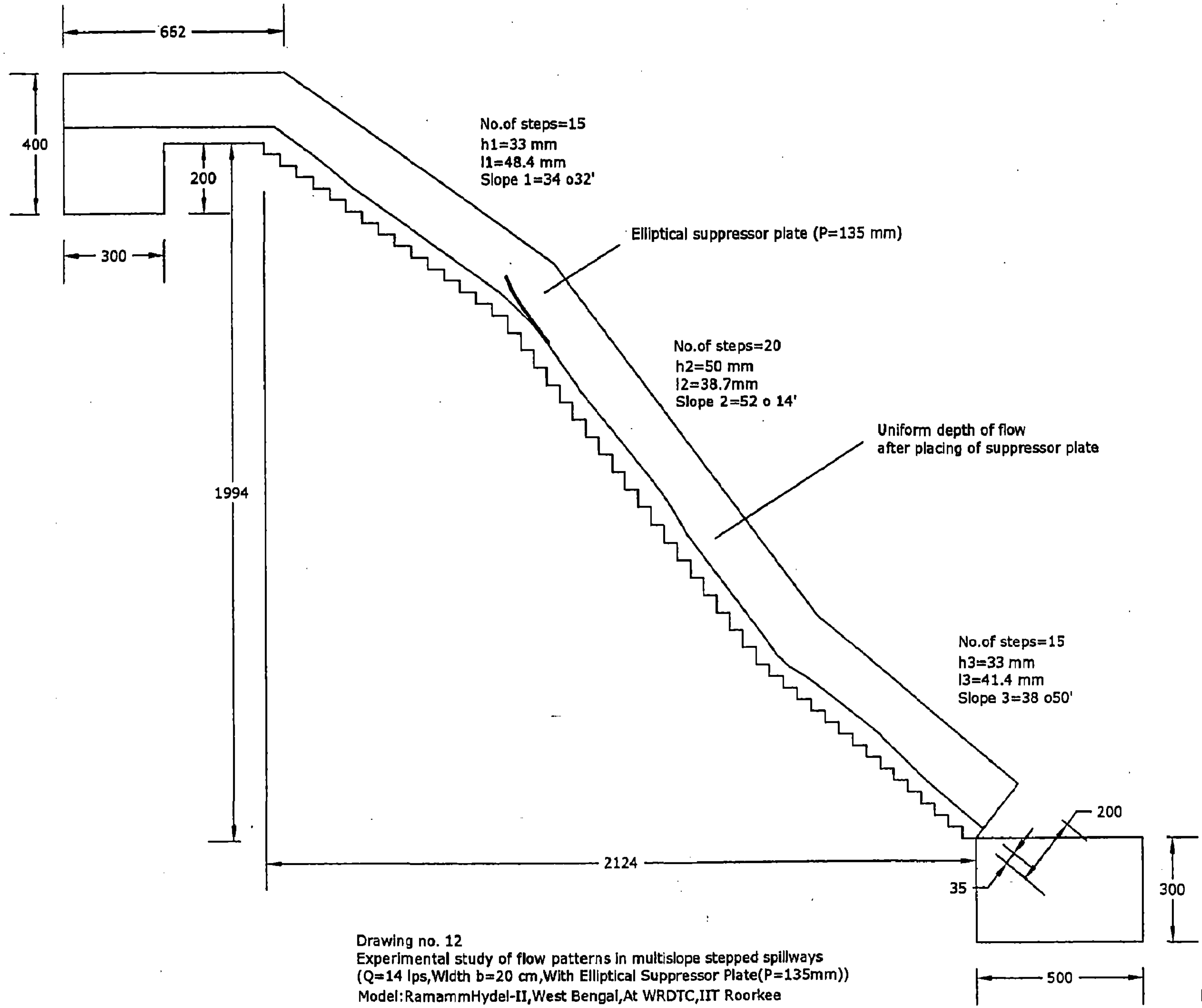
Drawing no. 9
Experimental study of flow patterns in multislope stepped spillways
(Q=14 lps,Width b=20 cm,With Circular Suppressor Plate)
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



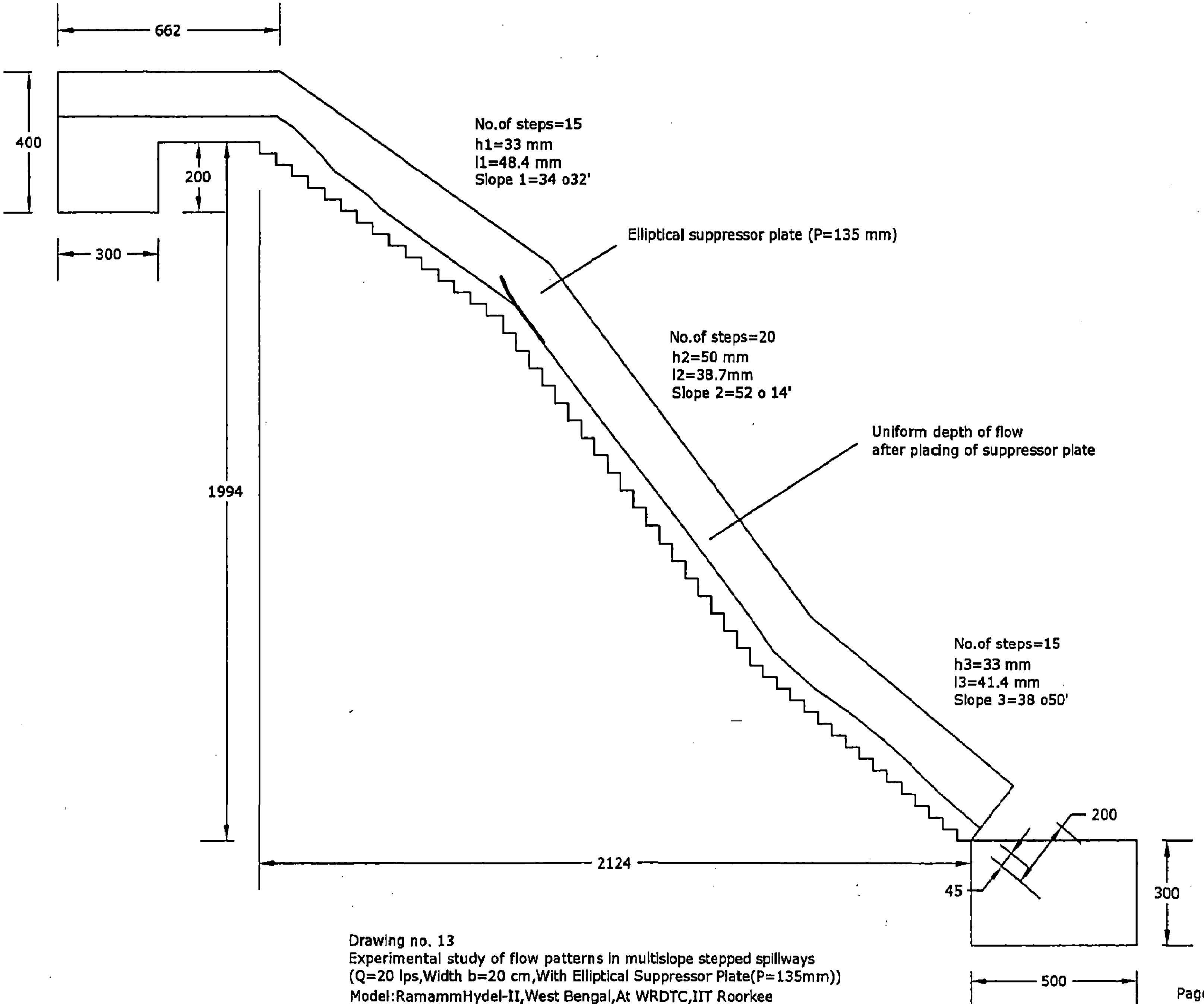
Drawing no. 10
Experimental study of flow patterns in monoslope stepped spillways
(Q=14 lps,Width b=20 cm,Without Circular Suppressor Plate)
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



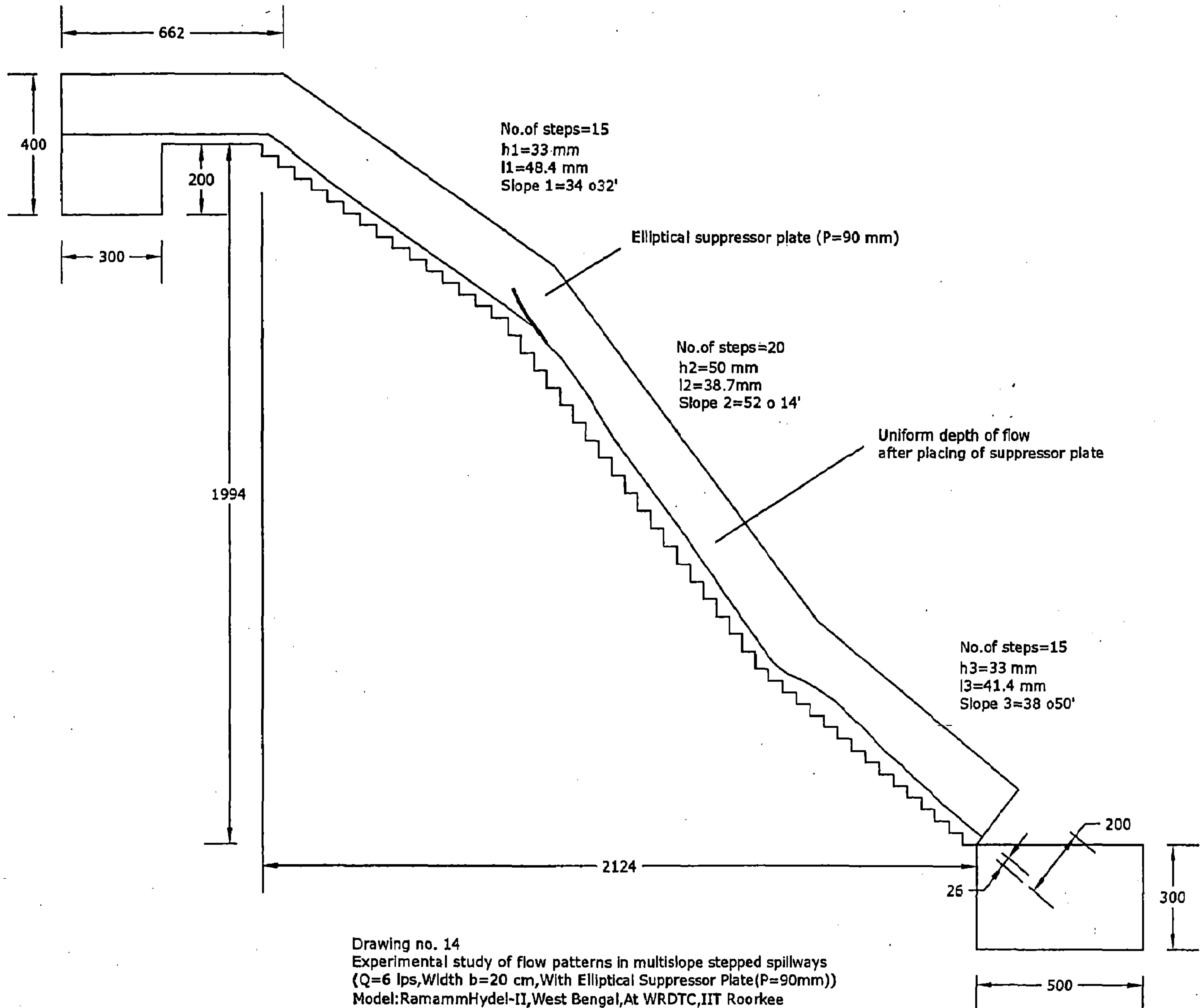
Drawing no. 11
Experimental study of flow patterns in multislope stepped spillways
(Q=6 lps,Width b=20 cm,With Elliptical Suppressor Plate(P=135mm))
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



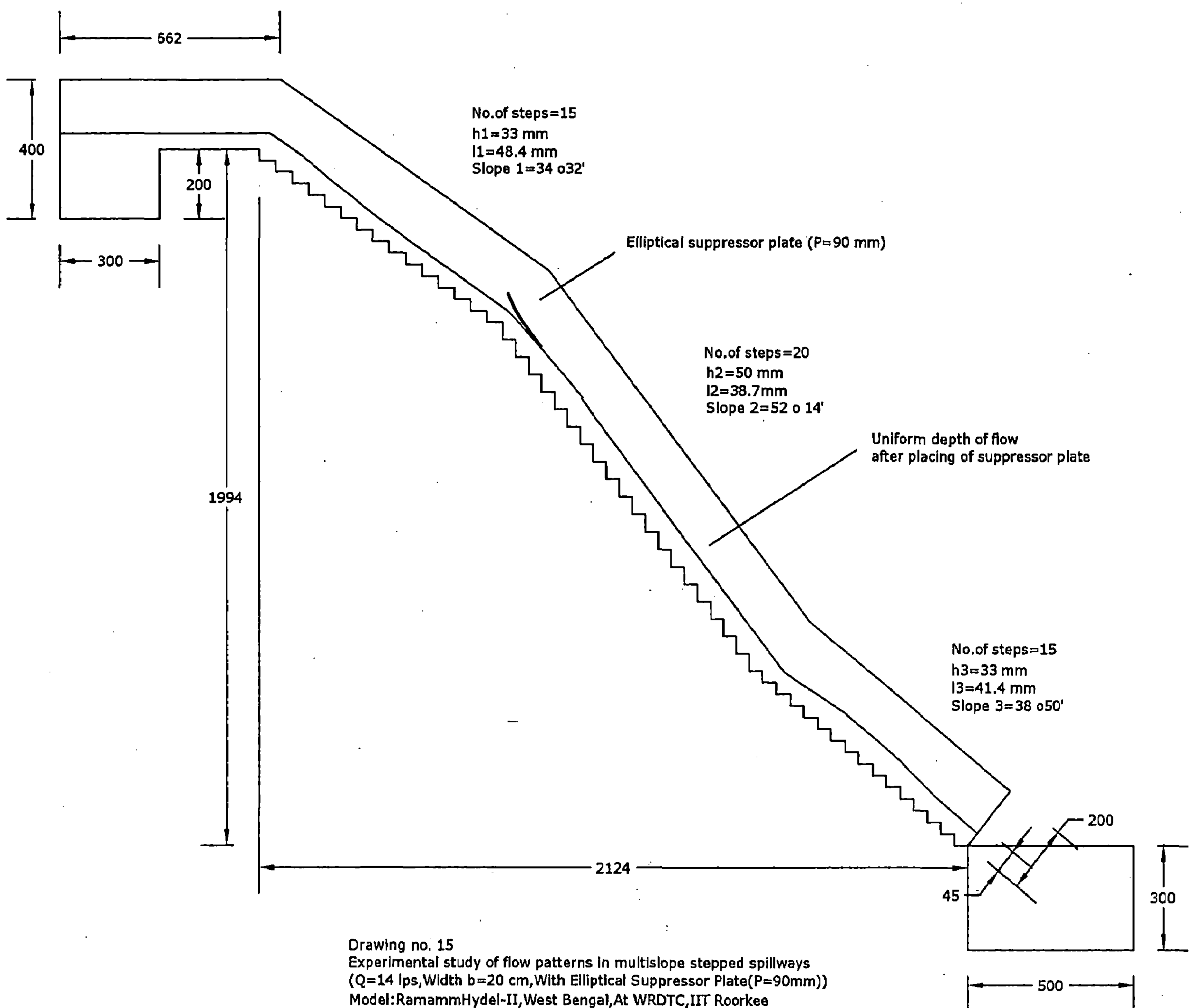
Drawing no. 12
Experimental study of flow patterns in multislope stepped spillways
(Q=14 lps,Width b=20 cm,With Elliptical Suppressor Plate(P=135mm))
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



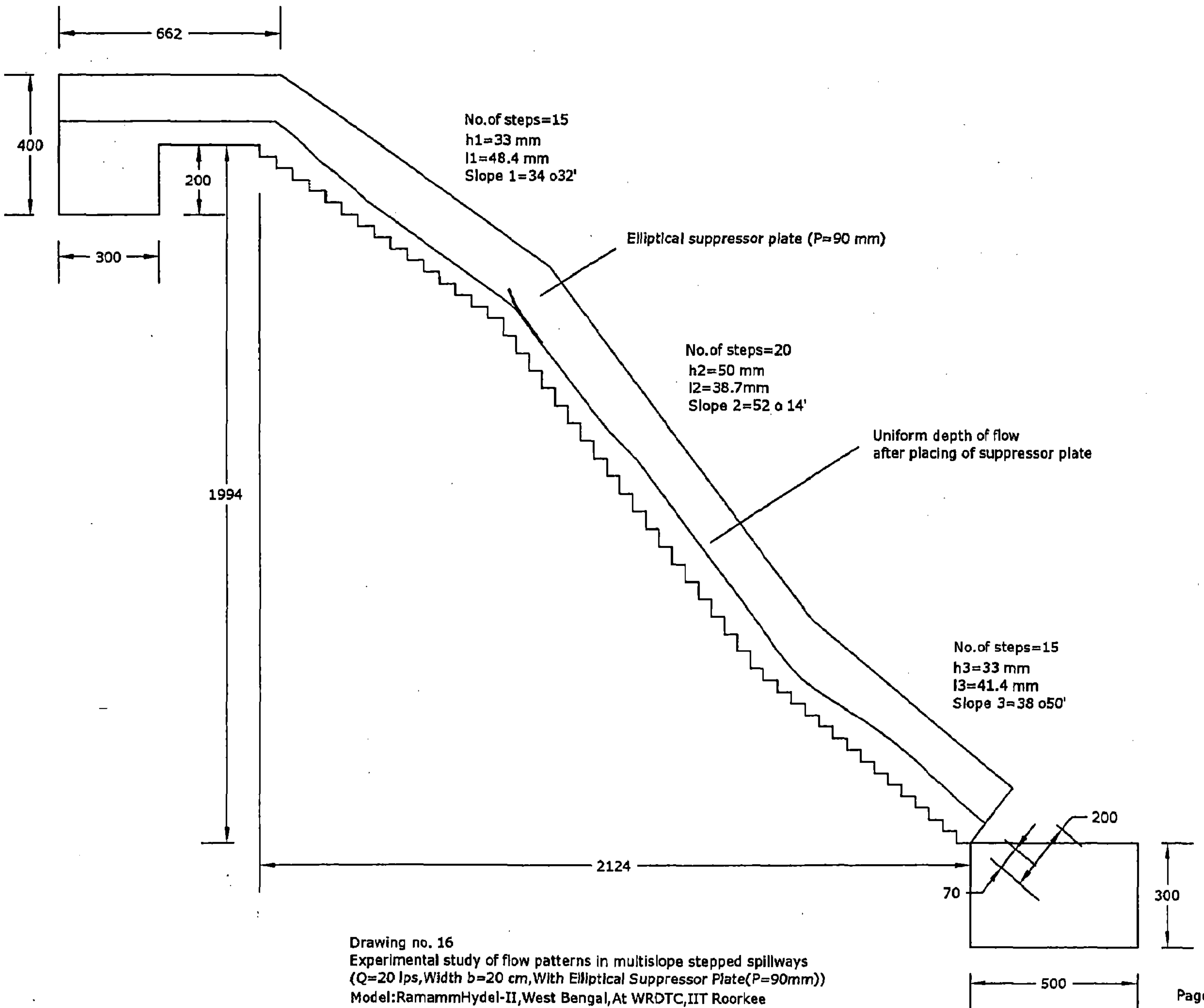
Drawing no. 13
Experimental study of flow patterns in multislope stepped spillways
(Q=20 lps,Width b=20 cm,With Elliptical Suppressor Plate(P=135mm))
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



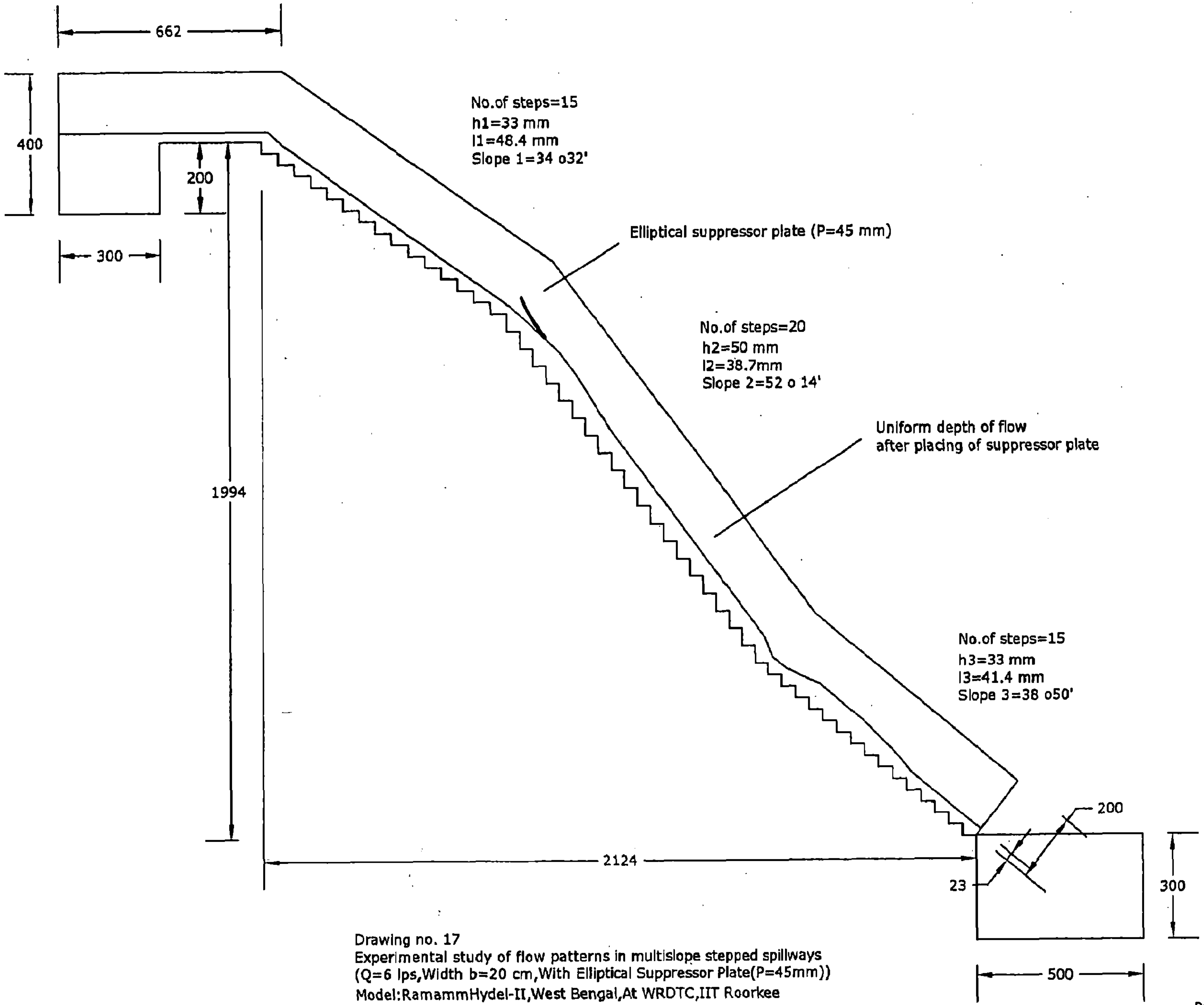
Drawing no. 14
Experimental study of flow patterns in multislope stepped spillways
(Q=6 lps,Width b=20 cm,With Elliptical Suppressor Plate(P=90mm))
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



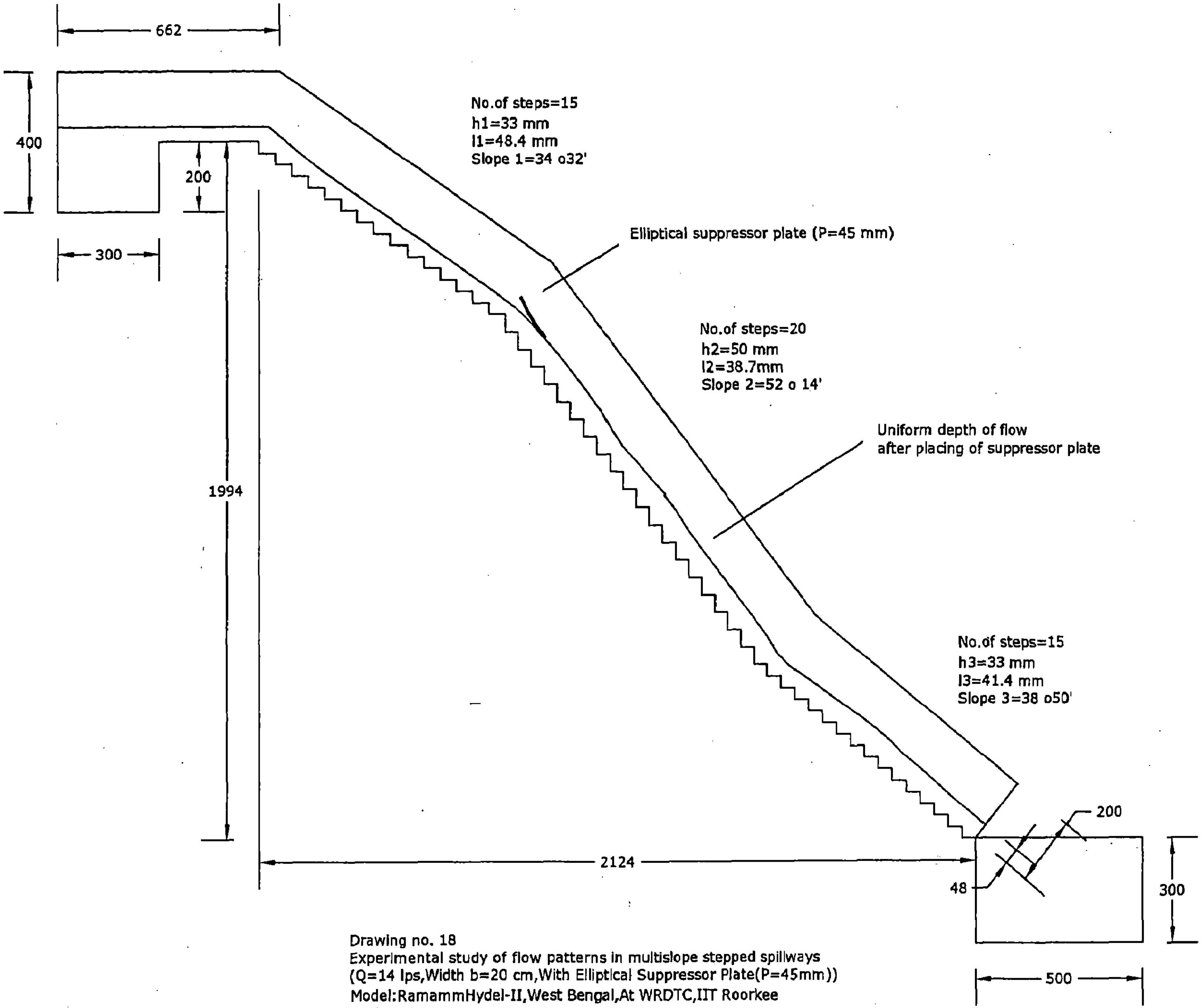
Drawing no. 15
Experimental study of flow patterns in multislope stepped spillways
(Q=14 lps,Width b=20 cm,With Elliptical Suppressor Plate(P=90mm))
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 .Dimensions are in mm



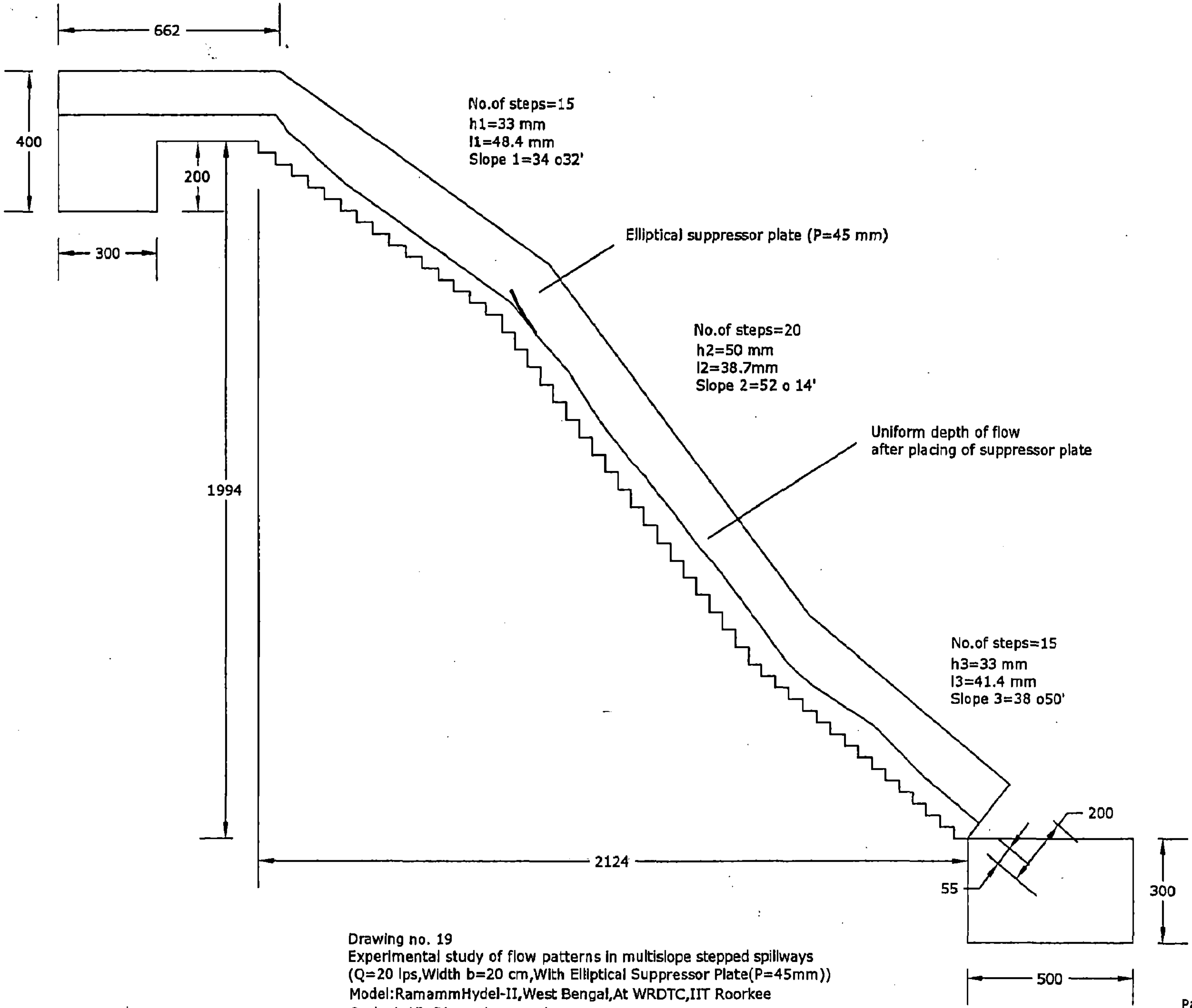
Drawing no. 16
Experimental study of flow patterns in multislope stepped spillways
(Q=20 lps,Width b=20 cm,With Elliptical Suppressor Plate(P=90mm))
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



Drawing no. 17
Experimental study of flow patterns in multislope stepped spillways
(Q=6 lps,Width b=20 cm,With Elliptical Suppressor Plate(P=45mm))
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



Drawing no. 18
Experimental study of flow patterns in multislope stepped spillways
(Q=14 lps,Width b=20 cm,With Elliptical Suppressor Plate(P=45mm))
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm



Drawing no. 19
Experimental study of flow patterns in multislope stepped spillways
(Q=20 lps,Width b=20 cm,With Elliptical Suppressor Plate(P=45mm))
Model:RamammHydel-II,West Bengal,At WRDTC,IIT Roorkee
Scale:1:15 Dimensions are in mm

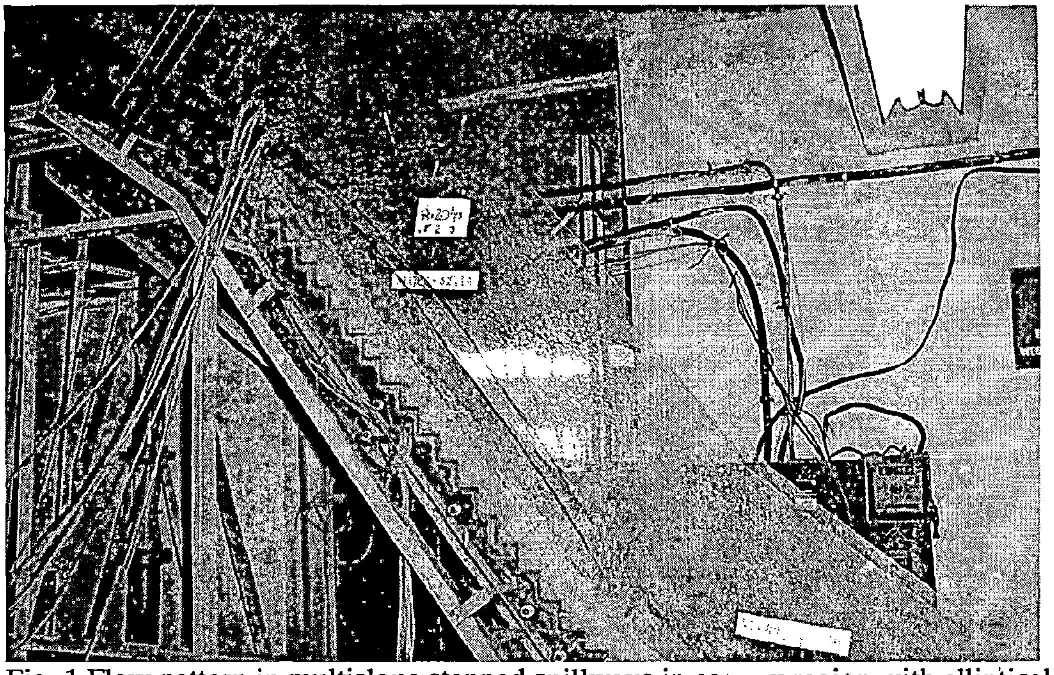


Fig. 1 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 20 lps per 20cm wide spillways.

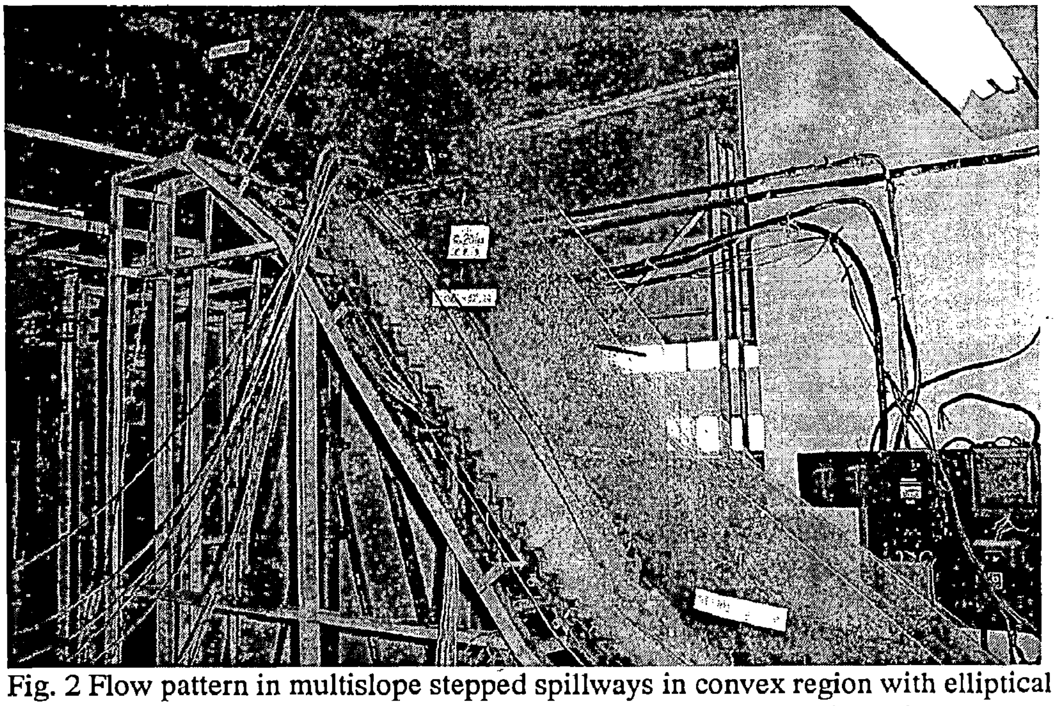


Fig. 2 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 20 lps per 20cm wide spillways.

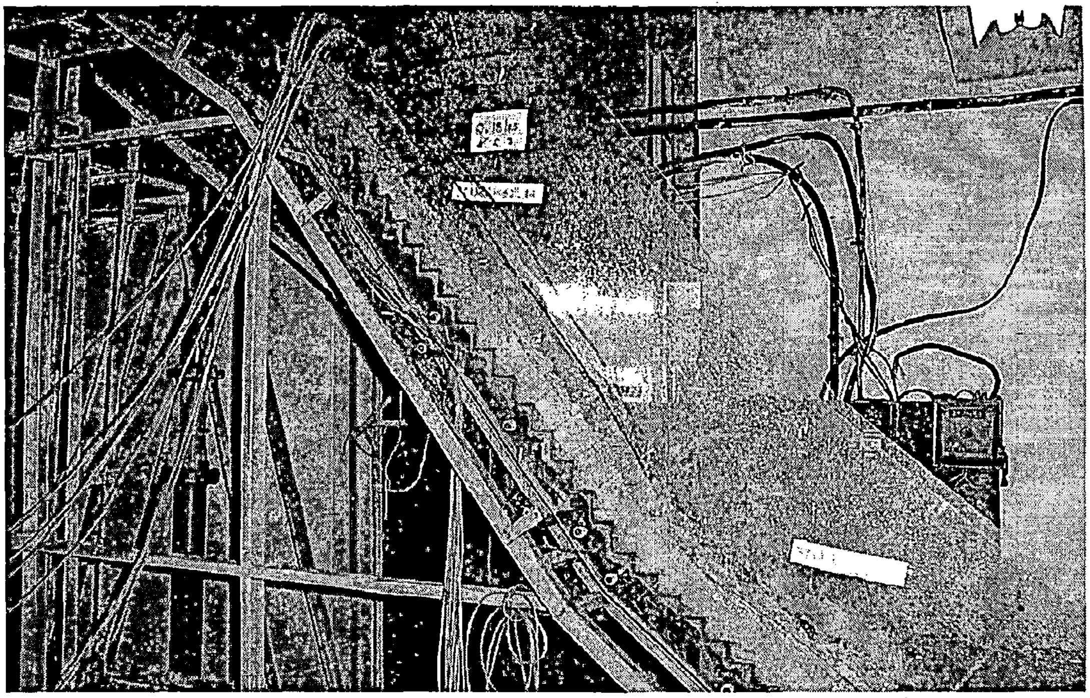


Fig. 3 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 18 lps per 20cm wide spillways

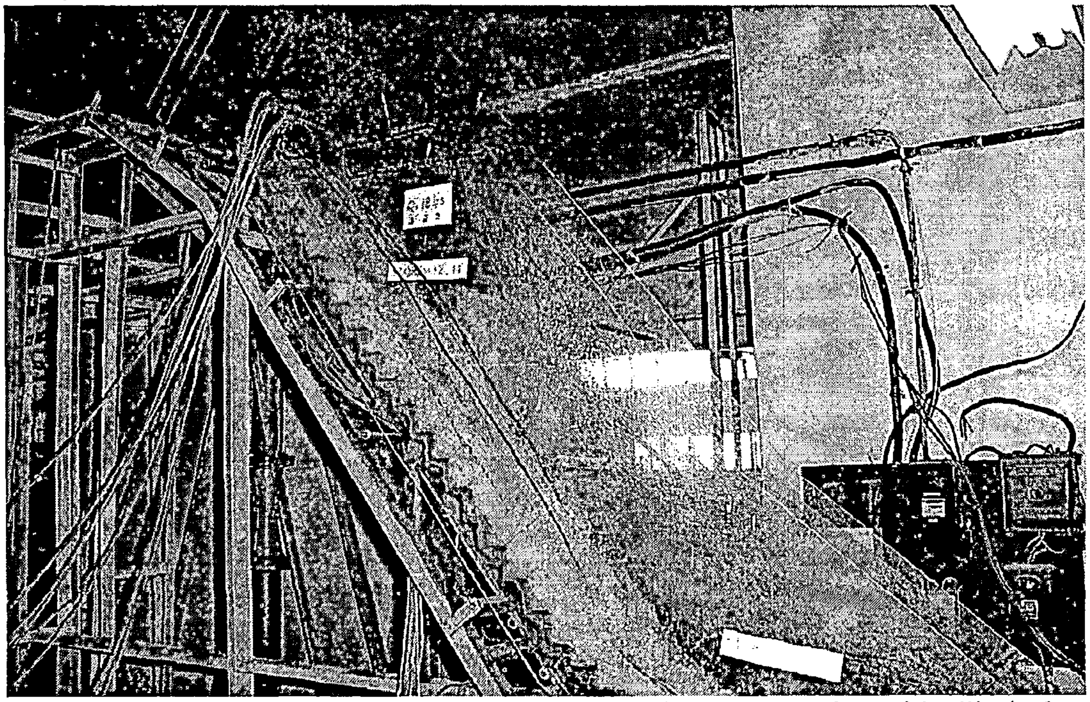


Fig. 4 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 18 lps per 20cm wide spillways

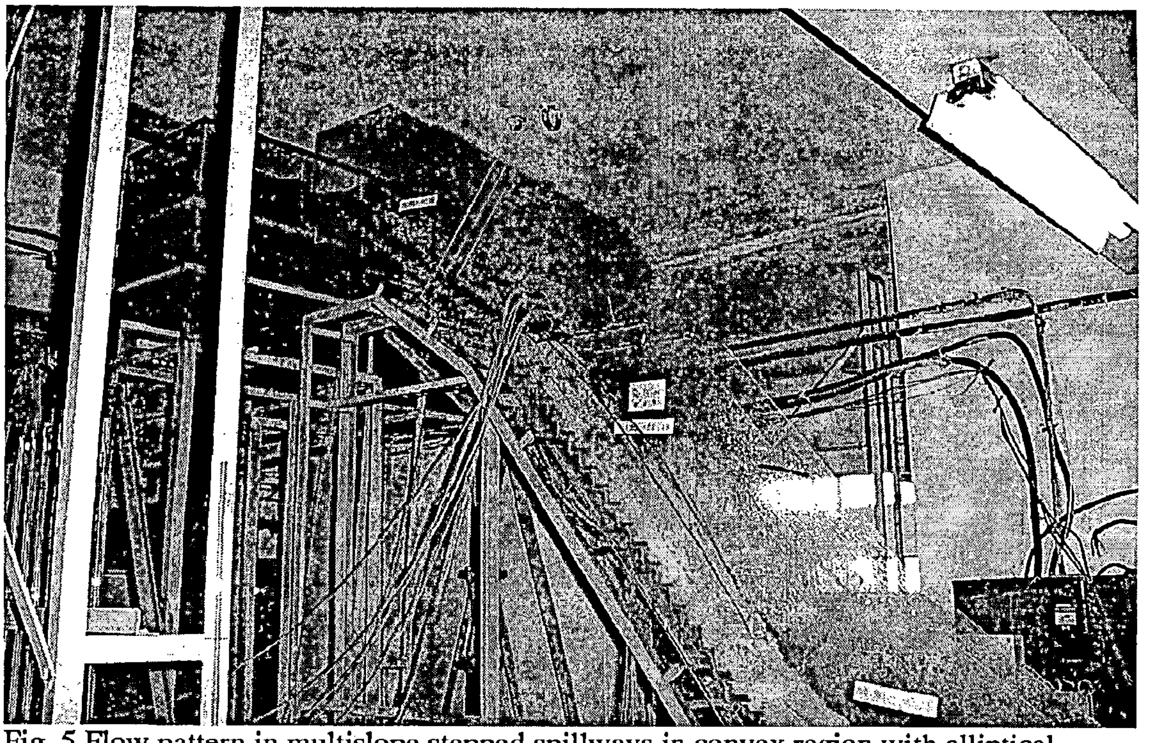


Fig. 5 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 14 lps per 20cm wide spillways

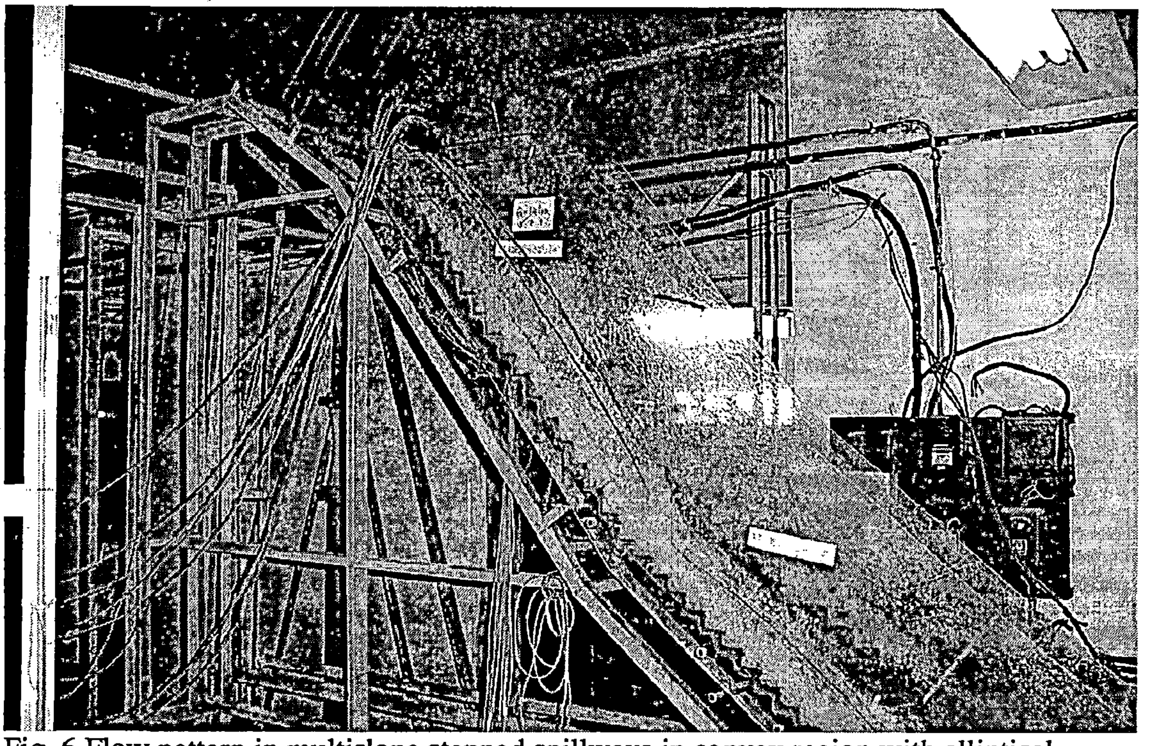


Fig. 6 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 14 lps per 20cm wide spillways

Fig. 7 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 10 lps per 20cm wide spillways

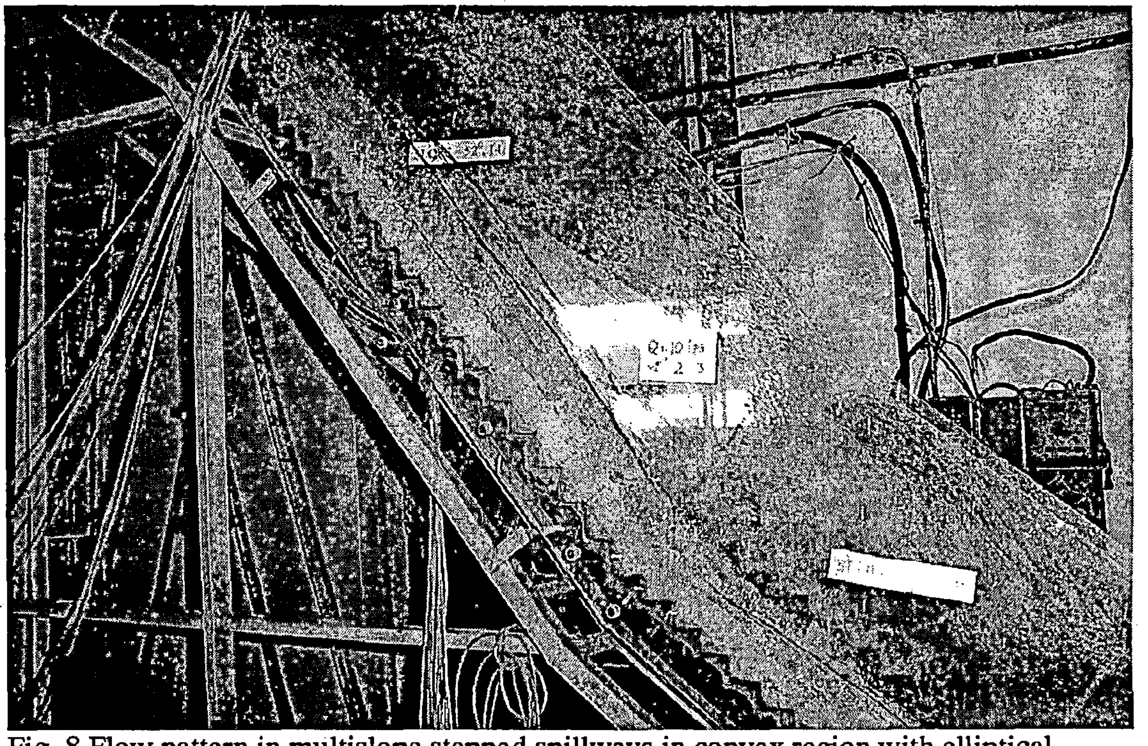


Fig. 8 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 10 lps per 20cm wide spillways

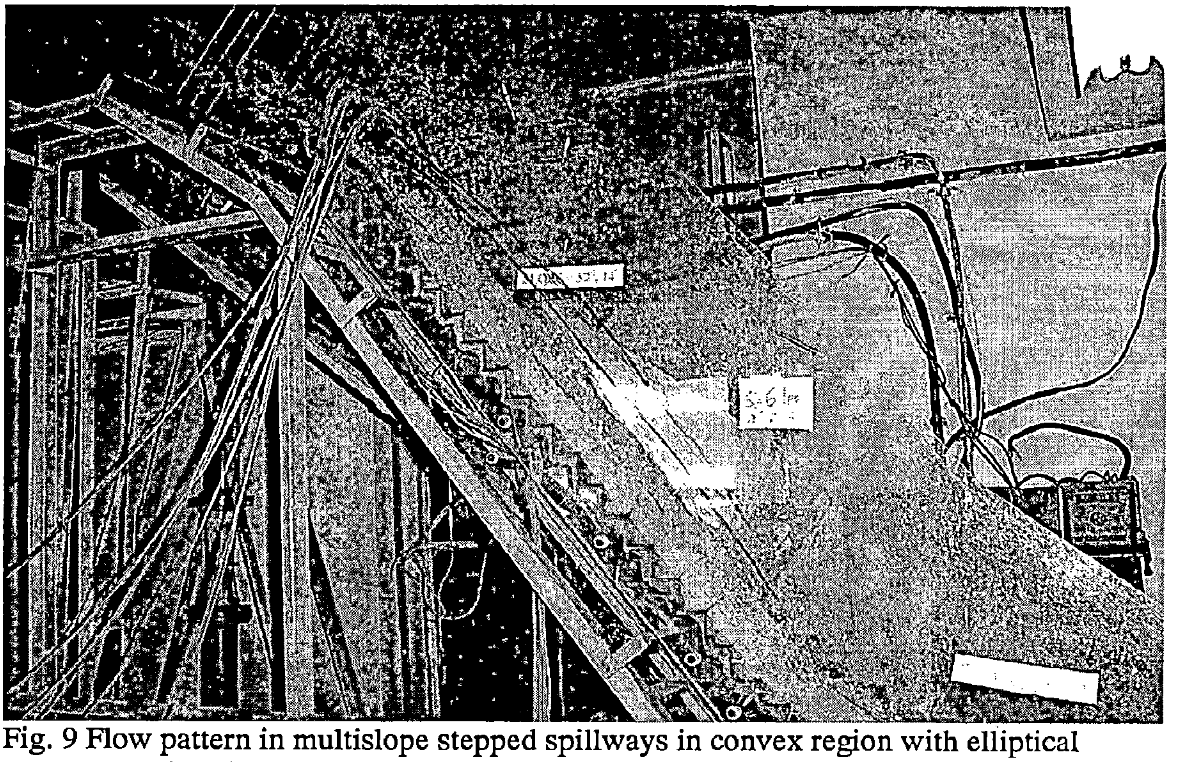


Fig. 9 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 6 lps per 20cm wide spillways

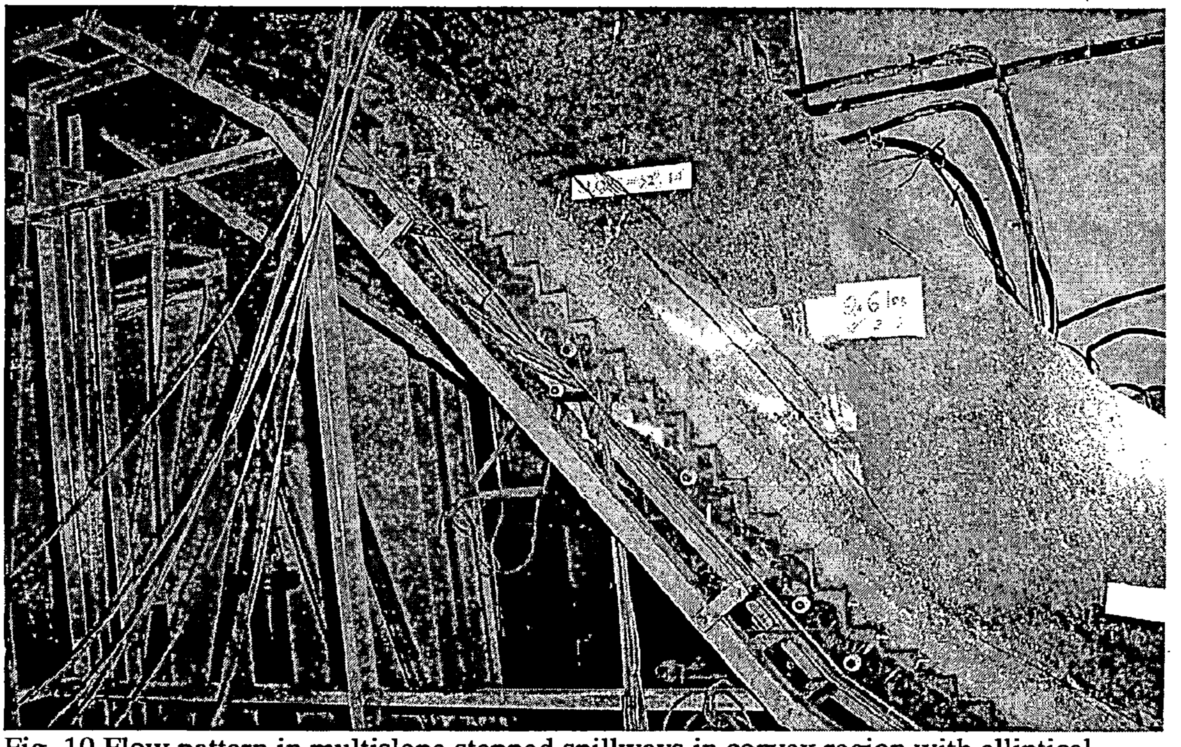


Fig. 10 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 6 lps per 20cm wide spillways

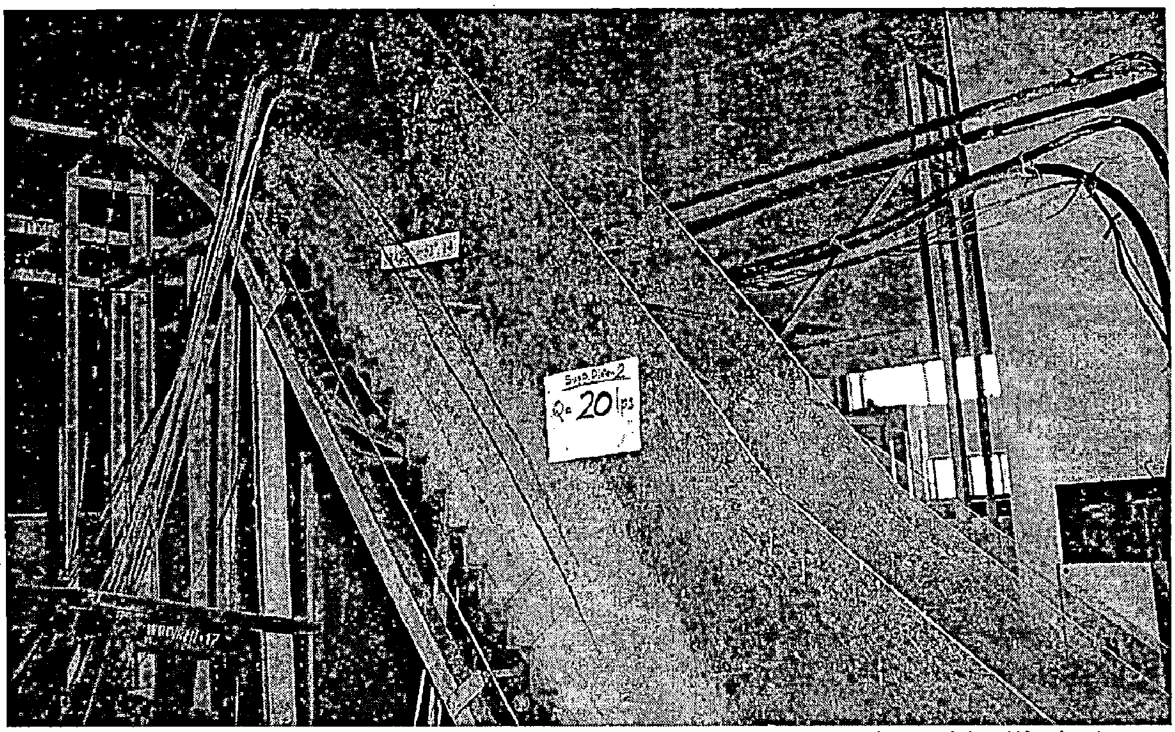


Fig. 11 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=90mm) at a discharge of 20 lps per 20cm wide spillways

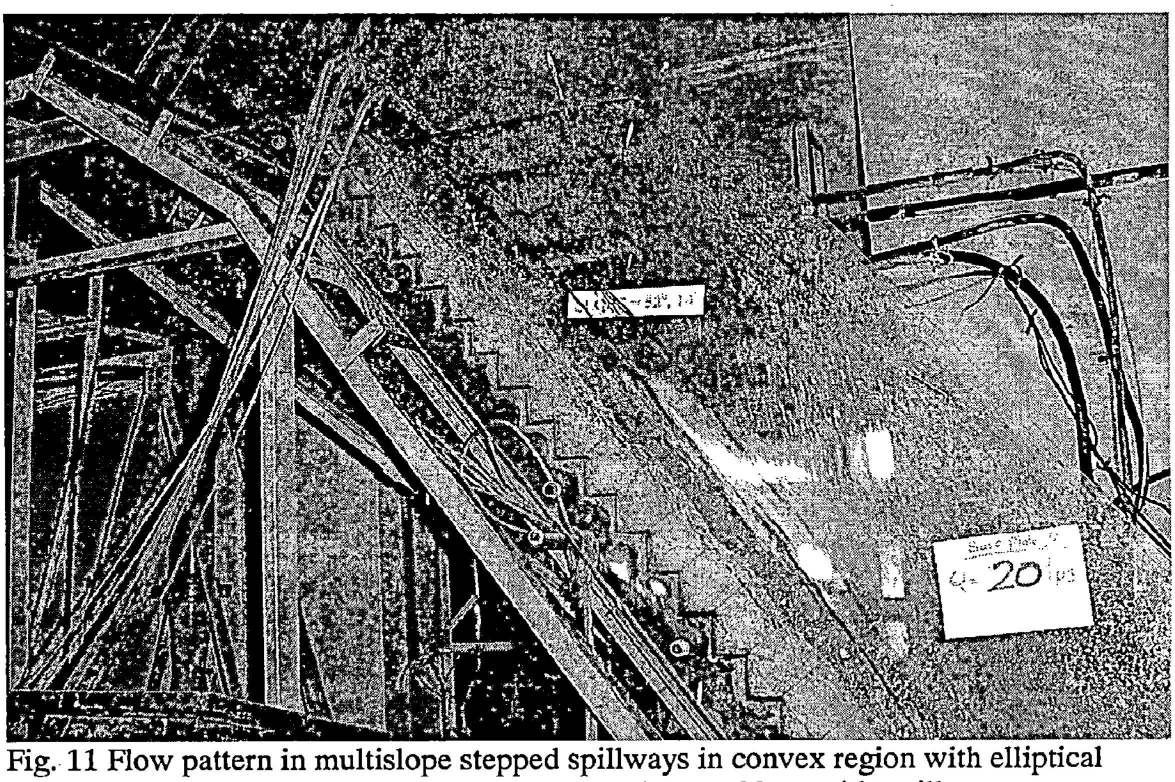


Fig. 11 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=90mm) at a discharge of 20 lps per 20cm wide spillways

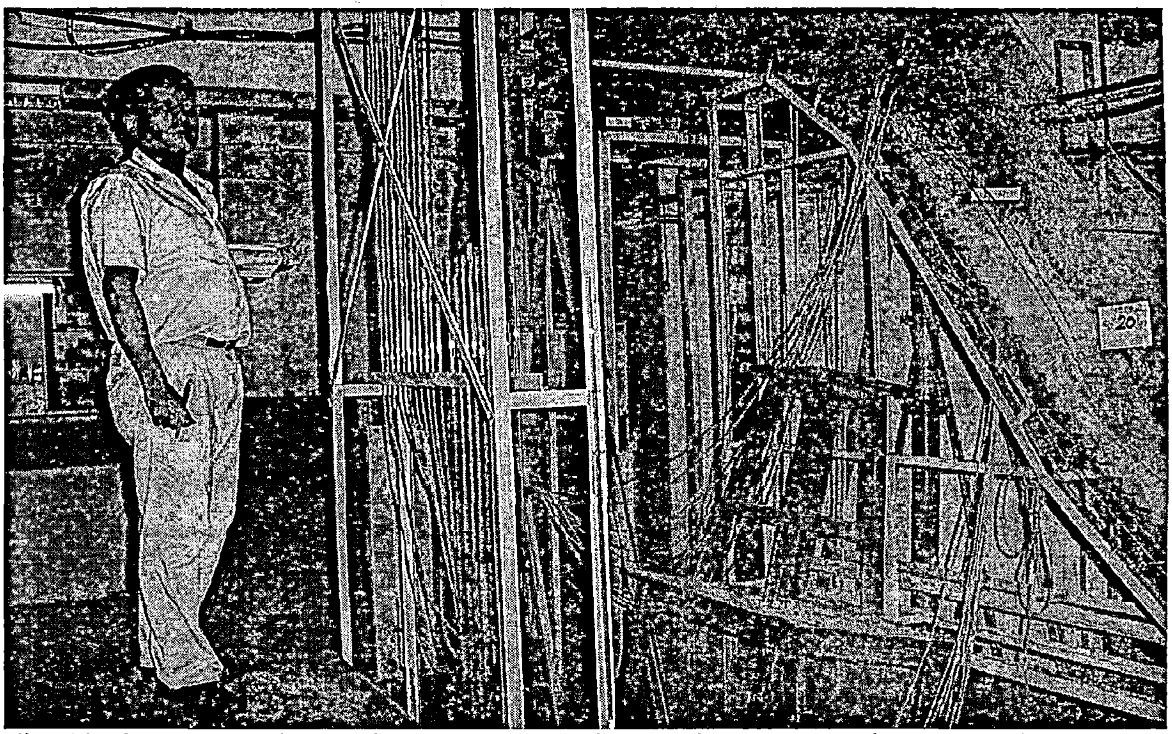


Fig. 12 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=90mm) at a discharge of 20 lps per 20cm wide spillways

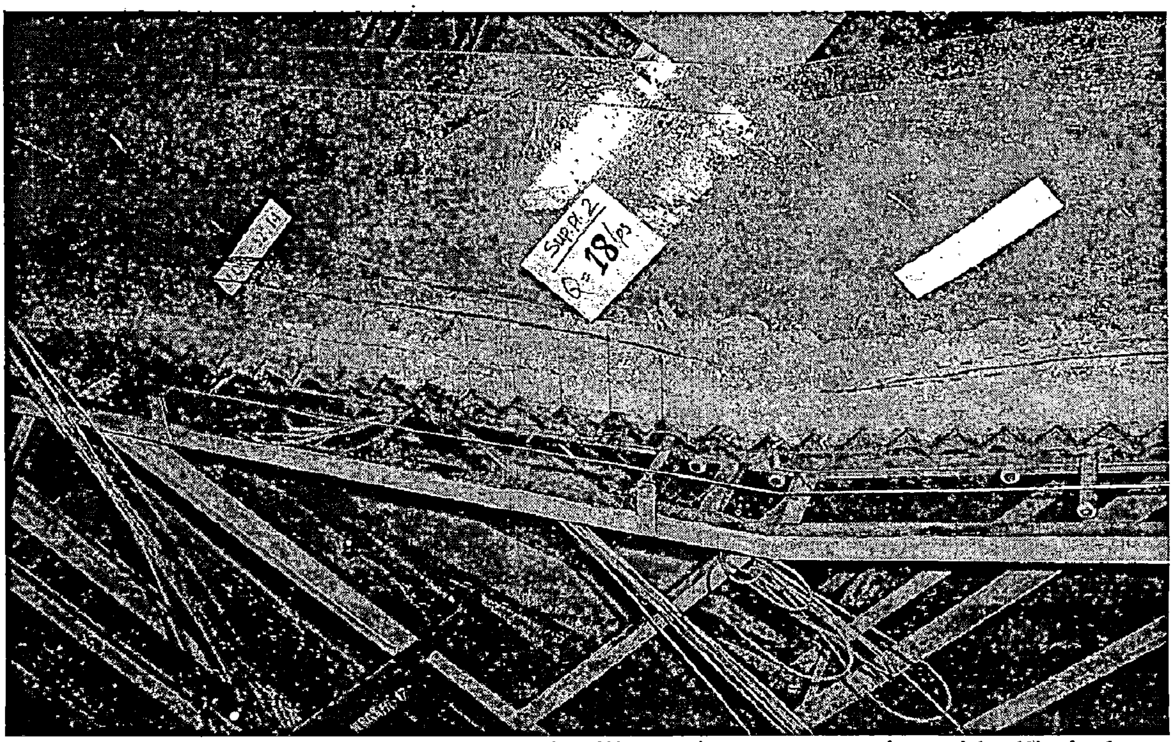


Fig. 13 Flow pattern in multislope stepped spillways in concave region with elliptical suppressor plate (P=90mm) at a discharge of 18 lps per 20cm wide spillways

Fig. 14 Flow pattern in multislope stepped spillways in d/s of convex region with elliptical suppressor plate (P=90mm) at a discharge of 18 lps per 20cm wide spillways

Fig. 14 Flow pattern in multislope stepped spillways in convex and concave region with elliptical suppressor plate (P=90mm) at a discharge of 14 lps per 20cm wide spillways

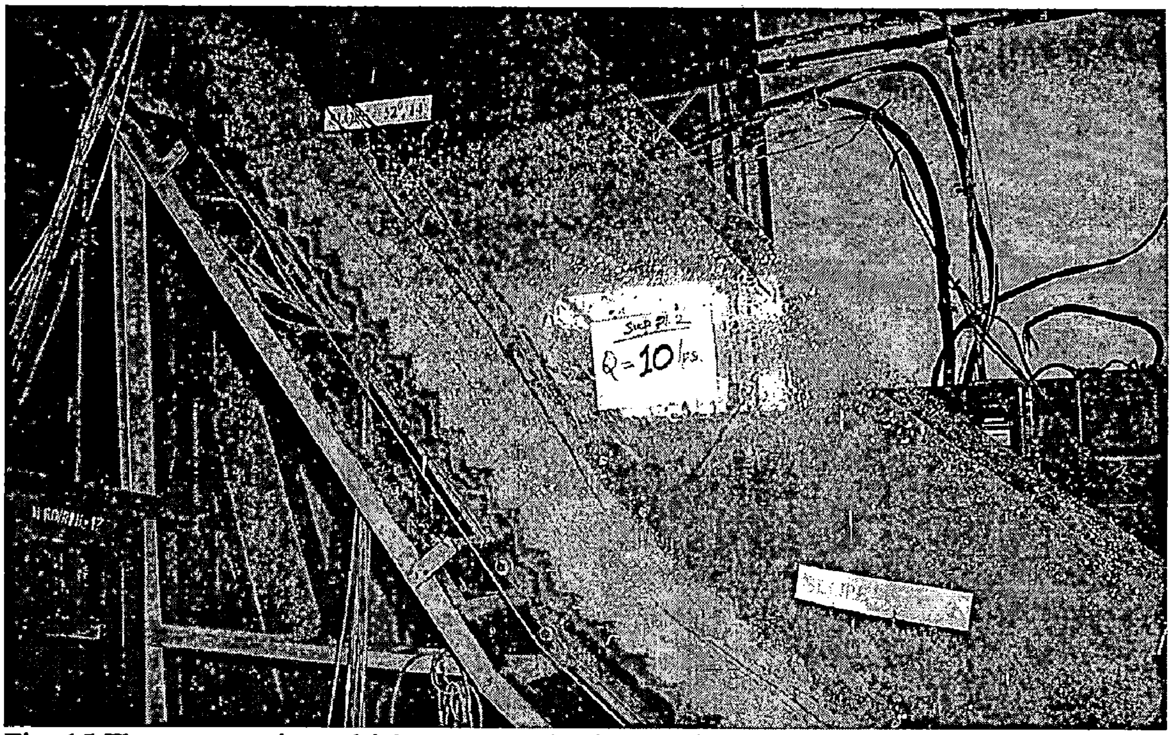


Fig. 15 Flow pattern in multislope stepped spillways in convex &concave region with elliptical suppressor plate (P=90mm) at a discharge of 10 lps per 20cm wide spillways

Fig. 16 Flow pattern in multislope stepped spillways in d/s of convex region with elliptical suppressor plate (P=90mm) at a discharge of 10 lps per 20cm wide spillways

Fig. 17 Flow pattern in multislope stepped spillways in concave region with elliptical suppressor plate (P=90mm) at a discharge of 10 lps per 20cm wide spillways

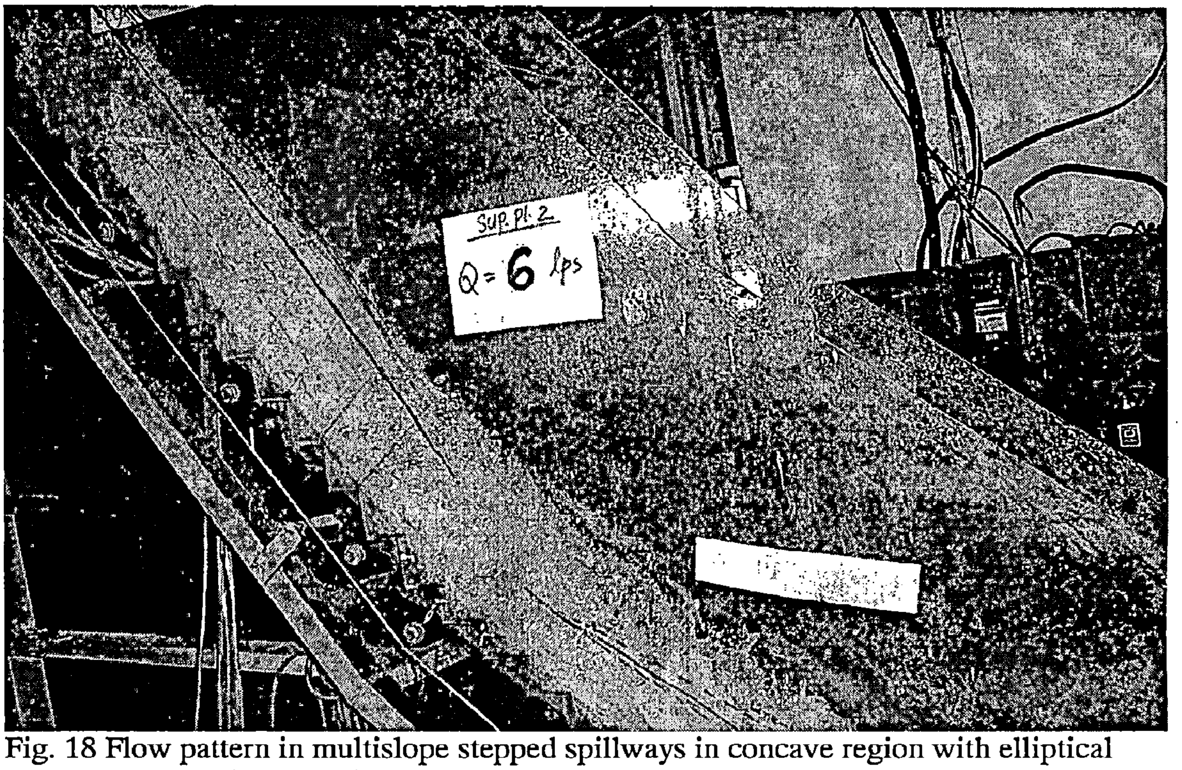


Fig. 18 Flow pattern in multislope stepped spillways in concave region with elliptical suppressor plate (P=90mm) at a discharge of 6 lps per 20cm wide spillways

Fig. 19 Flow pattern in multislope stepped spillways in d/s of convex region with elliptical suppressor plate (P=90mm) at a discharge of 6 lps per 20cm wide spillways

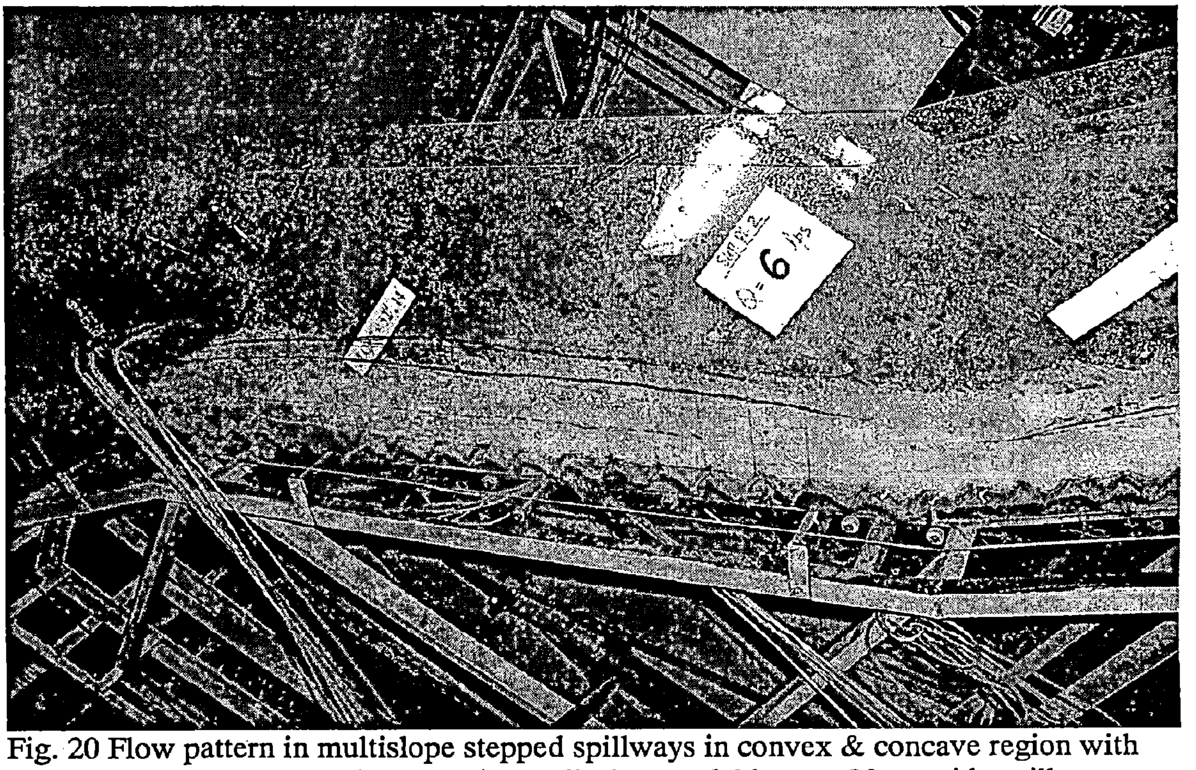


Fig. 20 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=90mm) at a discharge of 6 lps per 20cm wide spillways

Fig. 21 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 20 lps per 20cm wide spillways

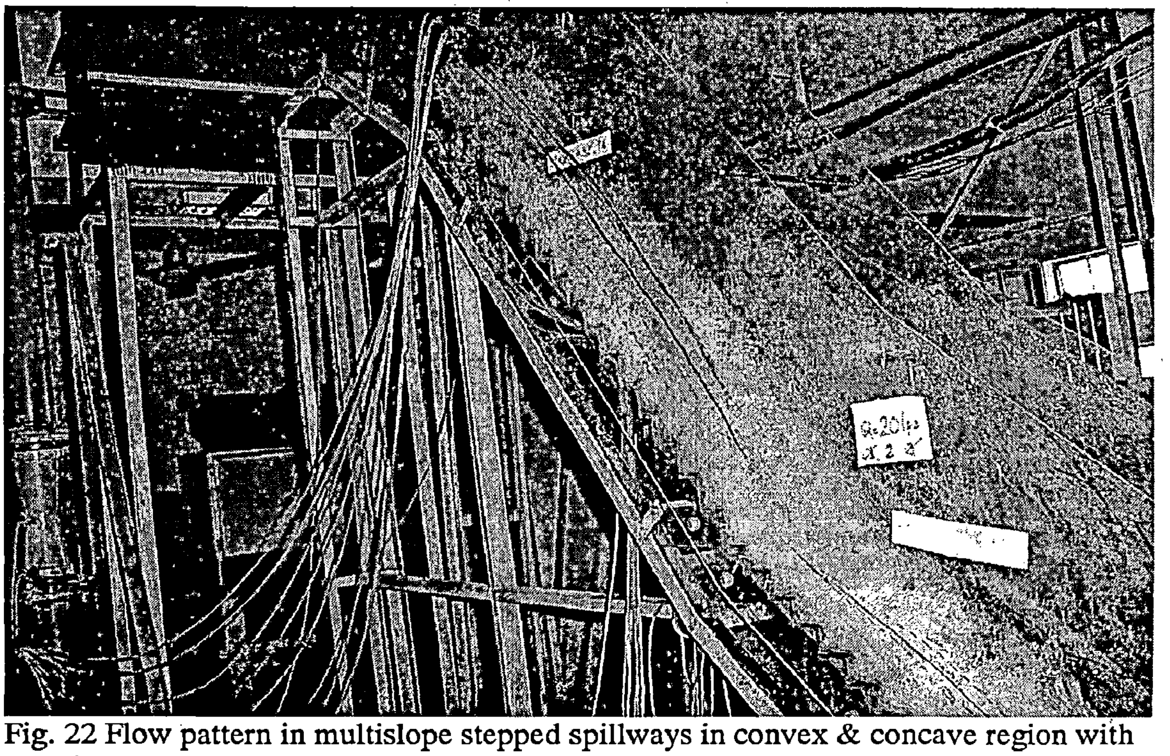


Fig. 22 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 20 lps per 20cm wide spillways

Fig. 23 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 18 lps per 20cm wide spillways

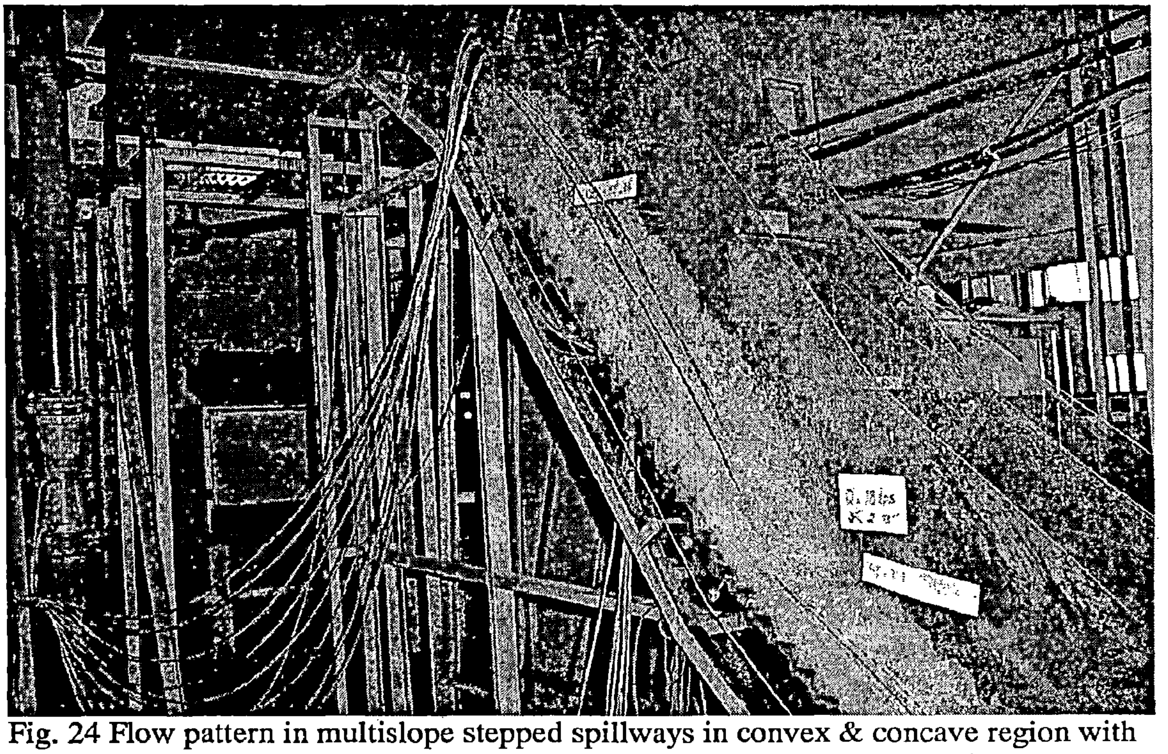


Fig. 24 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 18 lps per 20cm wide spillways

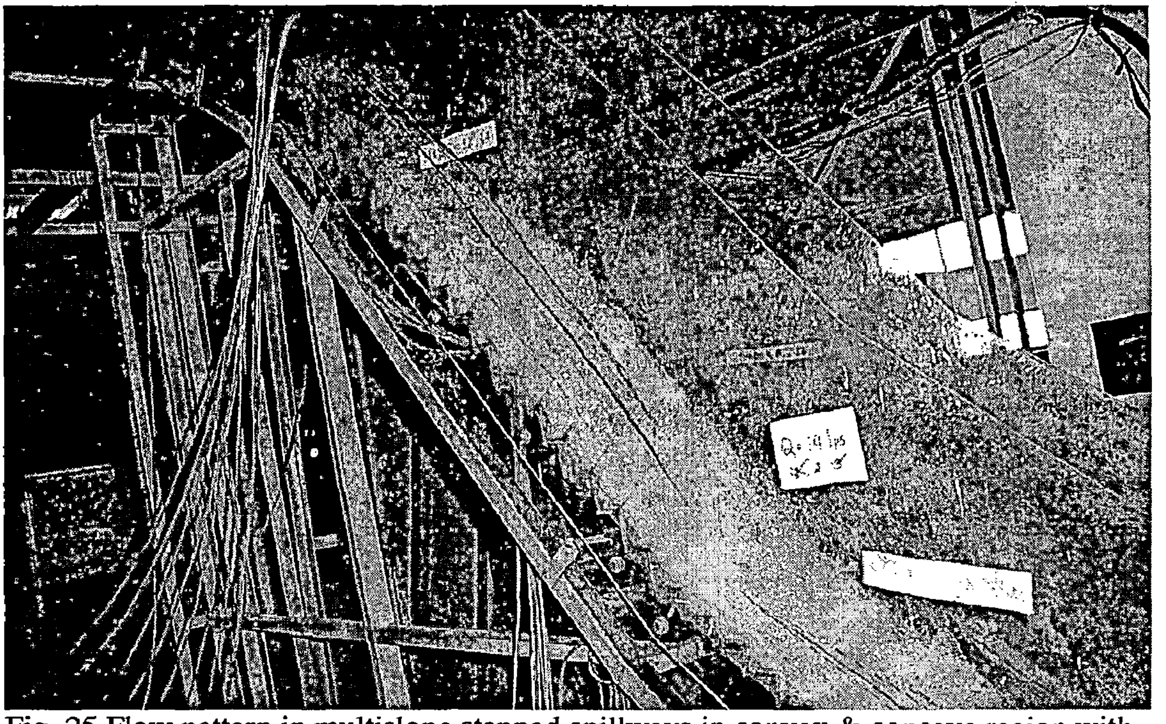


Fig. 25 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 14 lps per 20cm wide spillways

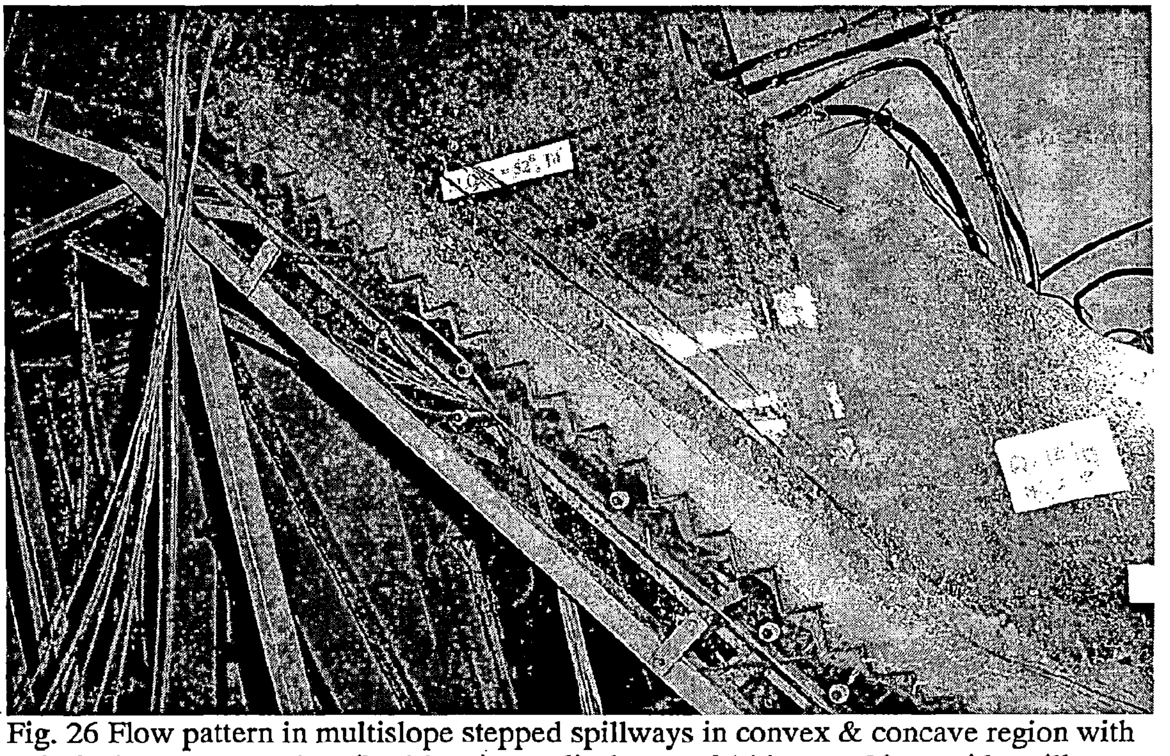


Fig. 26 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 14 lps per 20cm wide spillways

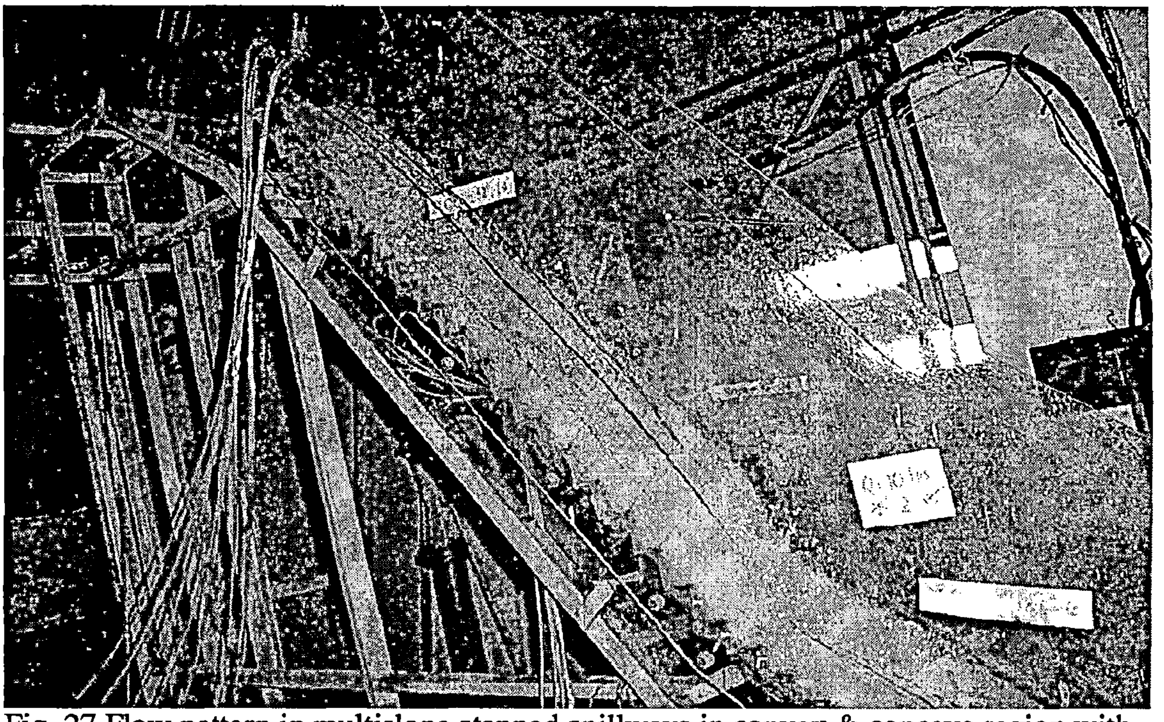


Fig. 27 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 10 lps per 20cm wide spillways

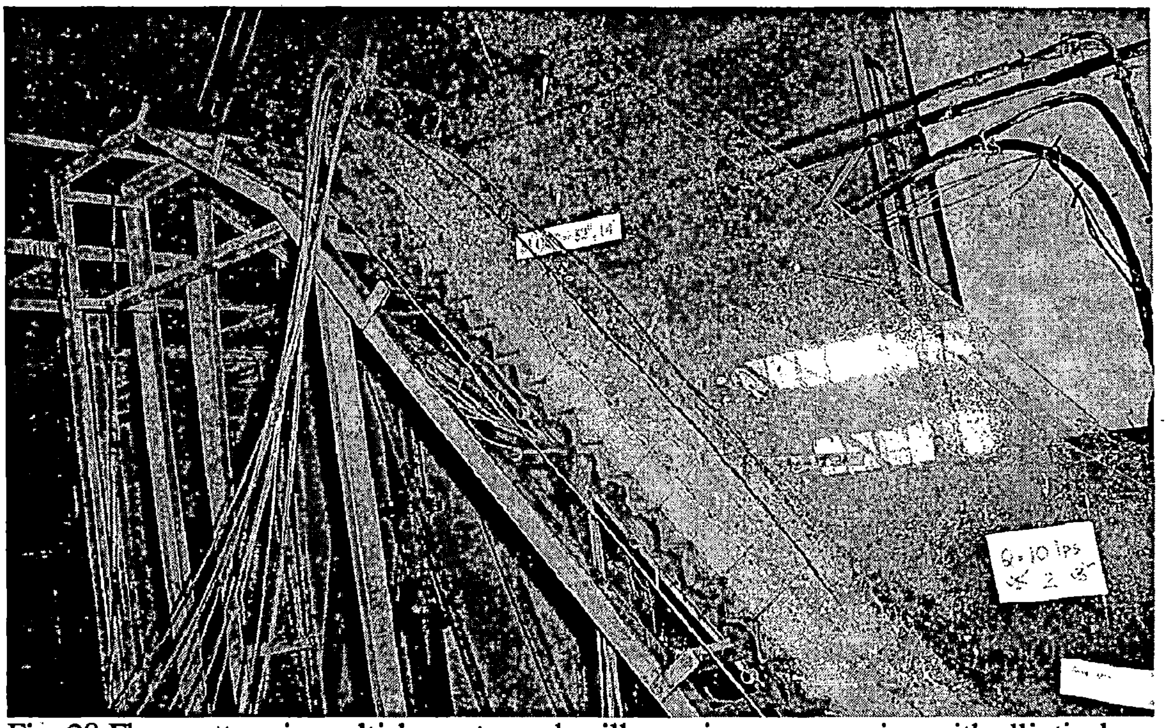


Fig. 28 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=45mm) at a discharge of 10 lps per 20cm wide spillways

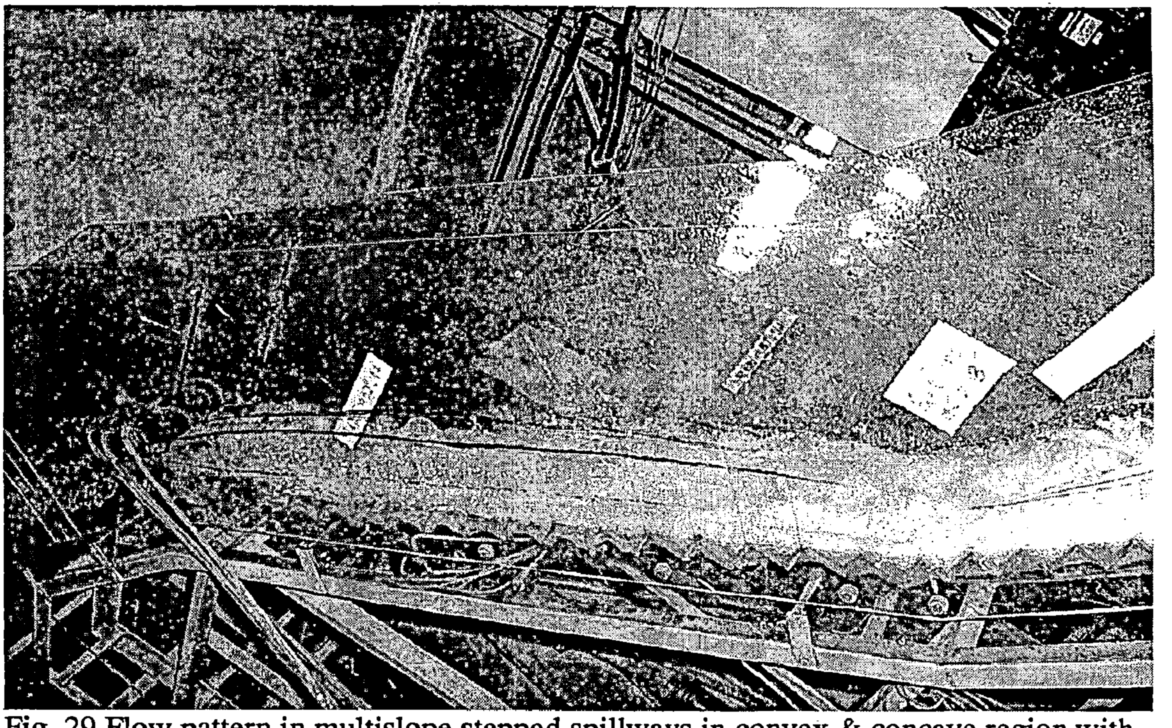


Fig. 29 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 6 lps per 20cm wide spillways

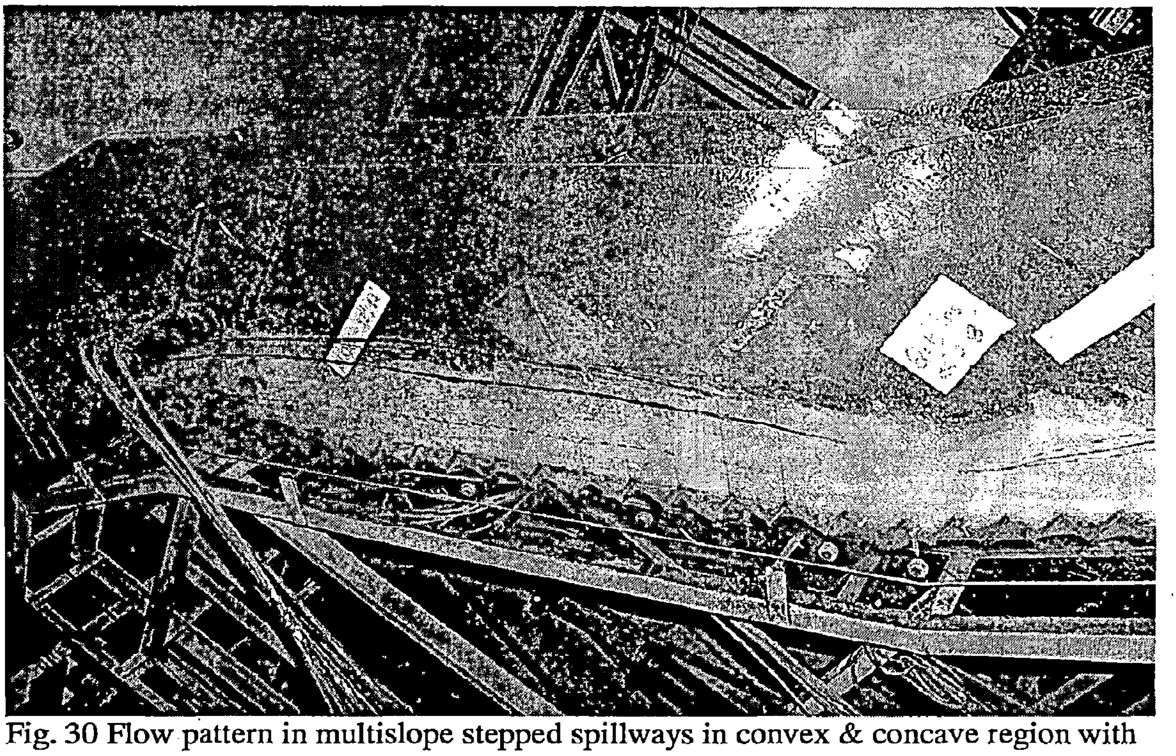


Fig. 30 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 6 lps per 20cm wide spillways

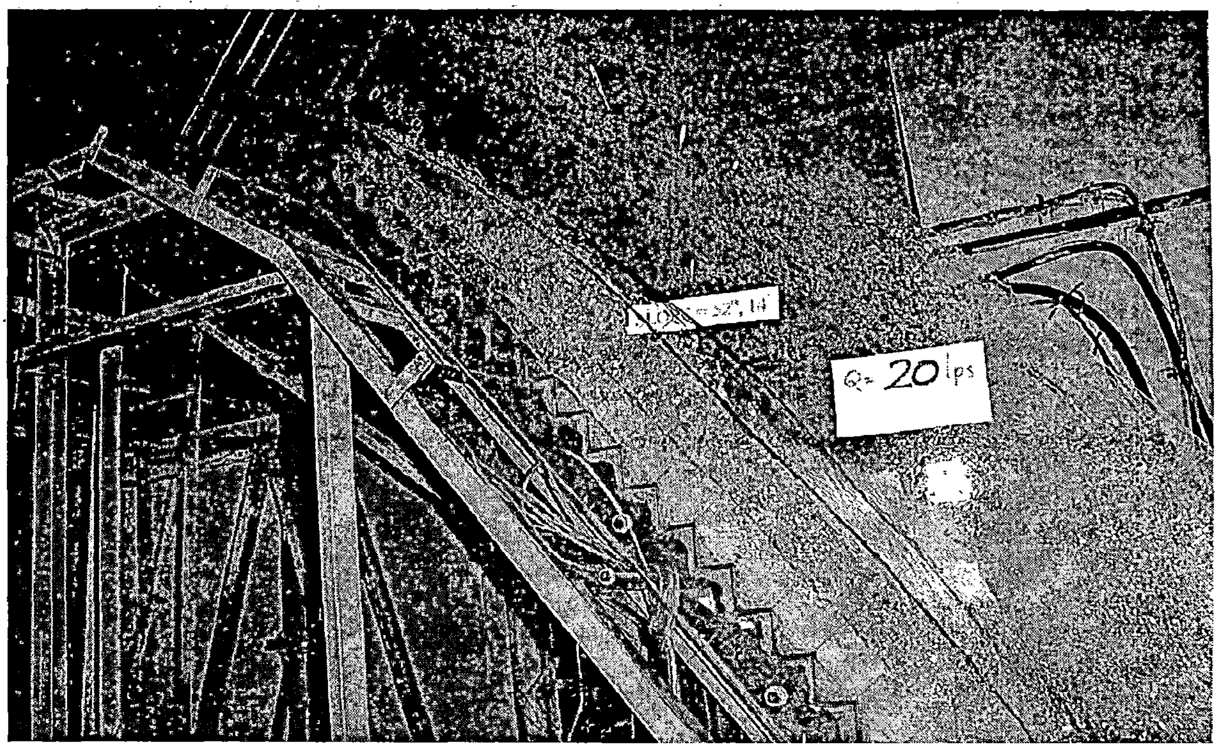


Fig. 31 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 20 lps per 20cm wide spillways.

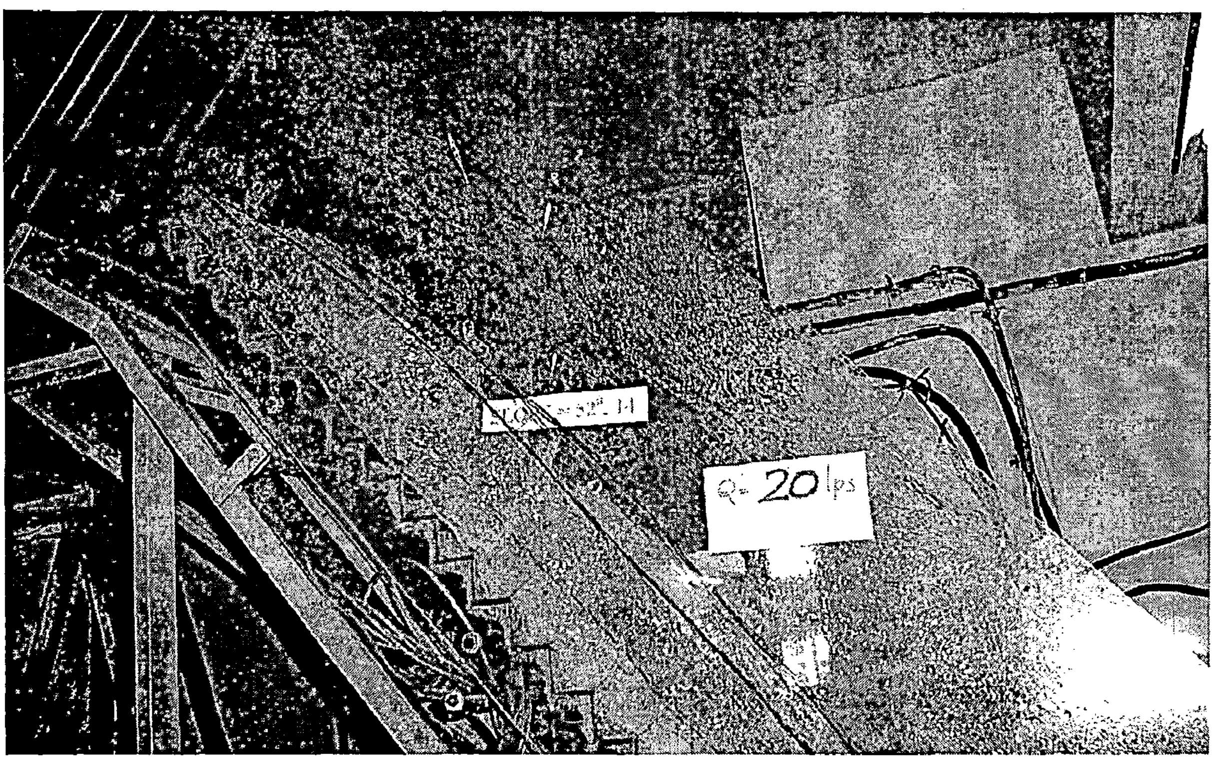


Fig. 32 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 20 lps per 20cm wide spillways.

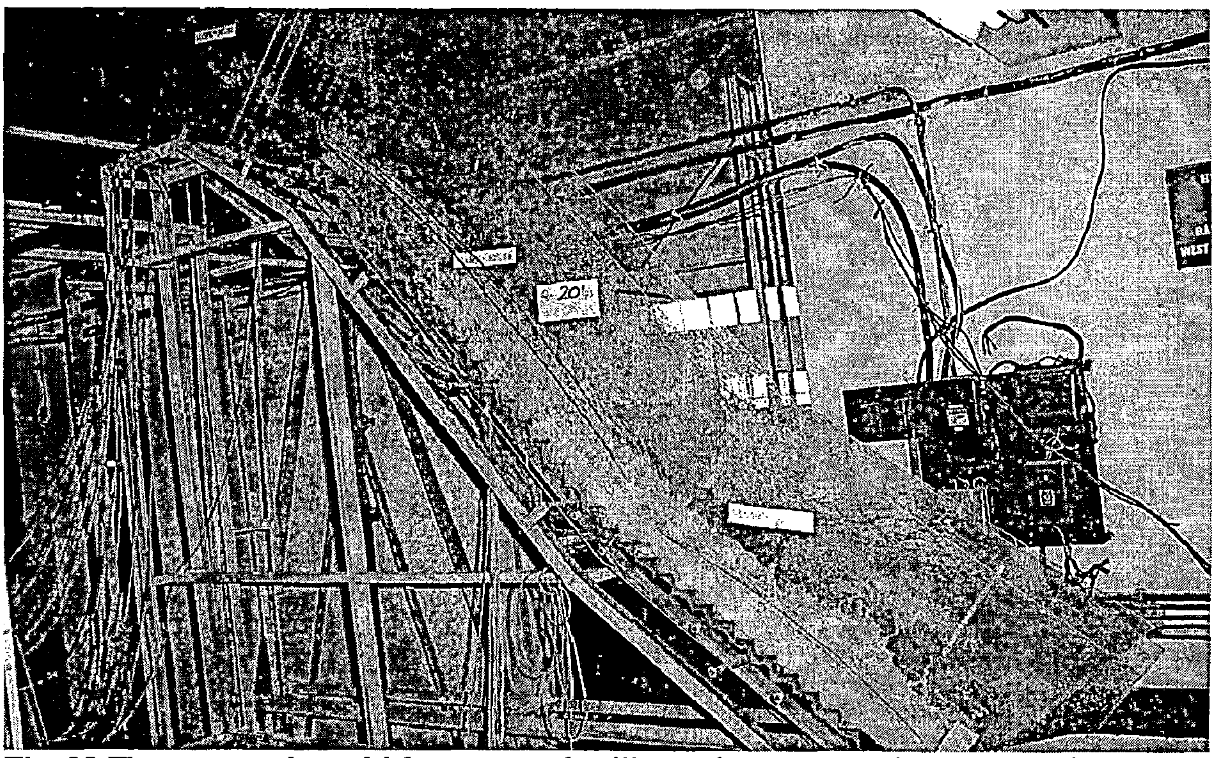


Fig. 33 Flow pattern in multislope stepped spillways in convex and concave region without suppressor plate at a discharge of 20 lps per 20cm wide spillways.

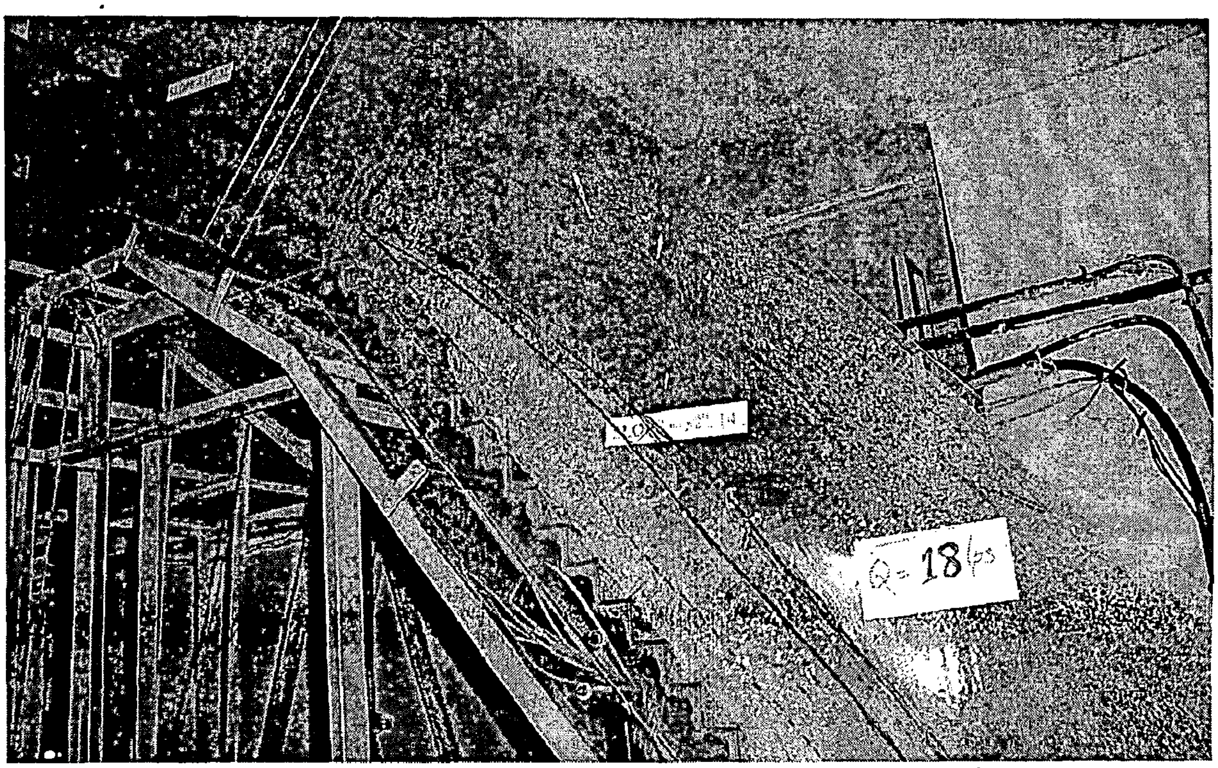


Fig. 34 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 18 lps per 20cm wide spillways.

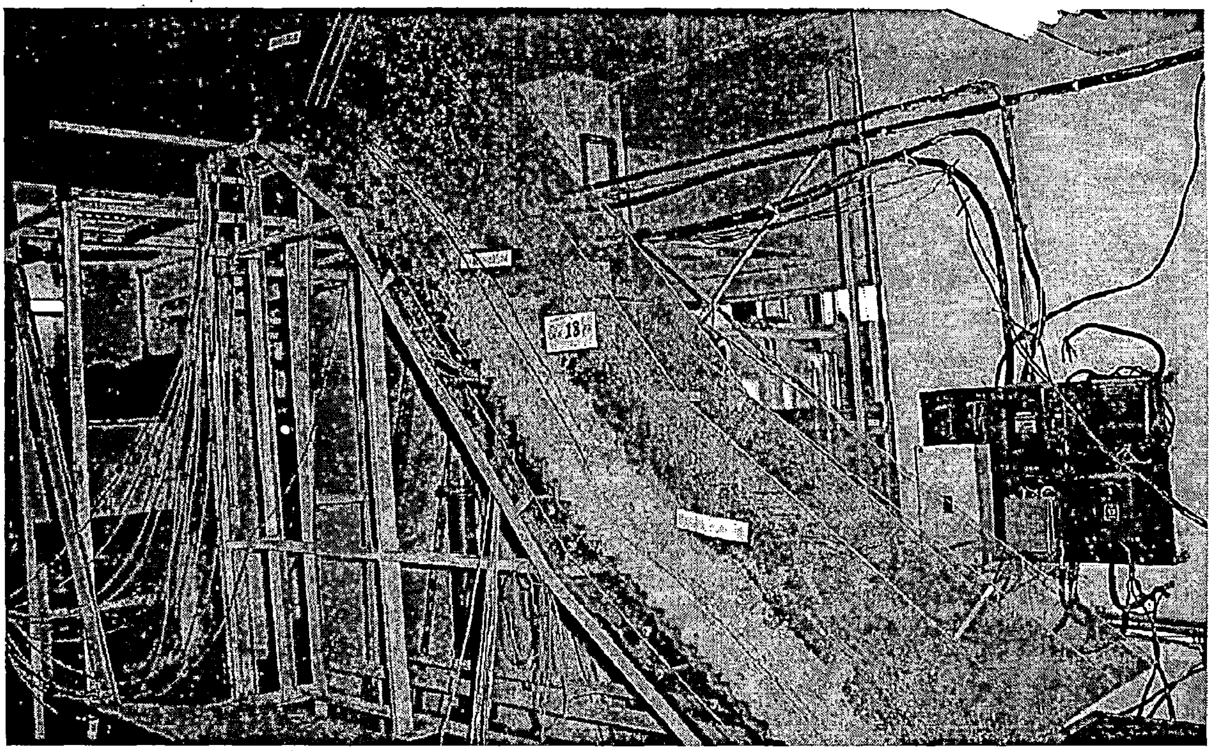


Fig. 35 Flow pattern in multislope stepped spillways in convex and concave region without suppressor plate at a discharge of 18 lps per 20cm wide spillways.

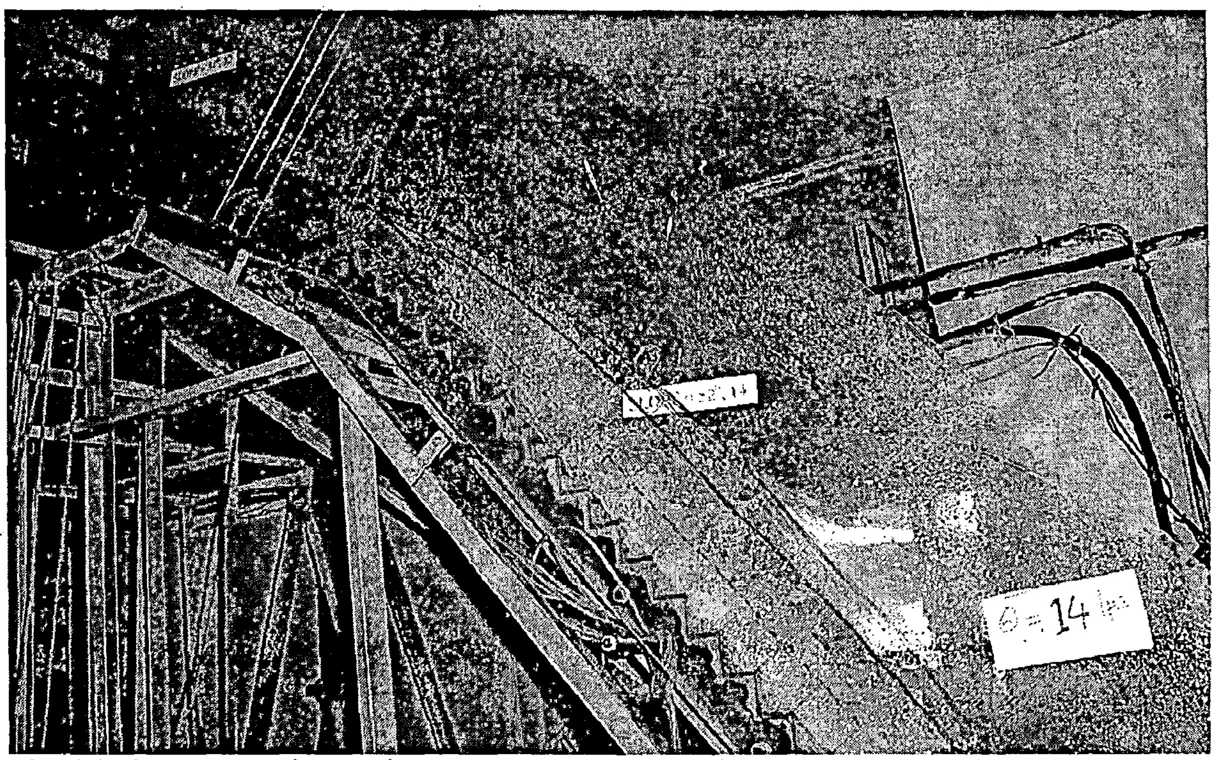


Fig. 36 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 14 lps per 20cm wide spillways.

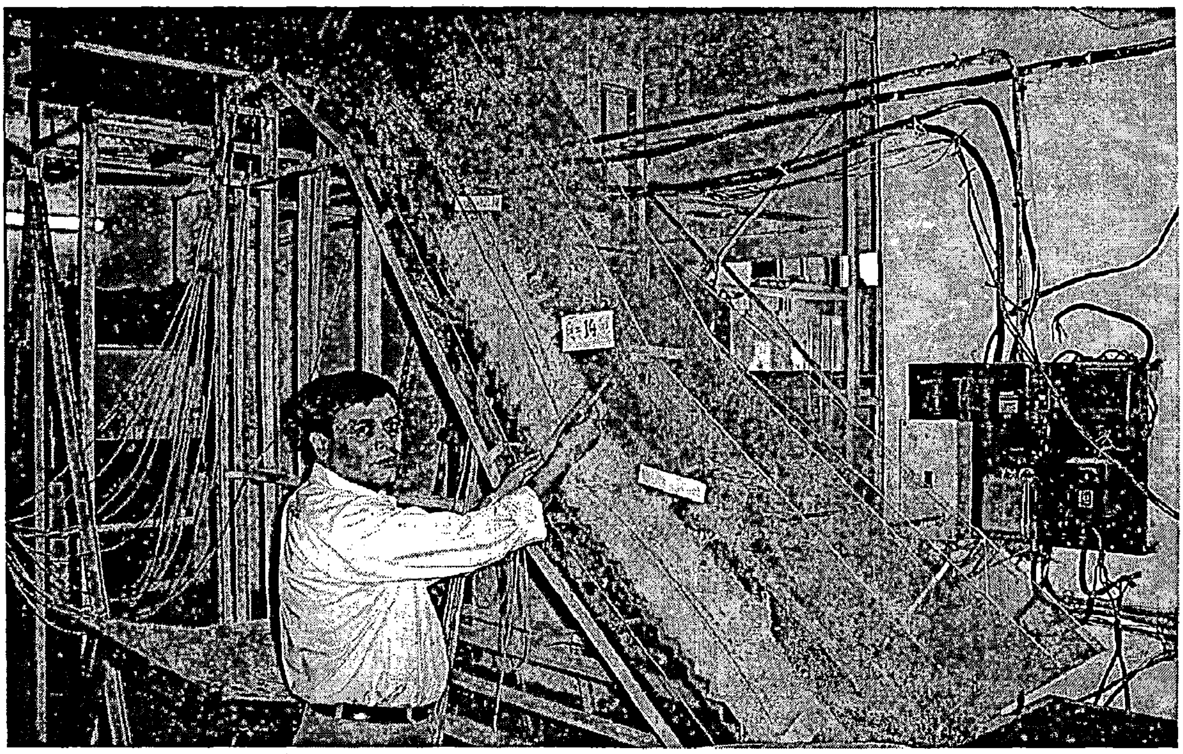


Fig. 37 Flow pattern in multislope stepped spillways in concave region without suppressor plate at a discharge of 14 lps per 20cm wide spillways.

Fig. 38 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 10 lps per 20cm wide spillways.

Fig. 39 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 10 lps per 20cm wide spillways.

Fig. 40 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 6 lps per 20cm wide spillways.

Fig. 41 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 6 lps per 20cm wide spillways.

Fig. 42 Flow pattern in multislope stepped spillways in convex region with circular suppressor plate at a discharge of 6 lps per 20cm wide spillways.

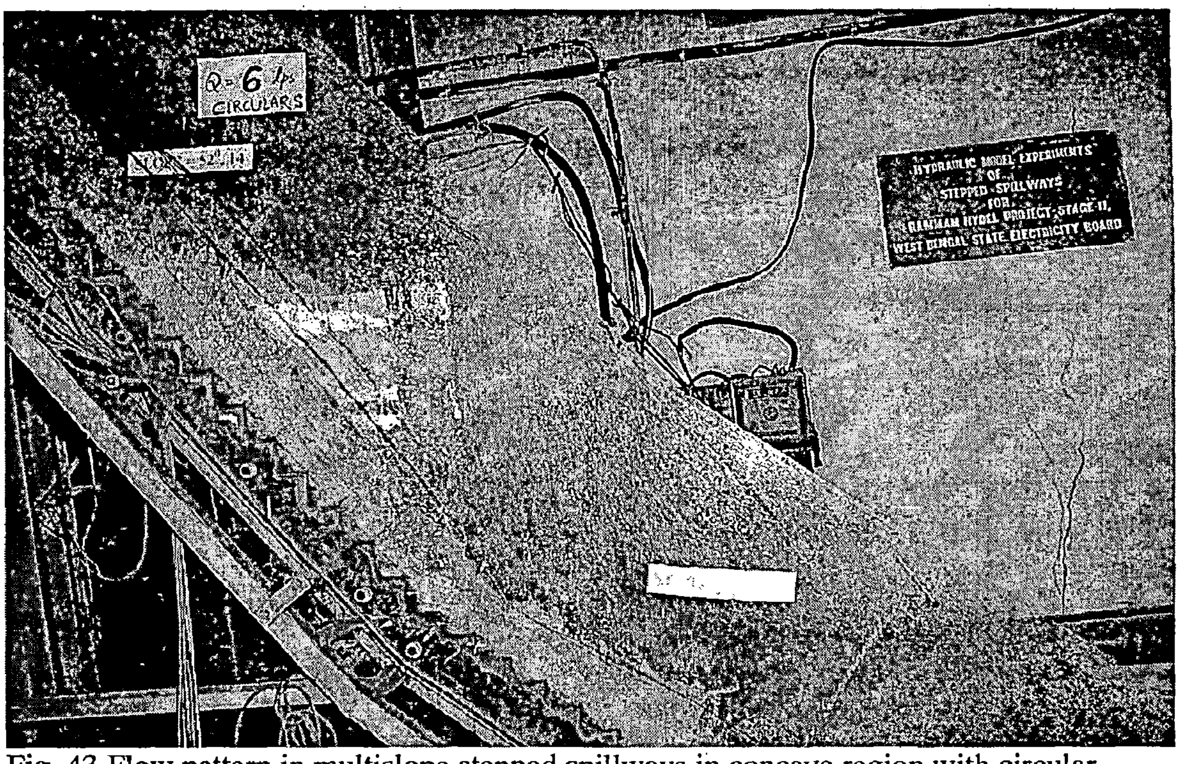


Fig. 43 Flow pattern in multislope stepped spillways in concave region with circular suppressor plate at a discharge of 6 lps per 20cm wide spillways.

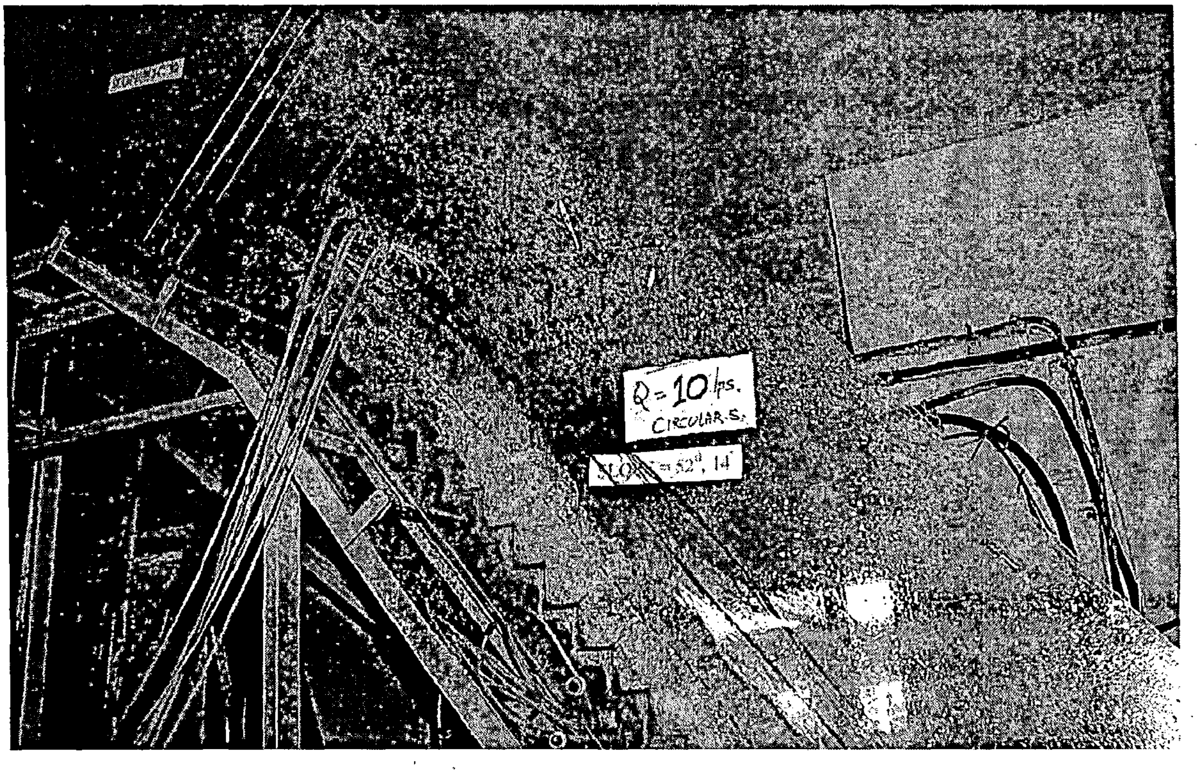


Fig. 44 Flow pattern in multislope stepped spillways in convex region with circular suppressor plate at a discharge of 10 lps per 20cm wide spillways.

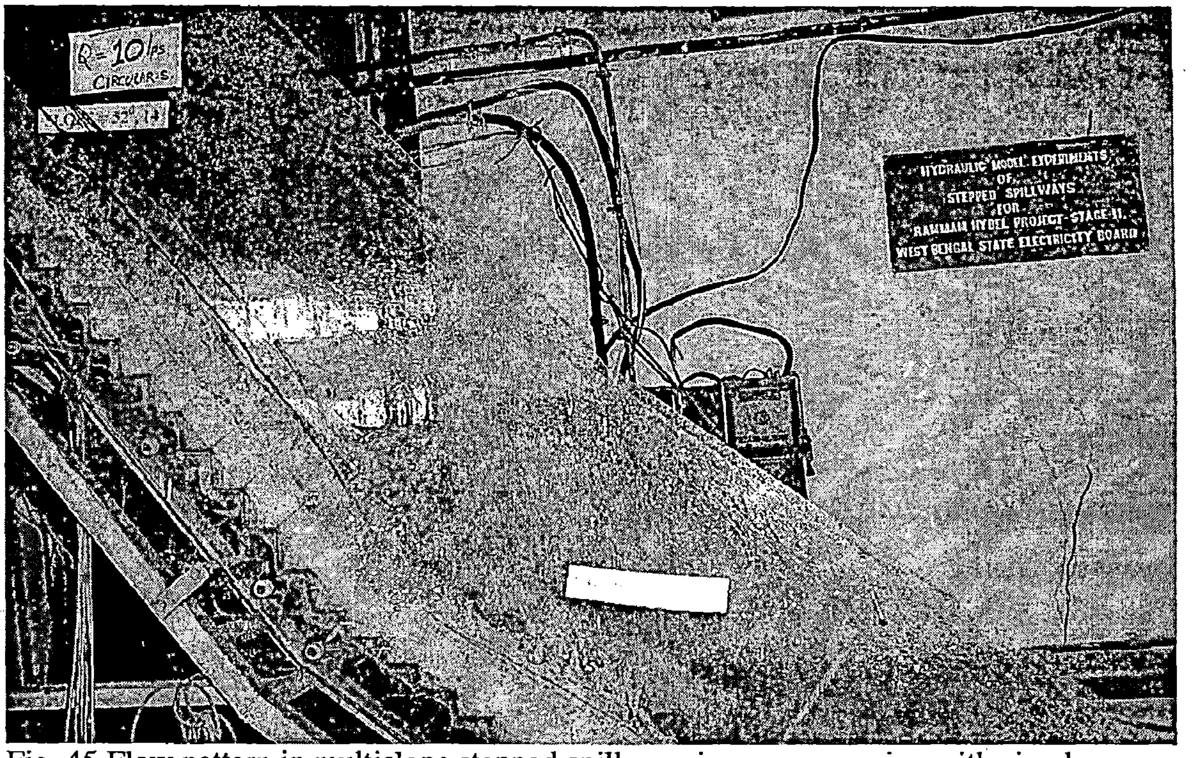


Fig. 45 Flow pattern in multislope stepped spillways in concave region with circular suppressor plate at a discharge of 10 lps per 20cm wide spillways.

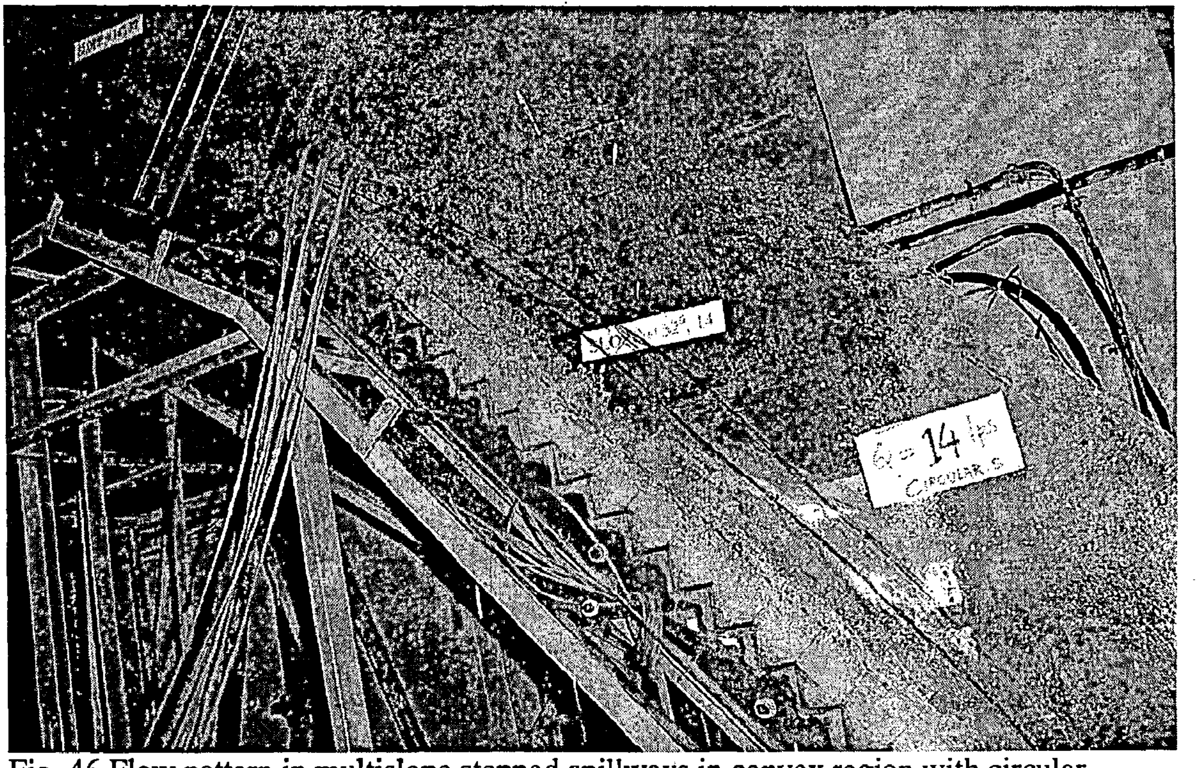


Fig. 46 Flow pattern in multislope stepped spillways in convex region with circular suppressor plate at a discharge of 14 lps per 20cm wide spillways.

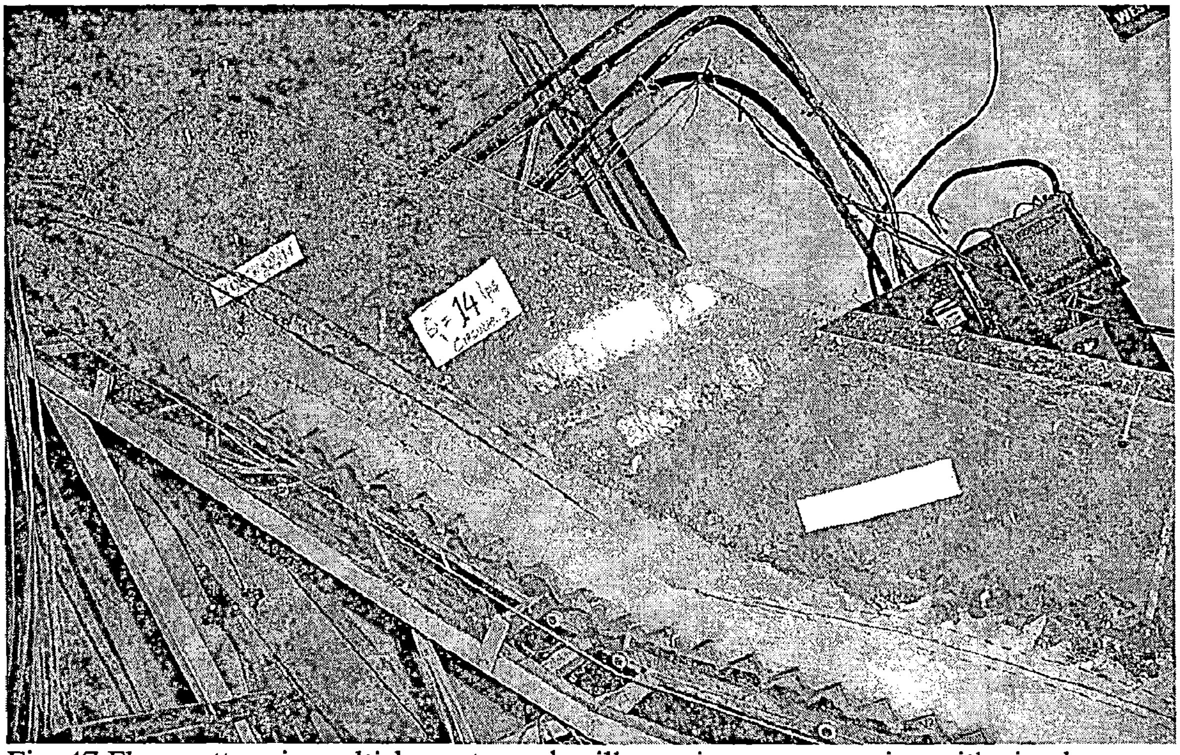


Fig. 47 Flow pattern in multislope stepped spillways in concave region with circular suppressor plate at a discharge of 14 lps per 20cm wide spillways.

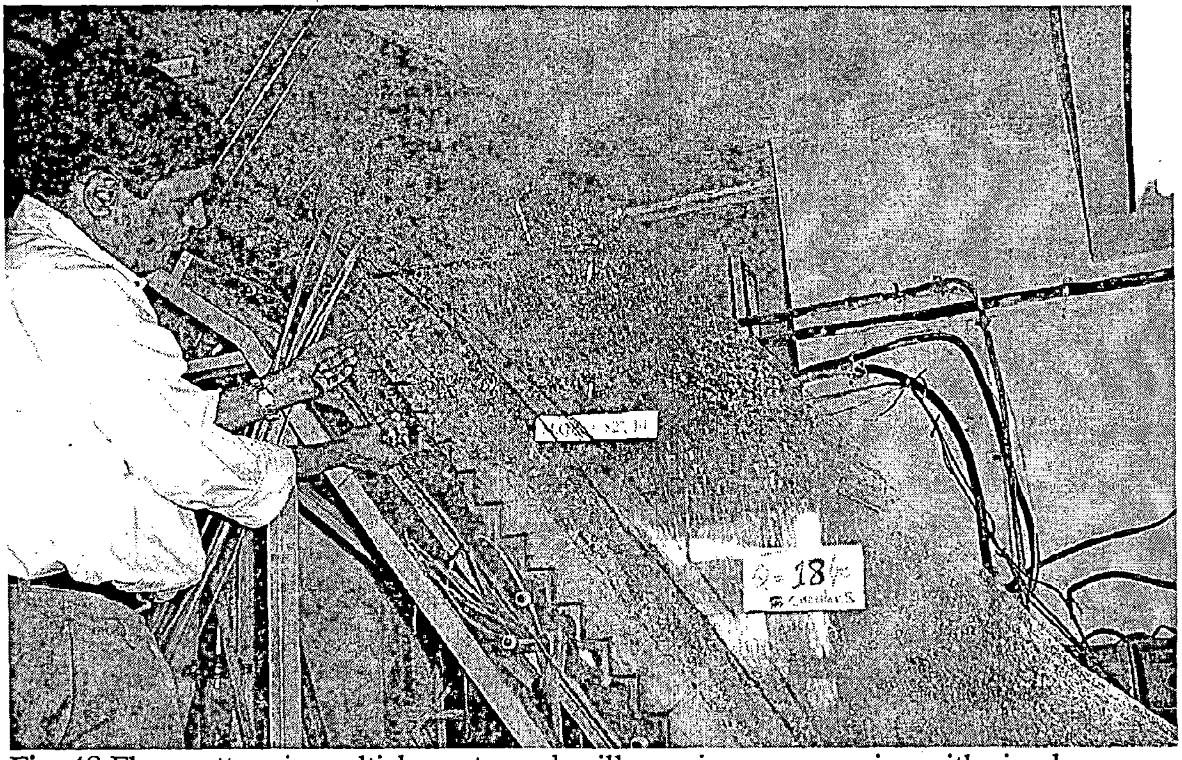


Fig. 48 Flow pattern in multislope stepped spillways in convex region with circular suppressor plate at a discharge of 18 lps per 20cm wide spillways.

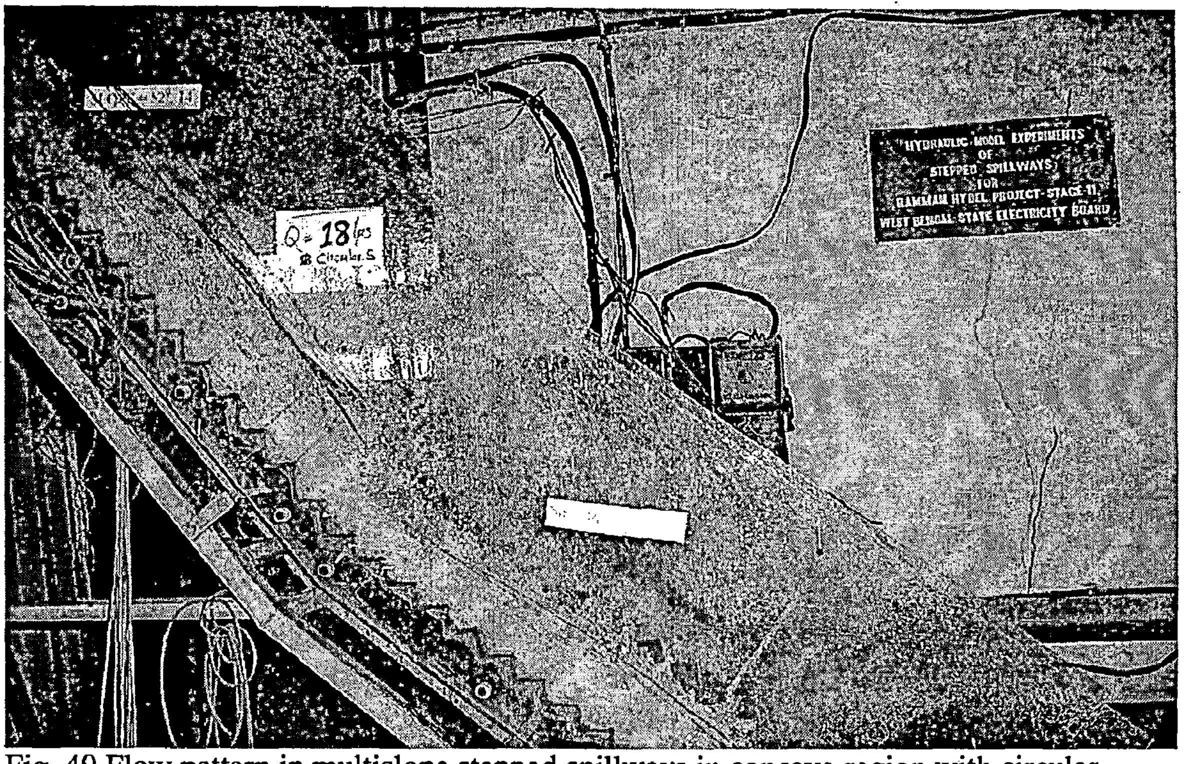


Fig. 49 Flow pattern in multislope stepped spillways in concave region with circular suppressor plate at a discharge of 18 lps per 20cm wide spillways.

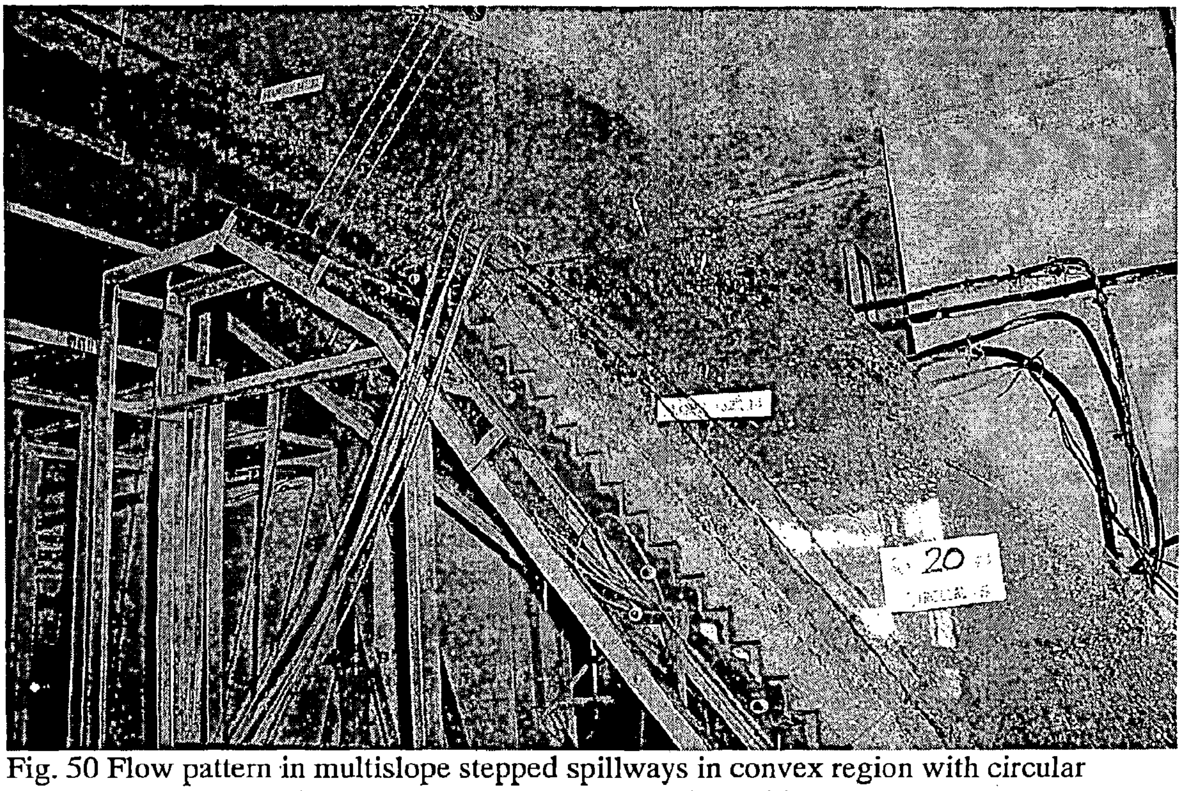


Fig. 50 Flow pattern in multislope stepped spillways in convex region with circular suppressor plate at a discharge of 20 lps per 20cm wide spillways.

Fig. 51 Flow pattern in multislope stepped spillways in convex and concave region with circular suppressor plate at a discharge of 20 lps per 20cm wide spillways.