EXPERIMENTAL STUDY OF FLOW PATTERN IN MULTISLOPE STEPPED SPILLWAYS

A DISSERTATION

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WATER RESOURCES DEVELOPMENT (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

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Ι

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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%.

List of figures

, Page n	os.
1. Fig. 1 Multi-slope stepped spillways: With four L-slopes	1
2. Fig. 2 Multi-slope stepped spillways: With four L-slopes	5
3. Fig.3.Nappe flow with flat slope	6
4. Fig.4.Nappe flow with pooled steps	6
5. Fig.5 Nappe flow regime with fully developed hydr.jump	7
6. Fig, 6. Nappe flow with partially developed hydraulic jump	8
7. Fig.7. Nappe flow without hydraulic jump	8
8. Fig.8. Flow at a drop structure	9
9. Fig 9. Variation of relative energy loss over several steps for $h/l = 0.421$	12
10. Fig.10 Consolidated results of variation of a with d _c /h for Horner and Moore	12
11. Fig.11 Nappe flow with pooled steps	13
12. Fig.12 Energy dissipation in nappe flow regime-comparision between	•
equations (for ungated & gated chute) by CHANSON and	
experimental data (MOORE 1943,RAND 1955,HORNER 1969,	
STEPHENSON 1979a).	15
13. Fig.13. Transition flow regime on steep slope	17
14. Fig.14 Transition flow on steep slope	17
15. Fig. 15 Section of stepped spillways showing flow patterns in skimming	
flow regime	19
16. Fig. 16 Skimming flow with stable cavity recirculation	19
17. Fig.17. Flow conditions for the transition from nappe to	~~
	23
18. 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)	
· · · · · · · · · · · · · · · · · · ·	24
19. Fig.19 Characteristics of the inception point of air entrainment (based on	24
experiments by BINDO et al 1993,FRIZEL&MEFFORD 1991,	
	25
	25 25
21. 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	
, ,	27
22. Fig. 22 Rapidly varied flow region at the inception point of free	_,
	30
23. Fig 23 Rapidly varied flow region at the inception point of free surface	-
	30
24. Fig.24. Flow pattern in the cavity between adjascent steps: Wake step	
interference sub regime in flat slopes	33
25. Fig.25 Flow pattern in the cavity between adjascent steps:	
Wake-wake interference sub regime in slope about 27 degrees	33
26. Fig.26. Flow pattern in the cavity between adjascent steps:	
Recirculating cavity flow sub regime in steep slope	34
27. Fig.27 ΔHres/Hres as a function of the mean air concentration Ce and the	
channel slope α	36

28. Fig 28 Step geometries	37
29. Fig.29 Multi-slope stepped spillways: With four L-slopes	40
30. Fig. 30. Multislope stepped spillways with suppressor plate: Showing t	he
effect of the plate in making the flow with uniform depths after it.	45
31. Fig.31 Section of elliptical suppressor plate (general)	45
32. Fig.32 Multislope stepped spillways with suppressor plate: Showing th	e
effect of the plate in making the flow with uniform depths after it.	46
33. Fig.33 Section of designed elliptical suppressor plate	47
34. 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.	49
35. Fig.35 Elements of simple circular curve	49
36. Fig. 36 Detail of convex curve at the junction point	50
37. Fig.37 Section of designed circular suppressor plate	51
38. Fig. 38 Section of designed angular suppressor plate	51
39. Fig. 39 Placement position of suppressor plate at the convex junction	
point of the multislope stepped spillways	52
40. Fig. 40 Experimental set up: Multislope stepped spillways	. 53
41. Fig. 41 Experimental set up: Monoslope stepped spillways	53
42. Fig.42 Graphs	Appendix B
43. Fig.43. Drawings and experimental photographs	Appendix C

List of Tables

\mathbf{P}_{i}	age nos.
1. Table of relations between D', K' and Cmean	28
2. Table of relations between α , C _e , Y ₉₀ /d _w , f _e /f and h/l	29
3. Model scale ratios	44
4. Table of relations between difference of mercury level x and flow	
of discharge Q in manometer.	54
5. Flow depths in multi-slope and mono-slope stepped spillways	55
6. Result table of d _w and V _w	77
7. Uplift water pressure at suppressor plates	78
8. Table of prediction of flow regimes: Theoretical, observational with or	
without circular suppressor plate	86
9. Table of water pressures at different points of steps for the study of	
cavitations risk with or without circular suppressor plate.	99
10. Table of calculation of cavitations numbers	125
11. Table of study of flow patterns in small and high flow rates.	126
12. 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 Appendix B	138
13. Table of calculation of d_w vs V_w and q_w graphs Appendix B	138

List of Symbols

 $d_c = Critical depth$ 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 $L_i = length of jump$ $d_o/d_w = Average water flow depth$ $q_w = Unit discharge$ g = Accelerations due to gravity Q = Dischargeb = Width of spillways (If not stated) σ = Surface tension $\rho w = \text{Water density}$ 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 $\lambda = (h^2 + l^2)^2$ $\tau o =$ Average shear friction K_s = Step roughness height R = Hydraulic mean radius $F = F_r = F_b = Froude no.$ $\Delta H = \Delta E = \text{Difference}$ between the maximum head and residual head C = Air concentration Y_{90} = Flow depth where C = 90% fe = Darcy friction factor ≈ √ ฉ ч 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

CONTENTS

	Page nos
Candidate's declaration	Ī
Acknowledgements	II
Synopsis	· III
List of figures	\mathbf{V} t
List of tables	VII
List of symbols	ΛЩ
Chapter-1 Introduction	1
1.1 Introduction	1
1.2 Present study and the objectives of the study	2
1.3 Scope and limitation of the study	. 2
1.4 Methodology used in the studies	3
1.5 Organization of the dissertation	3
1.6 Experimental Problems of the study	3
1.7 Findings of the study	3
Chapter-2 Review of literature	2 2 3 3 3 5 5 5
2.1 Multi-slope stepped spillways	5
2.2 Applications	5
2.3 Type of stepped channels	6
2.4 Flow regimes	· 7
2.4.1.1 Nappe (Jet) flow Regimes	7
2.4.1.2 Introduction	7
2.4.1.2 Hydraulic characteristics of nappe flow	9
2.4.1.3 Design of chute with nappe flow regime	10
2.4.2 Transition flow regimes	16
2.4.3 Skimming Flow Regimes	18
2.4.3.1 Introduction	18
2.4.3.2 Onset of skimming flow	20
2.4.3.3 Transition from nappe to skimming flows	22
2.5 Boundary layer growth	23
2.6 Uniform flow conditions	26
2.7 Flow aeration	27
2.8 Flow properties	28
2.8.1 Rapidly varied flow at inception point (Chanson 2001)	30
2.8.2 Gradually varied flow properties (Chanson 2001):	31
2.9 Flow resistance	31
2.10 Flow patterns	32
2.11 Velocity distribution	34
2.12 Energy dissipation	35
2.13 Selection of step height	38
2.14 Selection of training wall height of stepped spillways	38
2.15 Comparison between nappe and skimming flow regimes	
regarding energy dissipation	. 39
Chapter-3 Experimental study of flow patterns in multi-slope	er George
stepped spillways	40
3.1 Introduction	40
3.2 Model laws (Similarity laws) and scale ratios	40
3.3 The suppressor plate	44

3.3.1. Design of suppressor plates	46
3.3.2 Positioning of the suppressor plate	51
3.4 Experimental set up	52
3.5 Experimental procedures	54
3.6 Analysis of results	54
3.6.1 Introductions	54
3.6.2 Experimental data and calculations	54
3.6.2.1 Venturimeter Calculation	54
3.6.2.2 Experiment-1 (water flow depths without suppressor plate)	55
3.6.2.3 Calculation of rate of energy dissipation and residual head	63
3.6.2.4 Experiment-2 (water flow depths with circular suppressor plate)	66
3.6.2.5 Calculation of rate of energy dissipation and residual head	75
3.6.2.6 Experiment-3 (uplift water pressure at circular/elliptical	
suppressor plate)	78
3.6.2.7 Prediction of flow regimes	86
3.6.2.8 Experiment-4 (water flow depths without suppressor plate	
in mono-slope stepped spillways)	93
3.6.2.9 Calculation of rate of energy dissipation and residual head	95
3.6.2.10 Experiment-5 (water pressure at different points of steps	
for the study of cavitations risks)flow depths without	
suppressor plate in mono-slope stepped spillways)	99
3.6.2.11 Experiment-6 (water flow depths with elliptical	
suppressor plate no.1 i.e. $P = 135 \text{mm}$)	101
3.6.2.12 11 Experiment-7 (water flow depths with elliptical	
suppressor plate no.2 i.e. P =90mm)	109
3.6.2.13 Experiment-8 (water flow depths with elliptical	
suppressor plate no.3 i.e. $P = 45 \text{mm}$)	117
3.6.2.14 Calculation of cavitations number	125
3.7 The study flow patterns in the multi-slope stepped spillways	126
Chapter-4 Discussion of results and conclusions	129
References	132
Appendix A: It deals with the hydraulic design of stepped spillways by	
different methods.	133
Appendix B: Graphs (H _{res} /H _{max} verses H _{spill} /d _c & d ₉₀ verses distance x etc.)	138
Appendix C: Drawings and photographs of flow patterns in multi and	
mono-slope stepped spillways	179

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.

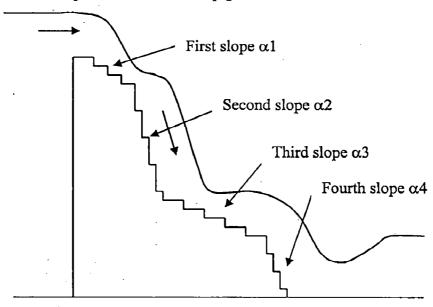


Fig. 1 Multi-slope stepped spillways: With four L-slopes

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 280 m3/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°32', 52°14' and 38° 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 d₉₀ graphs, H_{res}/H_{max} verses H_{spill}/d_e graphs, Velocity V_w verses d₉₀ graphs, and rate of flow q_w verses d₉₀ 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.

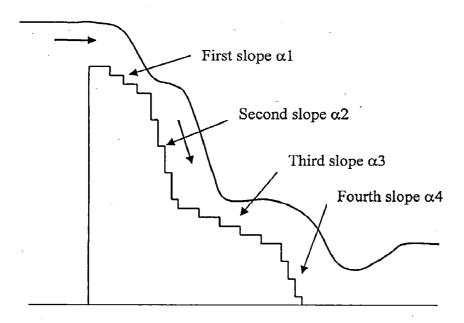


Fig. 2 Multislope stepped spillways: With four L-slopes

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.

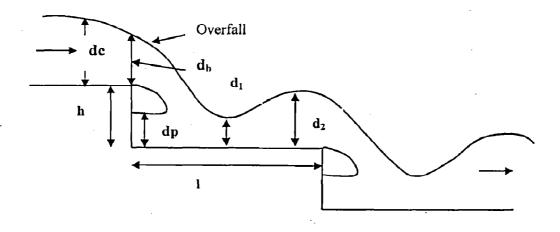


Fig.3. Nappe flow with flat slope

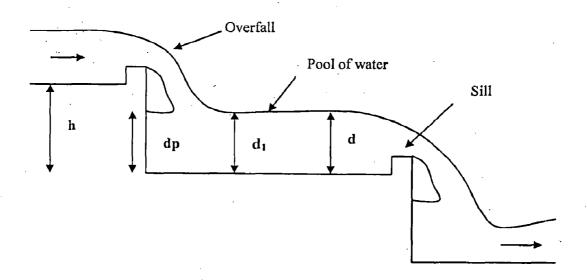


Fig.4.Nappe flow with pooled steps

- (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 stable. 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.

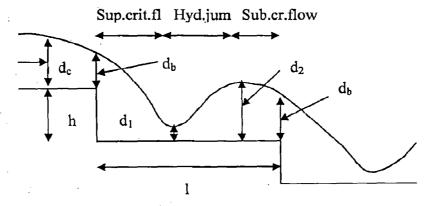


Fig. 5. Nappe flow regime with fully developed hydr.jump

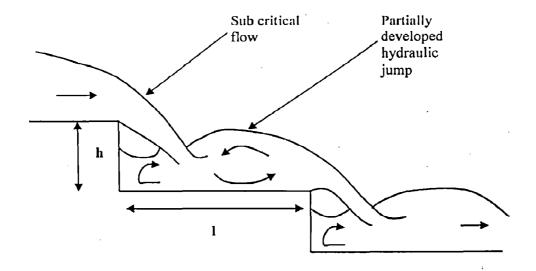


Fig.6.Nappe flow with partially developed hydraulic jump

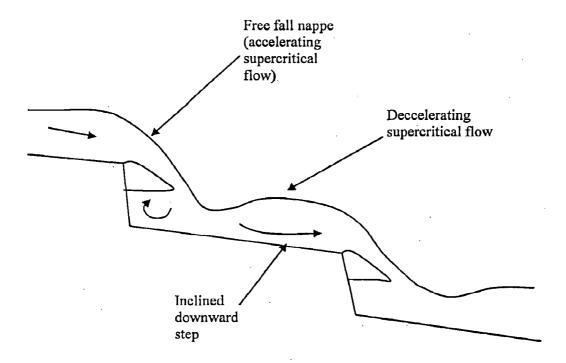


Fig.7 Nappe flow without hydraulic jump

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):

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

where d1 is the pre jump depth.

The total head H₁ at section 1 can be expressed non-dimensionally as:

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

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

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

where d_2 is post jump and $F_{rl} = \frac{qw}{\sqrt{gd_1^3}}$.

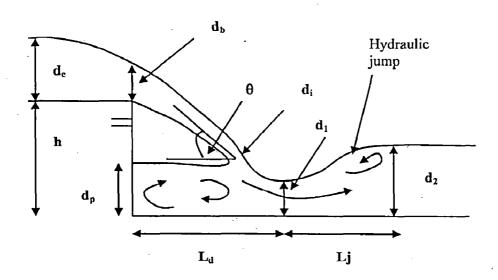


Fig.8 Flow at a drop structure

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

$$\frac{d_1}{h} = 0.54 \left(\frac{d_0}{h}\right)^{1.275}$$

$$\frac{d_2}{h} = 1.66 \left(\frac{d_0}{h}\right)^{0.81}$$

$$\frac{d_p}{h} = \left(\frac{d_0}{h}\right)^{0.66}$$
(7)

$$\frac{\mathrm{dp}}{\mathrm{h}} = \left(\frac{\mathrm{dc}}{\mathrm{h}}\right)^{0.66} \tag{7}$$

$$\frac{L_d}{h} = 4.3(\frac{d_c}{h})^{0.81} \tag{8}$$

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:

$$\frac{d_1}{h} = 0.687(\frac{d_c}{h})^{1.483} \tag{9}$$

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

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

$$\frac{L_{\rm j}}{d_{\rm l}} = 8[(\frac{d_{\rm c}}{d_{\rm l}})^{\frac{3}{2}} - 1.5]$$
 (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:

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

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:

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

$$\tan \alpha = \frac{h}{l} < 0.20 \tag{1}$$
 and
$$\frac{dc}{l} < \frac{1}{2} \tag{2}$$

where α is the slope of channel.

The two equations satisfy the equation,

$$(\frac{dc}{h})char = 0.0916(\frac{h}{l})^{-1.276}$$
 (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:

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

$$\alpha = a-b \log (d_c/h) \tag{2}$$

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 \triangle E/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.

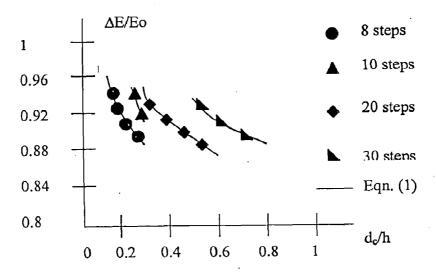


Fig 9. Variation of relative energy loss over several steps for h/l =0.421

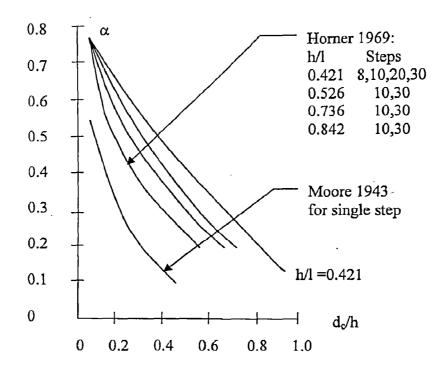


Fig. 10 Consolidated results of variation of a with d_c/h for Horner and Moore

(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:

$$d_c/h = \frac{(1.4 - h/l)^{0.26}}{1.4}$$

(1) for upper limit of nappe flow regime

 $d_c/h = 0.862 (h/1)^{-0.165}$

(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:

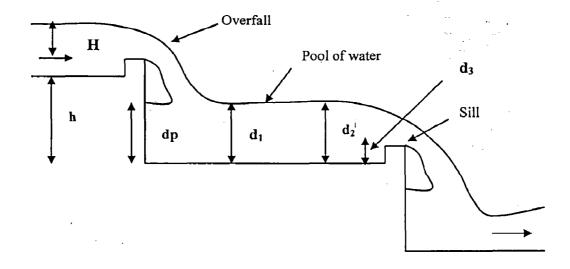


Fig.11.Nappe flow with pooled steps

If α is the slope of the step;

$$\tan \alpha = h/l \tag{1}$$

and dc is the critical depth;

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

specific discharge;

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

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

$$C_{\rm d} = 0.615 \left(1 + \frac{1}{1000H + 1.6}\right) \left\{1 + 0.5\left(\frac{H}{H + d3}\right)^2\right\} \tag{4}$$

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

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

$$d_1 = \frac{q}{V_1} \tag{6}$$

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

$$\frac{d^2}{dt} = \frac{1}{2} (\sqrt{1 + 8(\frac{d_0}{dt})^3} - 1)$$
 (7)

Height of the weir d₃ plus a 5% safety margin for d₂ amounts to:

$$d_3 = 1.05d_2 - H \tag{8}$$

Length of floor L;

$$L = L_d + L_i \tag{9}$$

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

$$L_{d} = 1512 \left(\frac{d_{3} + h}{H}\right)^{0.556} H \tag{10}$$

Length of jump Li,

$$L_i = 6d_2 \tag{11}$$

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

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

In dimensionless form the head loss yields:

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

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

 $H_{\text{max}} = H_{\text{dam}} + H_{\text{o}}$

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

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

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

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

$$\frac{\Delta H}{H_{max}} = 1 - \left[\frac{0.54 \left(\frac{d_e}{h}\right)^{0.275} + \frac{3.43}{2} \left(\frac{d_e}{h}\right)^{-0.55}}{\frac{H_{dam} + H_o}{d_e}} \right]$$
 (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.

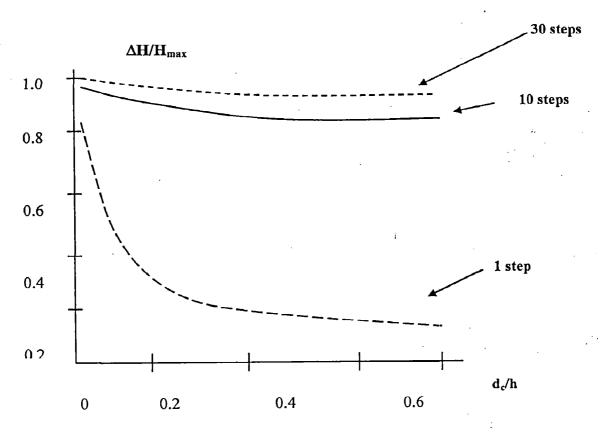


Fig.12 Energy dissipation in nappe flow regime-comparision between equations (for ungated & gated chute) by CHANSON and experimental data (MOORE 1943,RAND 1955,HORNER 1969,STEPHENSON 1979a).

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;

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

Where 1 is the length of step! Nappe flow situations with fully developed hydraulic jump occur for $\frac{d_e}{h} < (\frac{d_e}{h})$ 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:

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

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

$$\frac{d_1}{h} = 0.54 \left(\frac{d_c}{h}\right)^{1.275} \tag{3}$$

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

$$\tan \alpha < 0.2 \tag{1}$$

$$\frac{d_c}{h} < \frac{1}{3} \tag{2}$$

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:

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

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

$$\frac{d_c}{h} = 1.2 - 0.325(\frac{h}{l})$$
 (2) (TRA-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 quasiuniform flows only; for rapidly varied flows, the results are in accurate.

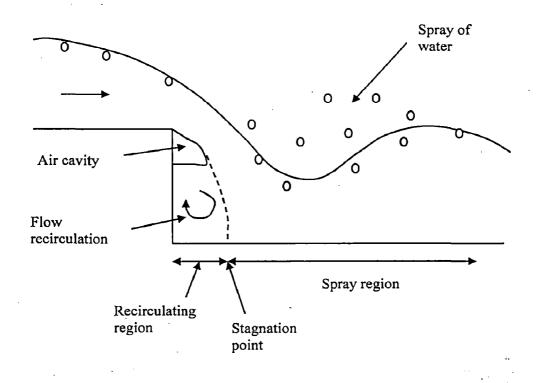


Fig.13.Transition flow regime on steep slope

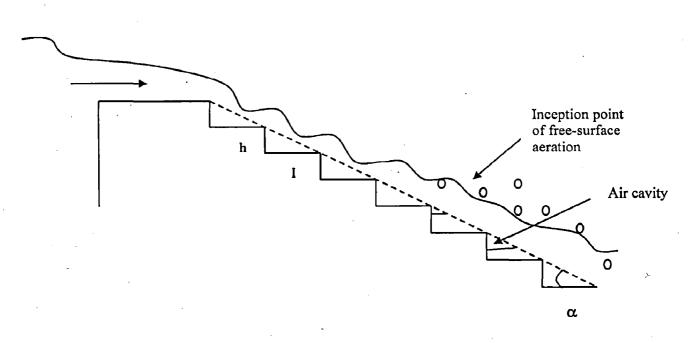


Fig.14 Transition flow on steep slope

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.

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.

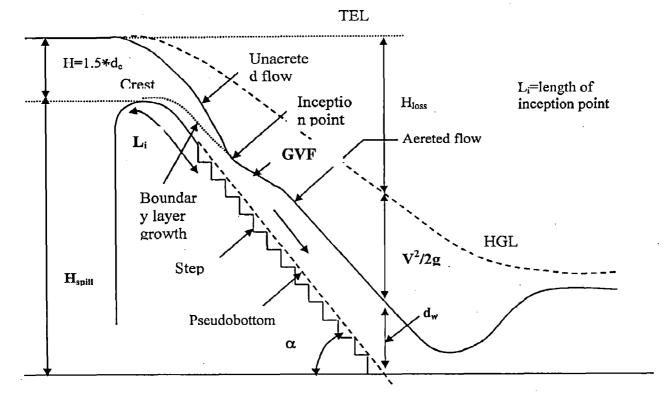


Fig.15. Section of stepped spillways showing flow patterns in skimming flow regime

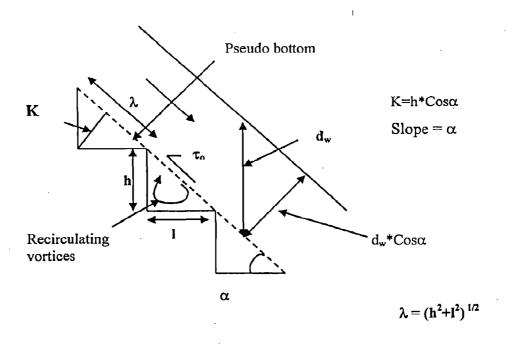


Fig.16.Skimming flow with stable cavity recirculation

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:

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

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.

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

$$\frac{dc}{h} = 0.91 - 0.14 \tan \alpha \tag{3}$$

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,

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

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

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

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

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

And again,
$$\tau = C_{fp} \frac{Vo^2}{2}$$
 (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),

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

Where q = discharge per unit width of spillways.

From equations (1)&(4),

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

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

$$E' = yo' + \frac{Vo^2}{2g} \tag{6}$$

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:

$$\Delta E = E' - E \tag{7}$$

 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 $\Delta E/E$, it can be shown that,

$$\frac{\Delta E}{E'} = \frac{(1-A) + \frac{Fo^2}{2} \frac{(A^2 - 1)}{A^2}}{1 + \frac{Fo^{2}}{2}}$$
(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', Δ E/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:

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

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

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,

$$\frac{dc}{h} = 0.91 - 0.14 \tan \alpha \tag{1}$$

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° < α < 55° .

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.

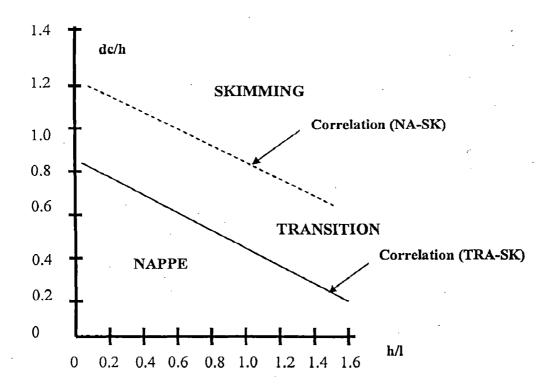


Fig.17 Flow conditions for the transition from nappe to skimming flow-Summary of experimental data (after CHANSON 2001)

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:

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

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

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

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

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:

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

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

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

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

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:

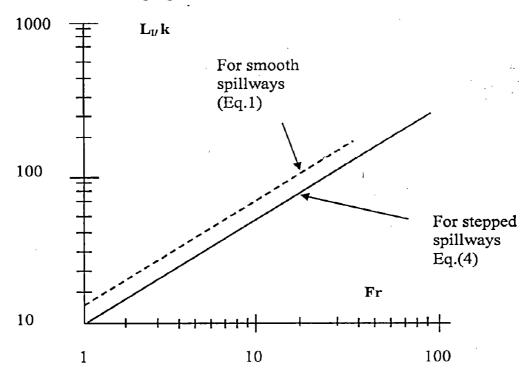


Fig.18. Characteristics of the inception point of air entrainment (based on experiments by BEITZ&LAWLESS 1992,BINDO et al 1993,FRIZEL&MEFFORD 1991,SORENSON 1985,TOZZI 1992) and equation by CHANSON 1994.

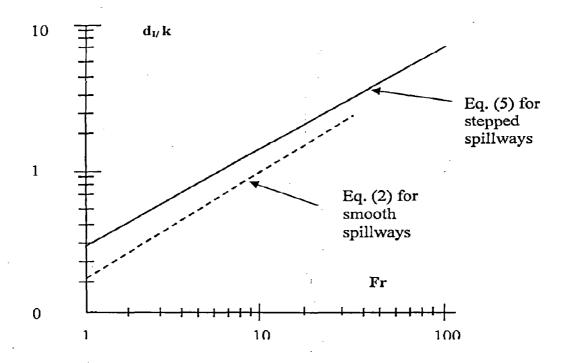


Fig.19 Characteristics of the inception point of air entrainment (based on experiments by BINDO et al 1993, FRIZEL&MEFFORD 1991, SORENSON 1985, TOZZI 1992) and equation by CHANSON 1994.

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

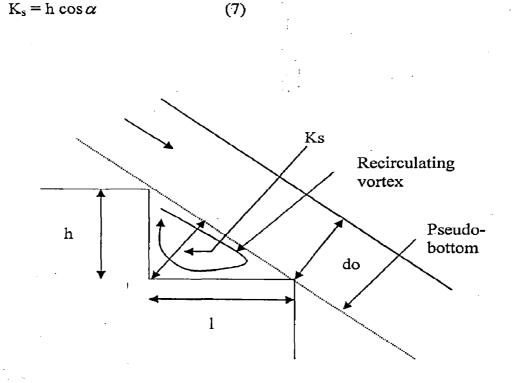


Fig. 20 Definition sketch of roughness height Ks

(b) Boes and Minor (2000):

Air entrainment: Where the turbulent boundary layer reaches the free surface, the degree of turbulence 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:

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

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:

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

$$dw = \int_{0}^{y90} (1-C)dy \tag{1}$$

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:

$$Cmean = \frac{1}{y90} \int_{0}^{y90} Cdy \tag{2}$$

and combining with equation (1), this yields:

$$Cmean = 1 - \frac{dw}{y90} \tag{3}$$

The mean flow velocity is defined as:

$$Uw = \frac{qw}{dw} \tag{4}$$

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):

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

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:

$$Ce=0.90 \sin \alpha \tag{2}$$

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.

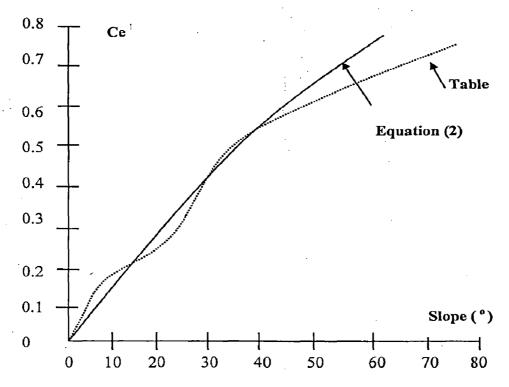


Fig 21 Uniform equilibrium air concentration Ce as a fn. Of chute slope α-Model data (STRAUB &ANDERSON 1958), prototype data (AIVAZYAN 1986) and equation Ce=0.9*sinα and Table of average air concentration in uniform self aerated flows

(b) Hager (1991):

Mean air concentration Cmean,

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

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

(c) Chanson (2001):

Void fraction or air concentration, C

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

$$Cmean = \frac{1}{y90} \int_{0}^{y90} Cdy \tag{2}$$

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:

$$Ce = 0.9 \sin \alpha \tag{3}$$

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:

$$\tau o P w = \rho w g A w \sin \alpha \tag{1}$$

where Pw is the wetted perimeter, ϖ 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):

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

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),

$$(Uw)o = \sqrt{\frac{8g}{fe}} \sqrt{\frac{DH\sin\alpha}{4}}$$
 (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;

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

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

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:

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

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

Table:

Slope	Ce	Y90/do	fe/f	h/l
α (degree)		_		
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.

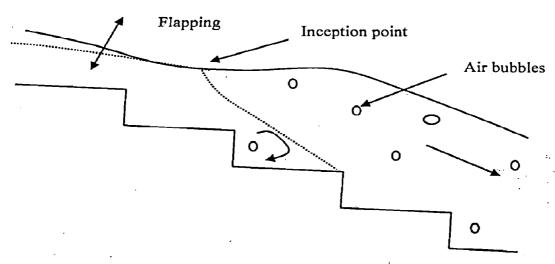


Fig.22. Rapidly varied flow region at the inception point of free surface aeration

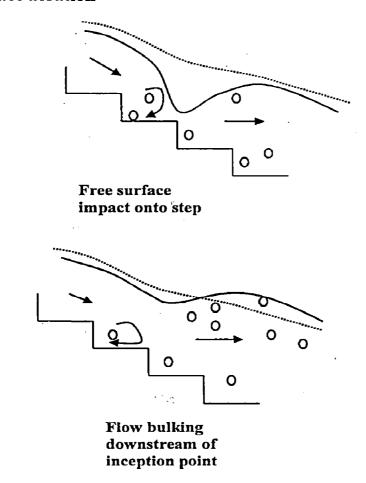


Fig.23 Rapidly varied flow region at the inception point of free surface aeration: Flow mechanisms next to the inception point

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:

$$\frac{\partial H}{\partial S} = -Sf \tag{1}$$

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 α) 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:

$$fe = f(\frac{Ks'}{D_H}; \text{Re}; \frac{Ks}{D_H}; \alpha; Cmean)$$
 (1)

where Reynold's no. 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:

$$f = f\left(\frac{Ks}{D_H};\alpha\right) \tag{2}$$

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

This equation (2) can be correlated by:

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

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;

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

The friction factors:

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

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

where the form coefficient w:

$$w = 0.9 - 0.38 \exp(\frac{-5h}{b})$$
 (4) for h/b > 0.04
 $w = 0.60$ (5) 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.

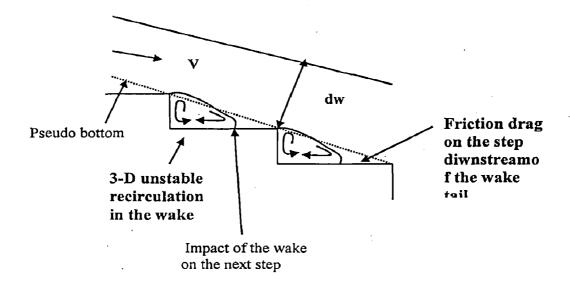


Fig.24. Flow pattern in the cavity between adjascent steps: Wake step interference sub regime in flat slopes

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.

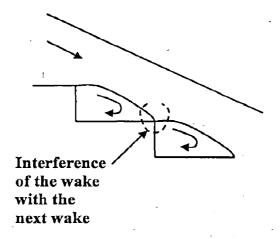


Fig.25 Flow pattern in the cavity between adjascent steps: Wake-wake interference sub regime in slope about 27 degrees

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.

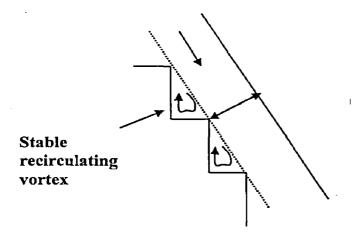


Fig.26 Flow pattern in the cavity between adjascent steps: Recirculating cavity flow sub regime in steep slope

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):

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

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):

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

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

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

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

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):

$$\frac{V90}{Uw} = \frac{1}{(1 - Cmean)} \left[\int_{0}^{1} (1 - C)y^{\frac{1}{N}} dy \right]^{-1}$$
 (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; $y = 0.23(\frac{l^4q^6}{hg^3})^{\frac{1}{12}}$; 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:

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

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:

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

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.

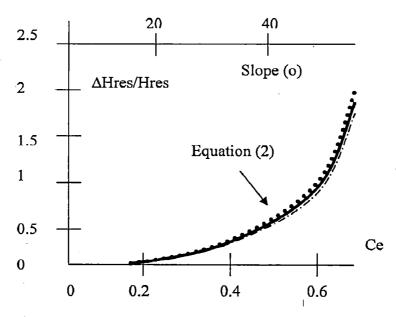


Fig. 27. $\Delta Hres/Hres$ as a function of the mean air concentration Ce and the channel slope α

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:

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

where V=q/y =velocity of flow.

Therefore $y = (\frac{qn}{\sqrt{S}})^{0.6}$ (2) where n =manning's roughness coeff.; R =hydraulic

mean radius = y for wide channel; $S = \sin \alpha = \text{slope}$ 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:

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

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

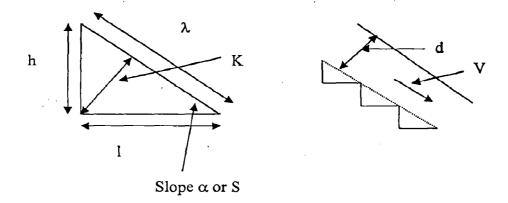


Fig 28 Step geometries

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:

$$\Delta E = Ec - Et \tag{4}$$

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 =300 and 500 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:

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

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 $\alpha = 30$ o and 50o respectively, the energy head at the spillway toe should be computed as:

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

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

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

So combining these two equations:

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

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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:0.8H	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:

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

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:

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

where Li is the length of inception point from crest:

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

The designed training wall height, h_d:

$$h_d = \eta d_{90} \tag{4}$$

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:

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

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:

$$hd = \eta y \tag{2}$$

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.

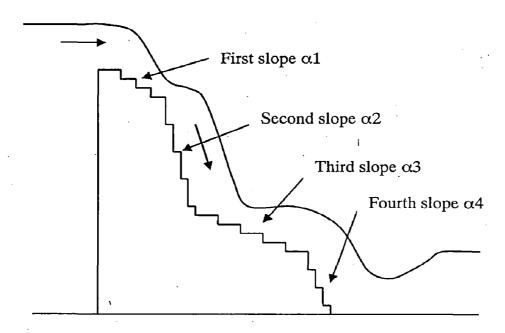


Fig. 29 Multi-slope stepped spillways: With four L-slopes

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:

Length scale ratio =
$$Lr = \frac{Lm}{Lp} = \frac{bm}{bp} = \frac{dm}{dp}$$
 etc (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)
$$\left(\frac{Ma}{Fv}\right)_{m} = \left(\frac{Ma}{Fv}\right)_{n}$$
 (1)

(ii)
$$\left(\frac{Ma}{Fg}\right)_{m} = \left(\frac{Ma}{Fg}\right)_{n}$$
 (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)

$$(v) \left(\frac{Ma}{Fs}\right)_{m} = \left(\frac{Ma}{Fs}\right)_{p} \tag{5}$$

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 similatude 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:

$$(Rn)_m = (Rn)_n$$

or,
$$\frac{\rho_{\rm m}V_{\rm m}L_{\rm m}}{\mu_{\rm m}} = \frac{\rho_{\rm p}V_{\rm p}L_{\rm p}}{\mu_{\rm p}} \tag{1}$$

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

or,
$$\frac{V_r L_r}{\mu_r} = 1$$
 (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;

$$(\operatorname{Fr})_{m} = (\operatorname{Fr})_{p}$$

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

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

or,
$$V_r = \sqrt{g_r L_r}$$
 (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,

$$(We)m = (We)p$$

or,
$$\frac{V_{m}}{\sqrt{\left(\frac{\sigma_{m}L_{m}}{\rho_{m}}\right)}} = \frac{V_{p}}{\sqrt{\left(\frac{\sigma_{p}L_{p}}{\rho_{p}}\right)}}$$
 (1)

or,
$$\frac{Vr}{\sqrt{\left(\frac{\sigma_r L_r}{\rho_r}\right)}} = 1$$
 (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 1	ratios
Description of quantities	Reynolds law	Froude law
Length	L _r	L,
Velocity	$\frac{\mu_{r}}{L_{r}}$	$L_{r}^{\frac{1}{2}}g_{r}^{\frac{1}{2}}$
Time	$\frac{L_{r}^{2}\rho_{r}}{\mu_{r}}$	$\frac{L_{r}^{\frac{1}{2}}}{g_{r}^{\frac{1}{2}}}$
Acceleration	$\frac{\mu_{\rm r}^2 L_{\rm r}^3}{\rho_{\rm r}^2}$	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	$\frac{\mu_{r}^{2}}{L_{r}^{2}}$	$\rho_r \mathbf{g}_r \mathbf{L}_r$
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.

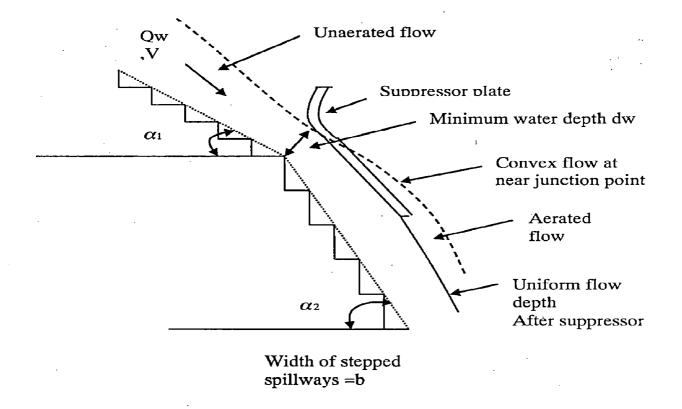


Fig.30 Multislope stepped spillways with suppressor plate: Showing the effect of the plate in making the flow with uniform depths after it.

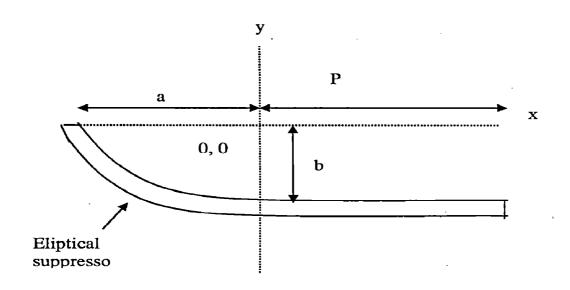


Fig 31 Section of elliptical suppressor plate (general)

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.

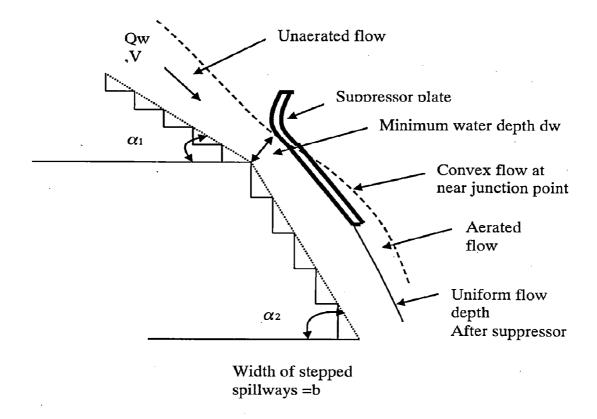


Fig.32 Multislope stepped spillways with suppressor plate: Showing the effect of the plate in making the flow with uniform depths after it.

(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;

$$a = \frac{Vw^2}{2g}\sin 2\alpha \tag{1}$$

$$b = \frac{Vw^2}{2g}\sin^2\alpha \tag{2}$$

P = straight portion

=equal to dw

= equal to a

= equal to (a+dw) (3)

For elliptical design,

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{4}$$

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

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

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

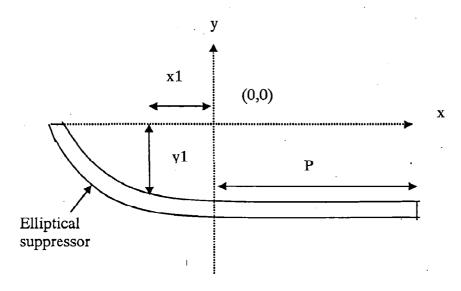


Fig. 33 Section of designed elliptical suppressor plate

(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;

$$a = \frac{Vw^2}{2g}\sin 2\alpha \tag{1}$$

$$b = \frac{Vw^2}{2g}\sin^2\alpha \tag{2}$$

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:

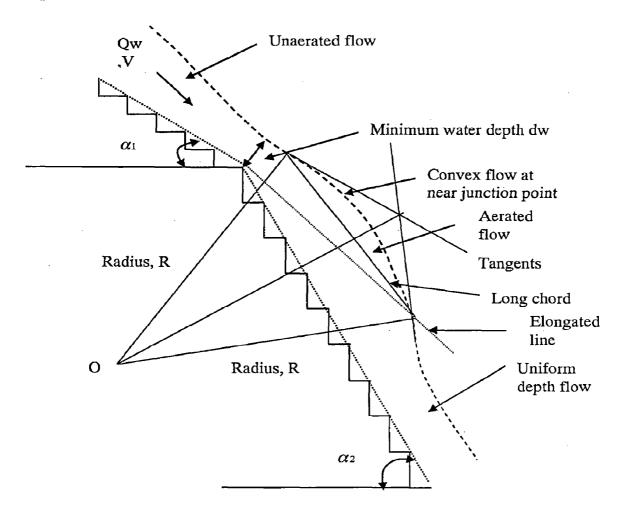


Fig.34 Multislope stepped spillways with curved (convex) flow at the junction point: Showing the elements of curve setting to find out the radius of curvature of flow.

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

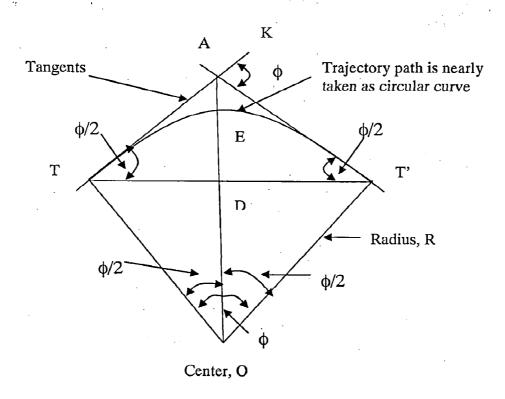


Fig. 35 Elements of simple circular curve

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

 $\angle KAT' = \phi$, 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

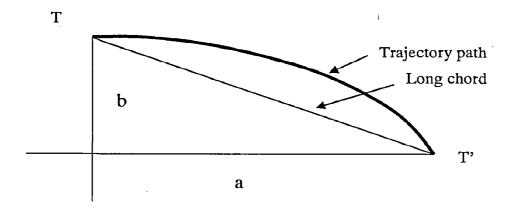


Fig. 36 Detail of convex curve at the junction point

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

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

where α is the spillway slope. And

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

From right angle triangle Δ TOD,

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

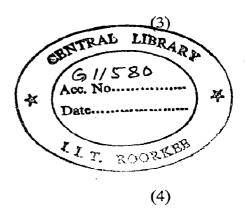
and we know TT'= 2 TD

$$= 2TO\sin\frac{\varphi}{2}$$
$$= 2R\sin\frac{\varphi}{2}$$

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



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.

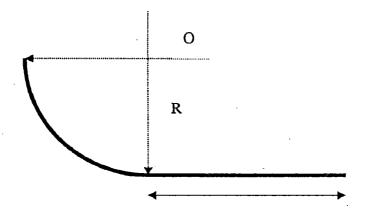


Fig. 37 Section of designed circular suppressor plate

(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.

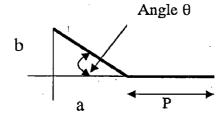


Fig. 38 Section of designed angular suppressor plate

Now the angle θ can be computed as

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

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.

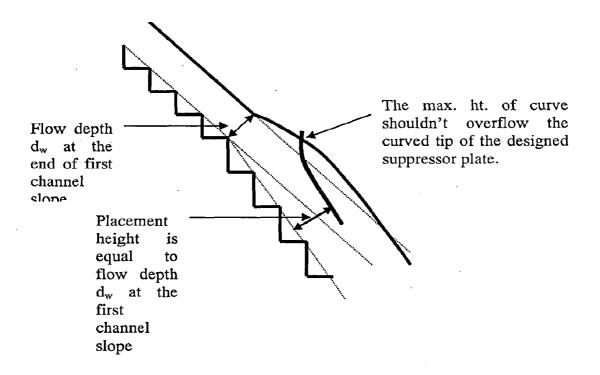


Fig.39. Placement position of suppressor plate at the convex junction point of the multislope stepped spillways

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*10⁵, 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.

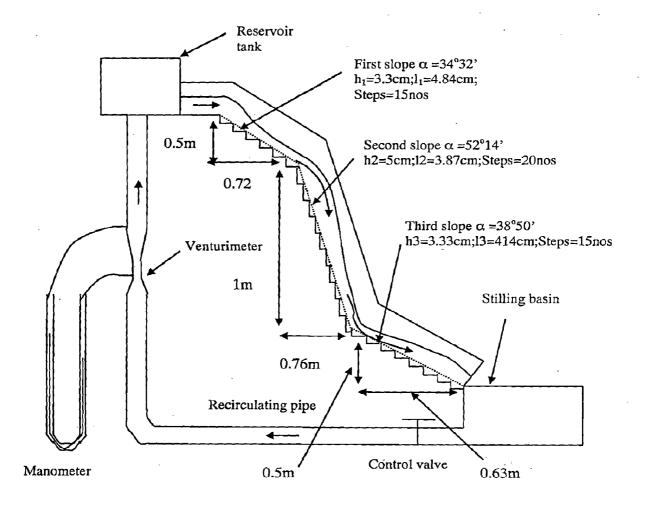


Fig. 40 Experimental set up: Multislope stepped spillways

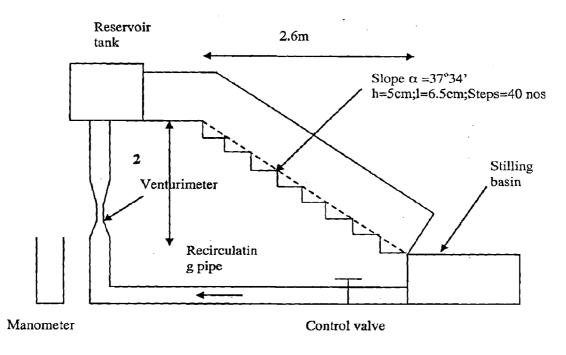


Fig.41 Experimental set up: Monoslope stepped spillways

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)
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^{-1}
^{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 - (7.854*10^{-3})^2\}
(2.827*10^{-3})^2
Q=0.0466*(x)^{1/2}
x = 460.5 * Q^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

		20										20	3	2.5	3	2.5	2.75			S	ŕ	20								
		19										19	3.8	3	3.6	2.8	3.3			100% recir.vortices		19								
	i	18			_							18	4	3	4	3	3.5			recir		18								١
		17										17	4	3	4.5	3.5	3.8		_	100%		17								1
		16										16	4.5	3.5	4.5	3.4	4					16								1
		15	33	2	3	2	2.5					15	4.5	3.5	4.5	3.5	4					15	3	2.5	3	2.5	2.8			I
	Ì	14	2.8	2	2.8	2	2.4					14	4.5	3.5	5	4	4.25					14	3	2.5	3	2.5	2.75			
	İ	13	2.6	7	2.6	2	2.3			steps.		13	5	3.5	5.5	4	4.5	-			i	13	3	2.5	3	2.5	2.75			
	ļ	12	2.6	2	2.6	2	2.3			in all s		12	5.5	3.5	5.5	3.5	4.5	-				12	4	2.5	4	2.5	3.3			1
		11	2.5	7	2.5	2	2.3			ated i		11	5.5	3.5	5.5	3.5	4.5		-	ex		11	5	3	4.5	3	3.9			
	ĺ	10	2.5	7	2.5	2	2.25			No air cavities, weak recirculating vortices were generated		101	5.5	3.8	5.8	4	4.78		_	50% rec.vortex		10	9	4	5.5	4.2	4.93		 	
		6	2.5	7	2.5	2	2.3			were		6	9	4	9	4	5	-	_	0% re		6	6.5	4	9	4.5	5.3		-	•
		8	2.4	2	2.4	2	2.2			rtices		8	6.5	5	6.5	5	5.8	-		5		8	7.5	4.5	7	S	9		-	
		7	2.3	1.9	2.3	1.9	2.1			io gi		7	7	5.5	7	5.5	6.3	-	-	 . <u>::</u>		7	7.5	4.5	8.9	5.3	9			•
		9	7	1.9	7	1.9	7			ulatir		9	7.5	9	7.5	5.8	6.7			25%air		9	∞	5	6.7	5.2	6.2	 		
1	=34°32	5	2	1.9	2	1.9	. 2			recirc	$\alpha_2 = 52^{\circ}14^{\circ}$	5	7.5	9	∞	9	6.9				=38°50'	5	7.5	5	6.5	S	9			
	- 1	4	2	1.9	2	1.9	7			veak	ς; = ζ ₂ Ο	4	7.5	9	1	5.5	6.5			S.	ļ ლ	4	7	4.5	6.5	4	5.5			
	ways	3	2	1.9	2	1.9	2			ities,	ways	3	6.5	5	6.5	S	5.8			avitie	ways	3	5.5	3.5	5	3	4.3			•
1	spilly	2	2	1.9	2	1.9	2			r cav	spillways	2	5	3.5	S	3.5	4.3			air	spillways	2	3	2.5	æ	2.5	2.8			
	pbed	1	3.5	2	3	2	2.6		46	No ai	padd	1	3.5	2	3.5	7	2.8		65	100% air cavities	pbed	1	3.5	2.5	3.5	2.5	3		50	
	Disch. Width Disch. Slope of stepped spillways a	perunit Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	_	Slope of stepped	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	1 -	1 23	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	•
	Disch.	perunit	(cum) spillw. length Max.	(b)	cum/m) Max.											0.03 Min.		•	•			-								•
	Width	of	spillw.	ways	(b m)											0.2					_									•
	Disch.	<u> </u>	(cum)	,			-			-		•				0.006		•												
<u> </u>	SN Mano	metre	reading	(x cm)			-									1.65					-	•								•
1	NS		_ <u></u>	<u></u>		 										T								.				(

CNI Man	┢	W/: 4+b	Diech	Dieck Width Diech Clone of ctorned enillerance	a pour	- Ilka	2 3/10	Cropr-	1620						ľ								
metre		- F	neminit	nermit Step nos	1 P	2			3 V	\ \	7 8	0	101	11	1	12	=	15	16	17	18	10	7
છ ો ∓ મે	<u> </u>	10	per unit	Mess	100		Щ.		7 7 7) V			\perp	1		1	7 6		2	+	9		3
Summal (according	(cmm)	winds (Min	9		ء اذ	ء اد	3 6	ء اد 					ی د	7	7	7	\dagger	+	+	+	
	_	Ways		MIII.			╗	1 1	1 1	1 L		\perp			1	7 (7 6	7	\dagger	+	+	\dagger	Т
1		(E)	cum/m) Max.	Max.	21		Ц.	_ _	7 (7	ر ر	_				30	3	3	·	+	+	+	\dagger	
				Min.	33	3	3	7	7	7	2 2	2	2	7	2	7	7	2		_	-	-	
		_		Aver.(d _{wps})	3.4	3.3	3.3	2.3	2.3 2.	3 2.	5 2.5	5 2.5	2.5	2.5	2.5	2.5	2.5	2.5			,		
	•			Inception																			
			,	length(cm)	50												-						
		-			No air c	cavit	ies,we	ak re	circul	cavities, weak recirculating vortices were	vortice	S Wer		generated	in all	steps.							
				Slope of stepped spillways	s padd	pillw	ays α ₂	2 =52°1	914														
				Step nos.	FT	\$7	3	4	5	9	2 2	6 8	10	11	12	13	14	15	16	17	18	19	20
		-	-	Max.	3.5	5.5	7	8 8	8.5 8	.5 8.	5 8	3 7.5	6.5	6.5	9	9	9	6.5	5.5	5.5	5	4.6	4
				Min.	2.5	4	9	6.5	6.5 6	6.5	7 6.5	9 9	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	3 7	6.5	6.5	9	9	9	6.5	5.5	5.5	5	4.6	4
2.95	5 0.008	8 0.2		0.04 Min.	2.5	3.8	5.5	9	6.5 6	6.5	7 6.5	5 5	5	4.5	4.5	4	4	4.5	4.5	4.2	4	4	3
				Aver.(dwps)	3	4.6	6.3	7.1	7.5 7	7.5 7.8	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)	06.						i	_					-						
					100% air	air ca	cavities		25	25%air		20%	rec.vortex	tex] 				1	100% recir.vortices	cir.vo	rtices	
				Slope of stepped spillways	s padd	pillw	ays α ₃	3 =38°	050			_											
		-		Step nos.	1	2	3	4	5	9	7 8	6 8	10	11	12	13	14	15	16	17	18	19	20
				Max.	4	3.5	Ь.	6.5	7.5 7	5 7	.5 7.5	7	7	7	9	5.5	4	4					
	-	_		Min.	3	3	3.5	4.5	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	.5 7.	5 7.5	7	7	9	9	5	4.5	4.5					
	_	_		Min.	2.5	2.5	3 4	4.5	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.	5 6.5	5 6	9	5.5	5.3	4.38	3.88	3.9			_		
				Inception																_	_		
				length(cm)	. 50																		
					100% re	recirc	ecirculating	ig vor	vortices i	in all s	steps												
																				,			

Disch. Width Disch. Slope of stepped spillways $\alpha_1 = 34^{\circ}32$ (Q) of perunit Step nos. 1 2 3 4 5 (cum) spillw length Max 5 5 4 3 3
2.5 2.
1
Min. 2.5 2.5
Aver.(d _{wps}) 3.8 3.8
Inception
length(cm) 50
Flow patt No air cavities, weak recirculating vortices were generated in
tepped
Step nos. 1 2
Max. 4 6
Min. 3 4
Max. 4 6
0.05 Min. 3 4
Aver.(d _{wps}) 3.5 5
Inception
length(cm) 90
Flow patt 100% air cavities
Slope of stepped spillways
Step nos. 1 2
Max. 5 4
Min. 4 3
Max. 5 4
Min. 3.5 2.5 3.5
Aver.(d _{wps}) 4.4 3.4 4
Inception
length(cm) 60
Flow patt 100% recirculating vortices in all steps

SN Mano	Disch	ı. Wıdt	nj Dasch.	Disch. Width Disch. Slope of stepped		spillways		$\alpha_1 = 3$	=34°32															_
metre	<u>©</u>	of	peruni	perunit Step nos.		2	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18	19	8
Ħ	reading (cum)) spillw	(cum) spillw. length	Max.	9	9	5	5	5	5	4	4	4	4	4	4	4.5	4.5	4.5		-	_	-	
(x cm)	_	ways		Min.	5	5	4	4	4	4	3	3	3	3	3	3.5	3.5	3.3	m	-	-		-	
, j		(p m)	cum/m) Max.) Max.	9	9	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	-	-	-	-	
	<u>.</u>			Aver.(dwps)	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	3.85	3.8	4.1	-	-	-	-	
				Inception		_		-	_		-				_	_		-		H	\vdash	\vdash	-	
			_	length(cm)	09									-		-		-	-	\vdash	-	\vdash	-	
				Flow patt	No air cavities, weak recirculating vortices up to	cavi	ies,w	eak r	ecircu	ılatin	g vor	ticesu	p to 1	2thst	ep&st	rong	12thstep&strong vortices onwards	s onv	/ards.					
				Slope of stepped	s padd:	spillways	ays c	$\alpha_2 = 5$	=52°14'															
				Step nos.	F	2	3	4	5	9	7	8	6	10	11	12	13	141	15	16	17	18	19	8
	_			Max.	5	7	8.5	10	11	11	11	11 1	12.5	12.5	12 1	11.5	11	10	01	9.5	9.5	8	7	6.5
		:		Min.	3.5	5.5	6.5	8	6	6	6	6	10	10	6	8.5	6.5	9	9	9	5.5	5	5	5
				Max.	5.5	6.5	8.5	9.5	11	11	11	11 1	12.5	13	12 1	11.5	11.5	10.5	9.5	2	9.5	∞	7	6.5
5.6	6.63 0.012	2 0.2		0.06 Min.	4	4.5	6.5	7.5	9.5	6	6	6	9.5	9.5	6	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	6.6	10	10	10	11 1	11.3	11	10	8	.25	7.8	∞	7.5	6.5	65	5.75
				Inception								_	_				-		\vdash	-	-	-	-	
				length(cm)	120											-	-	-	-	\vdash	-	-	-	
				Flow patt	100% air cavities	air c	vities		2	25%air	Į.	5(o% re	50% rec.vortex	×	10	100% recir.vortices	cir.vor	tices					
				Slope of stepped		spillways	ays c	$\alpha_3 = 3$	=38°50'							ı								
				Step nos.		7	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18	19	20
				Max.	9	5	5.5	6.5	6	11	9.5	10	11	11.5	8.5	∞	∞	8	7.5	-	-	_	-	
		_		Min.	5	4	4	4.5	5.5	9	9	6.5	7	7	5	4	4	4	4.5	-	-	_		
				Max.	6.5	5.5	5.6	6.5	5.5	10	10	11 1	11.5	12	6	8.5	8.5	7.5	7.6	\vdash	-	-	-	
				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	-	-	-	-	
<i>:.</i>				Aver.(dwps)	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		ļ			
				Inception						-									_	-		-		
				length(cm)	70					\dashv						-		-		-	-	-		
				Flow patt	100% recirculating vortices in all steps	recir	ulati	ov gr	rtices	in al	1 step	S							-					

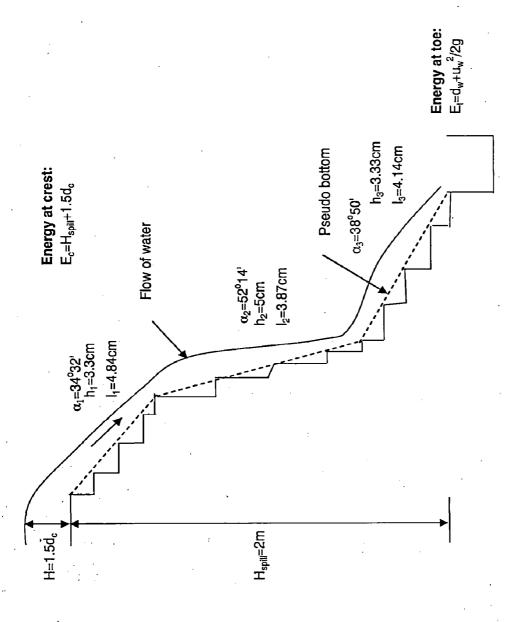
	18	T]			Ţ	Γ			2	9.5	5	10	5.5	7.5	Γ		I	Γ	20	Г	Ι		Г	_	·		\Box
		ļ	L	_	<u> </u>	_	L	<u> </u> -		i			2	L			_	_					_	_	_			L	
	15										19	9.5		10	5.5	7.5		Ì			19								
	18							1			18	101	5.5	11	9	8.1					18								
	17								ļ.		17	11	9	12	7	6	-				17		-	-			-		-
	16	1			 		-	T			16	11	9	12	7	6		-			16	-			-		\vdash		
	151	4.6	3.5	5	3.5	4.2		 	wards		15	11	7	12	7	9.3		-	rtices	!	15	7	4.5	7.5	5	9			Н
	14	4.6	3.5	5	3.5	4.15			r cavities, weak recirculating vortices up to 14th step&strong vortices onwards.		14	12	7.5	13	∞	10.1	_		100% recir.vortices		14	8	5	8	5.5	6.63	-	-	
	13	4.6	3.5	5	3.5	4.15			vortic		13	13	6	14	9.5	11.4	-		0% re		13	8.5	5.5	6	6.5	7.38	Ė		
	12	4.6	3.5	S	3.5	4.2.	-		rong		12	13	10	14	10	12	-	-	=		12	10	6.5	10	6.5	8.3 7			
	11	4.6	3.5	5	3.5	4.2	-		p&st		11	14	10	15	11	13	_	-	×		11	10	7	10	7	8.5		-	
	10	4.6	3.5	5	3.5	4.15	-		4thste		10	15	11	16	10.5	13.1			50% rec.vortex		10	10	7	101	7	8.5			
	6	5	3	5	3	4 4		 -	to 1		6	14	11	15	11 1	13 1			% rec		6	11	7.5	11	8	9.3		<u> </u>	
	8	5	3.	5	3	4	-	_	icesn		8	14	11	13	10	12		-	50		<u>∞</u>	11	7.5	11	8	.3	H		
	7	5	3	5	3	4	 -		yvort		7	13	10	13	10	11		_			7	10	6.5	11	7	6 5.			steps
	9	5	3	5	3	4	\vdash		lating		9	12	9.5	12	6	11	_		25%air		9	10	5.8	11	9	.1 8	_		a
=34°32'	5	5	3	5	3	4	-		circu	=52°14'	5	11	6 6	11	9.5	6.6			2,	=38°50'	5	6	9	6	5.5	7.4 8.			tices
	4	9	4	9	4	5	-		eak re	$\alpha_2 = 52$	4	9.5	8	10	8	8.9				3 =38	4	7	4.5	7.5	5	, 9			recirculating vortices in
spillways a	3	9	4	9	4	5			ies,w	ays o	3	8.8	Ż	6	7	8			air cavities	ays α_3	3	5	4	5	4.5	4.6			ulatin
pillw	2	9	4	9	4	5			cavit	spillways	2	7	5.5	7	5.5	6.3		_	air ca	pillways	2	5.5	4	5.5	3.5	4.6			ecirc
		7	4.5	9	4	5.4	ε	09	No air	1	1	5	3.5	5.5	3.5	4.4		120	100%	92	1	9	5	6.5	4.5	5.5		80	100%
Disch. Width Disch. Slope of stepped	perunit Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	Flow patt	Slope of stepped	Step nos.	Мах.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt 1	Slope of stepped	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt 1
Disch.	perunit		<u>Б</u>	cum/m) Max.	<u></u>	:	نينا		,						0.07 Min.			-			V. 2	<u> </u>	<u></u> ,					I	
Width	of 1	(cum) spillw, length	ways	(p m)		·									0.2					_									\dashv
Disch.	<u>©</u>	_													9.03 0.014						_		ŧ		_	•			
SN Mano	metre	reading	(x cm)		-						_				9.03				•			•		_				•	
SN		. ,													2														\exists

reading (cum) ways (9) of perunit (Step nots. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 reading (cum) ways (9) (2 m) ways (1 1 2 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1	Z	SN Mano	Disch.	Width	Disch.	Disch. Width Disch. Slope of stepped	ls padd	spillways	α_1	1=34°32	32,				1										
(vcm) spillor, length Max. 7.5 7 7 6 6 5 5 5 4.5 4.5 4.5 4.8 5 5 5 4.8 7 7 7 6 6 6 7 4 4 4 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5					perunit	Step nos.	1	7	3	4	5					L_	12		14	15	16	17	18	19	20
(\$\(\text{(Rem)}\) (\$\(\text{(Ways}\) (\$\((Wa		reading		spillw.	length	Max.	7.5	7	7	9	9			4.	4		4.8	5	iS	4.8	_	<u> </u>	-	_	
(b m) cum/m) Max. 10 9 7 6 6 5 5 4 4 4 5 5 5 5 5 6 7 7 8 6 7 8 6 8 7 8 6 8 7 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8		(x cm)			<u>(</u>	Min.	9	9	5	5	5			3.	3	3.5				3.5	-	-	-	-	
Min. 8 7 6 5 5 4 4 4 3 5 3 3 5 4 4 4 3 8 4 8 4 8 8 8 8 8 8 8 8 8 8 8 8	- 1			(p m)	cum/m	Max.	10	6	7	9	9-			4		_	S	5	5	5			-	-	
Aver.(d _{wps}) 79 73 53 55 55 45 45 45 45 4						Min.	8	7	9	5	5			3.	S.	3.5	4	4	4		-	-	-		
Flow part No size cavities, weak recirculating vortices up to 12th step&strong vortices onwards. Slope of stepped spillways 02, =52°14' Min. 38 5.5 7 8 9 10 11 12 13 13 13 13 13 13						Aver.(d _{wps})	i	.3	3	.5	.5	5 4	4			4				4.3			 		
Flow pair No air cavities, weak recirculating vortices up to 12thsrep-&strong vortices onwards.		·				Inception															T	-	\vdash	T	
Flow patt No air cavities, weak recirculating vortices up to 12thstep&strong vortices onwards.						length(cm)	09			-	-	_	_								\vdash	\vdash	\vdash		Γ
Slope of stepped spillways $\alpha_2 = 52^{\circ}14$. Step nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 Max. 55 7 8 5 10 11 13 13 13 15 15 14 14 13 13 13 13 13 13 13 13 13 13 13 13 13							No air	caviti	es,we	ak re	circul	ating 1	vortice	sup to	, 12th	step&	stron	g vorti	ces on	wards					
Step nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 11 11 11 11 11 11						Slope of ste	pped s	illwa	ys a	, =52	14'			}											
Min. 3.8 5.5 7 8.5 10 11 13 13 13 15 15 14 14 13 13 13 13 14 17 10 10 9 9 9 9 7 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6						Step nos.	1	7	3	4	5						12	13	14	15	16	17	18	19	20
Min. 3.8 5.5 7 8 9 10 11 11 12 12 11 10 9 9 9 9 7 6 6 6 6 6 8 Min. 5.5 7 9 11 11 12 13 14 17 17 15 15 14 14 13 14 13 12 11 11 11 11 11 11 11 11 11 11 11 11						Max.	5		5.	10		3 1				14	14	13	13	13	12	12	Ħ	11	11
Hax. 5.5 7 9 11 11 12 13 14 17 17 15 15 15 14 14 13 14 13 12 11 11 10 9 9 9 7 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6						Min.	i	5.5	7	8						11	10	6	6	6	6	1	७	9	9
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 6 8 Not. (dwys.) 4.6 6.3 7.8 9.1 9.9 11 12 12 14 13.8 13 13 13.3 11.3 11.3 11 11 9.8 8.8 8.5 8 1						Max.	5.5	7		_	_					15	15	14	14	13	14	13	12	H	10.5
120	5				0.08	Min.	1	5	5.5		43					11	11	6	6	6	6	7	७	9	9
100% air cavities 100% air cavities 100% air cavities 100% recirvortices 100% recirvortices 100% recircularing vortices in all steps						Aver.(d _{wps})	í	3							13.	13	13			11	11	8.6		8.5	8.38
1 120 1 120 1 120 1 120 1 100% recir.vortices stepped spillways α₃ =38°50¹ 1 00% air cavities 90%air 50% rec.vortex 100% recir.vortices 1 2 3 4 5 6 7 8 6 7 8 8.5 9 8 7 6 6 6 6 10 11 12 13 12 12 12 12 12 12 12 12 12 12 12 12 12			·· .			Inception											-			_	-	-	-		
100% air cavities 90% air 50% rec.vortex 100% recir.vortices 100% air cavities 38°Sortex 1			_			length(cm)	120				_		_						_	_			-	-	
stepped spillways α ₃ =38°50· 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 6 4.5 6 7.5 6 6.5 7 8 8.5 9 8 7 6 7 7 7 8 8 8 7 6 6 6 6							100% a	ir cav	rities.		96	%air	50%	rec.voi	rtex			100%	ecir.vo	ortices					
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=34°32'	5	5.5	4.5	5	4	4.8	-	-	ecirc	=52°14'	5	11	6	11	9.5	9.9			5	8°50'	5	10	6.5	11	7	9.8			ortice
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vays	3	7	5.5	7	5.5	6.3			ities,v	vays	8	6	7	9.5	7	8.1			air cavities	pillways	3	6.5	5	9	5	5.6			recirculating vortices in
spillways	. 2	6	4	6	7	8				spillways	2	7.5	5.5	∞	9	6.8	1			spilly	2	7	5.5	9	S	5.9			
padd	1	6	7	6	7	8		09	No air	pbed	T	5.5	4	9	4	4.9		120	100%	padd	T	∞	9	7.5	5.5	8.9		80	100%
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isch.	runit			(b m) cum/m) Max.											0.09 Min.	<u> </u>					-	<u> </u>		<u> </u>	· <u> </u>		L		
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	12	5.5	4	5.5	4	4.8			v gno		12	14	11	16	11	13		-	1		12	12.5	6	13.5	6	11		-	
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	9	9	5	9	4.5	5.3	<u> </u> -	_	lating		9	12	11	14	11	12		_	90%air		9	11	7.5	11	7.5	9.1		<u>.</u>	in all
32,	<u>v</u>	6.5	4.5 4.	9	4.5 4	5.4 5			circu	14	5	11	6	12	9.5	10		_	9	.050	5	10	7.5 7	11	7	8.9 5		_	tices
=34°32	4	8	9	∞	9	1		-	ak re	=52°14	4	11	8.5	11	8.5	9.5	-	_		3=38°50	4	7.5	9	∞	6.5	7			g vor
ıys α ₁	5	9.5	7.5	6	7	8.3		-	es,we	ıys α ₂	60	6	~	ن,	7	8.1		-	/ities	ıys α ₃	3	6.5	5.5	7	9	6.3			ecirculating vortices in
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Disch. Width Disch. Slope of stepped sp	perunit Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	Flow patt	Slope of stepped sp	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps.)	Inception	length(cm)	Flow patt	Slope of stepped sp	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps.	Inception	length(cm)	Flow patt
ch.	unit	th T		cum/m) Max.		<u>, </u>	<u>, —</u>	<u>, — </u>	, —	<u>, w</u>	100	<u>1 = </u>	<u>1 🚝 </u>	<u> </u>	0.1			<u>. —</u>		<u> </u>	101				<u> </u>				
h Dis	per	v. leng	<u>ੰ</u> ਉ		_										2		. -						_						
Widt	jo	ylliqs	ways	(p m)											0.2														
Disch.	<u>(</u>	(E	,												0.05														
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SN Mano	me	reac	<u>×</u>	, 		_									8 18														
<u> </u>					<u>L</u>									_											_				

3.6.2.3 Calculation of rate of energy dissipation and residual head:



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

Hence value of n is 0.05

n LHS RHS 0.04 4.704 3.498 0.05 3.848 3.832

Equations to be solved: Tatewar & Ingle (1996) & Knight & Mc Donald(1979) Methods $Z^{0.1}$ Ing^{0.5}=0.25+19log(λ /|\,+5.75\log($Z^{0.6}$ /\,K\) \ $Z=qn/(\sin\alpha)^{0.5}$
qw=0.02cum/0.2m=0.1cum/m

Calculations:

", 1g) ^{1/3} .	H _{spill}	2			k(m)	0.026	Solving Manning's n from eq.(1)	LHS	3.84801193	log(\/\)	0.10680811	RHS	3.83236537	Put different values of n & check whether LHS=RHS
Critical depth $(dc)=(q_w^2/g)^{1/3}$			አ (m)	0.053	cosα	0.779	ing's n f	۲	0.006 1.2788					lues of 1
al depth	d _{c (m)}	0.10	_	0.033 0.041 0.053	$\sin \alpha$	0.627 0.779	g Mann	Z	0.006	/k}		0.6/k}		ferent va
Critic	ď	0.1	0.21	0.033	۵	38.83	Solvin	п	0.05	$\{z^{0.6/k}\}$	1.862	log{z^0.6/k}	0.27	Put dif

```
Uniform velocity, uw = qw/dw

uw (mts)
2.09

Change in energy between crest and toe of spillways: AE=Ec-Et
Ec =Hspill+1.5dc Ec(m)
2.151

Et =dw+uw^2/2g Et(m)
0.270
AE(m)
1.881

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

dw(m) 0.048

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

of perunit Step nos. 12 2 2 2 2 2 15 15 15 15 15 15 15 15 15 15 15 15 15	With the use	With the use of circular suppressor	inlan 	r supp	ressor	1													ļ			ŀ		
of perunit Step nos. 1 spillw. length Max. 2.5 (b m) cum/m) Max. 2.5 Min. 2.4 Aver.(d _{wps}) 2.5 Inception 30 Flow patt No air Step nos. 1 Max. 2.5 Min. 1.5 Max. 2.5 Min. 1.5 Aver.(d _{wps}) 2.5 Flow patt 100% Step nos. 1 Max. 2.5 Min. 1.5 Min. 2.5 Min. 1.5 Aver.(d _{wps}) 2.1 Inception 1.5 Aver.(d _{wps}) 2.1 Inception 1.5 Aver.(d _{wps}) 2.1 Inception 1.5	sch	Wi	idth	Disch.	Slope of ster	ed	pillw			32.	}	}	ļ			ļ		!	}					
spillw. length Max. 2.5 (b m) Min. 2.4 (b m) Min. 2.4 Min. 2.4 Aver.(d _{wps}) 2.5 Inception 30 Flow patt No air Slope of stepped sign 2.5 Max. 2.5 Min. 1.5 Aver.(d _{wps}) 2 Step nos. 1 Inception 35 Flow patt 100% Step nos. 1 Max. 2.5 Min. 2 Min. 2.5 Min. 2.5 Min. 1.5 Aver.(d _{wps}) 2.1 Inception 1.5 Aver.(d _{wps}) 2.1 Inception 1.5	9	ot		perunit	Step nos.	ᆔ	7	6	4	5	9	<u></u>			0 11	1 12	13		14 15	5 16	17	18	19	20
(q) Min. 2.4 Min. 2.4 Aver.(d _{wps}) 2.5 Inception Bength(cm) 30 Flow patt No air Step nos. 1 Max. 2.5 Min. 1.5 Max. 2.5 Min. 1.5 Aver.(d _{wps}) 2.5 Flow patt 100% Step nos. 1 Max. 2.5 Min. 1.5 Aver.(d _{wps}) 2.1 Inception	(mm	spil	Ilw.		Max.	- : 1	5	5	۲.	<u>بر</u>	2	5.	.5	5.	5 2.5	5 2.5	5 2.5	5 2.5	5 2.5					
(b m) cum/m) Max. 2.5 Min. 2.4 Aver.(d _{wps}) 2.5 Inception 30 Flow patt No air Slope of stepped s; Max. 2.5 Min. 1.5 Max. 2.5 Nineption 35 Flow patt 100% Step nos. 1 Max. 2.5 Min. 1.5 Aver.(d _{wps}) 2.1 Inception 1.5 Aver.(d _{wps}) 2.1 Inception 1.5 Aver.(d _{wps}) 2.1 Inception 1.5		wa)		(b)	Min.	2.4	4		2	7		.5	.5	1	5 1.5	5 1.5	5 1.5	1	5 1.5	2				
Min. 2.4 Aver.(d _{wps}) 2.5 Inception 30 Flow patt No air Slope of stepped sign 1.5 Max. 2.5 Max. 2.5 Min. 1.5 Aver.(d _{wps}) 2.5 Flow patt 100% Step nos. 1 Max. 2.5 Aver.(d _{wps}) 2 Min. 2 Max. 2.5 Min. 2 Max. 2.5 Min. 2 Max. 2.5 Min. 2 Max. 2.5 Min. 1.5 Aver.(d _{wps}) 2.1 Inception Incepti		<u>e</u>	E)	cum/m)	Max.					_				7	5 2.5	5 2.5	5 2.5	5 2.5	5 2.5	16				
Aver.(dwps) 2.5 Inception 30 Iength(cm) 30 Flow patt No air Slope of stepped s Step nos. 1 Max. 2.5 Min. 1.5 Aver.(dwps) 2 Inception 1.5 Flow patt 100% Step nos. 1 Max. 2.5 Min. 1.5 Aver.(dwps) 2.1 Inception 1.5 Aver.(dwps) 2.1 Inception 1.5 Aver.(dwps) 2.1 Inception 1.0					Min.	4.					ن,	ı.	.5	1	5 1.5	5 1.5	1.5	1	5 1.5	100				
Inception 30 Flow patt No air Slope of stepped s Step nos. 1 Max. 2.5 Max. 2.5 Min. 1.5 Aver. (d _{wps}) 2 Inception 35 Flow patt 100% Step nos. 1 Max. 2.5 Min. 2.5 Min. 1.5 Aver. (d _{wps}) 2.1 Inception 1.5 Max. 2.5 Min. 1.5 Aver. (d _{wps}) 2.1 Inception 1.5 Inception					Aver.(d _{wps})	55		ll		2.4	7	7				2	2	7	2 2	<u></u>				
Flow patt No air					Inception		-		-	-	_	_				_	_	_						
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Slope of stepped stepped stepped stepped stepped step nos.						No air	caviti	es,we	ak re	circu	lating	; vorti	ces,ne	ither E	lappe	nor s	skimming flow	ng flo	ě		}			
Step nos. 1 2 3 4 5 6 7 8 Max. 2.5 4 4.5 5.5 5.5 5.5 5.5 5.5 Min. 1.5 3 4 4.5 5.5 5.5 5.5 5.5 5.5 Max. 2.5 4 4.5 5.5 5.5 5.5 5.5 5.5 Aver.(d _{wps}) 2 3.5 4.3 5 5.3 5.3 4.8 4.8 Inception Inception Step nos. 1 2 3 4 5 6 7 8 Max. 2.5 2.5 5 5 6.5 7 7 6.5 Min. 1.5 1.5 2.5 3.5 4.4 5 5.5 Min. 1.5 1.5 2.5 3.5 4.5 5.6 Aver.(d _{wps}) 2.1 2.1 3.8 5 5.8 5.7 6.1 5.5 Inception Inceptin					Slope of ster	s pad s	pillwa	ıys α	2=52	14'														
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Max. 2.5 4 4.5 5.5 5.5 5.5 5.5 5.5 5.5 5.5 5.5					Min.	1.5	3		1.5	5	5	4	L	3,	5 3.5	3		8	3 2.5	2.5	2.5	2.5	2.5	2.5
O.02 Min. 1.5 3 4 4.5 5 5 4 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 4 8 4 8 4 8 4 5 6 7 8 8 4 5 6 7 8 4 5 6 7 7 6 5 4 5 6 7 6 5 4 5 6 7 7 6 5 4 5 6 7 7 6 5 4 5 3 4 5 6 7 7 6 5 4 5 3 4 5 6 7 7 6 5 4 5 3 4 5 3 4 5 3 4 5 4 5 3 3 5					Max.	2.5	<u> </u>		5.	3	نج	٤.	5 5		9 10	10		6	8 8.5	8	7	5	5	4.5
s) 2 3.5 4.3 5 5.3 5.3 4.8 4.8 (a) 35 (a) 35 (b) 35 (b) 36 (a) 4 (b) 36 (a) 4 (b) 4 (a) 4 (b) 4 (a) 4 (b) 4 (a) 4	90		0.2	0.05	Min.	1.5	3		1.5	5	5	4		3	5 3.5		3	ю	3 2.5	2.5	2.5	2.5	2.5	2.5
100% air cavities 10%to40% vortex 100% air cavities 10%to40% vortex 1 2 3 4 5 6 7 7 8 2.5 2.5 5 6.5 7.5 7.2 7.5 7.5 7.5 2.5 2.5 4.5 5.5 6.5 7 7 6.5 1.5 1.5 2.5 3.5 4 4 5 3.5 8, 2.1 2.1 3.8 5 5.8 5.7 6.1 5.5 1.0 1.0					Aver.(d _{wps})			4.3							5 6.8	3 6.5		6 5	5.5	5.3	4.8	3.8	3.75	3.5
100% air cavities 100%to40% vortex stepped spillways $\alpha_3 = 38^050^\circ$ 2.5 2.5 2.5 7.5 7.5 7.5 7.5 2.5 2.5 3 4.5 5 4.5 7.5 7.5 2.5 2.5 3 4.5 5 4.5 7.5 7.5 2.5 2.5 4.5 5.5 6.5 7 7 6.5 1.5 1.5 2.5 3.5 4 4 5 3.5 s) 2.1 2.1 3.8 5 5.8 5.7 6.1 5.5 tool 10 10 10 10					Inception	-				-				_	_	 								
100% air cavities 10%to40% vortex stepped spillways $\alpha_3 = 38^{\circ}50^{\circ}$ 1 2 3 4 5 6 7 8 2.5 2.5 5 6.5 7.5 7.2 7.5 7.5 2.5 2.5 3 4.5 5 4.5 5 4.5 2.5 2.5 4.5 5.5 6.5 7 7 6.5 1.5 1.5 2.5 3.5 4 4 5 3.5 s) 2.1 2.1 3.8 5 5.8 5.7 6.1 5.5 tool 10 10 10 10 10 10 10					length(cm)	35				_														
tepped spillways α ₃ =38°50' 1 2 3 4 5 6 7 8 9 10 2.5 2.5 5 6.5 7.5 7.2 7.5 7.5 7 6 2.5 2.5 4.5 5.5 6.5 7 7 6.5 6 4.5 1.5 1.5 2.5 3.5 4 4 5 3.5 3 2.5 3) 2.1 2.1 3.8 5 5.8 5.7 6.1 5.5 4.9 4 1.0 10						100%	air ca	vities		%to4	0% vc	rtex	100	% reci	r.vorti	Sac							,	:
2.5 2.5 5 6.5 7.5 7.2 7.5 7.5 7 65 2.5 2.5 2.5 4.5 5.5 6.5 7 7 7 6.5 6 4.5 3.5 3 2.5 3 2.1 2.1 3.8 5 5.8 5.7 6.1 5.5 4.9 4			-		Slope of ster		pillwa			,20,						1								
2.5 2.5 5 6.5 7.5 7.2 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5					Step nos.	1	2	3	4	5	9	7			0 11	1 12	13	3 14	4 15	16	17	18	19	20
2 2 3 4.5 5 4.5 5 4.5 3.5 2.5 2.5 4.5 5.5 6.5 7 7 6.5 6 1.5 1.5 1.5 2.5 3.5 4 4 5 3.5 3 2.1 2.1 2.1 3.8 5 5.8 5.7 6.1 5.5 4.9 10 1					Max.	5.			.5	.5	.2	.5 7	.5		6 5	5 4.5	3.5		3					
2.5 2.5 2.5 4.5 5.5 6.5 7 7 6.5 6 1.5 1.5 2.5 3.5 4 4 5 3.5 3 2.1 2.1 2.3 3.8 5 5.8 5.7 6.1 5.5 4.9 10 10					Min.	. 2	2	\Box	1.5	_	1.5	Щ	3			3 2.5	5 2.5		2 2	-				
1.5 1.5 2.5 3.5 4 4 5 3.5 3 2. 2.1 2.1 3.8 5 5.8 5.7 6.1 5.5 4.9 10 10 10			-		Max.	.5				5.5	7				5 5	5 4.5	3.5		4 3.5	10				
10 10 10 10 10 10 10 10 10 10 10 10 10 1					Min.	1.5	.5			4	4	3	.5	2.	5 3	3 2.5	2.	5 2.	5 2.5	- 10				
		•	-		Aver.(d _{wps})	.1		3.8					4		4 4	3.5		3 2.88	8 2.8					
					Inception					_					_	_		_	_					
					length(cm)	10				\square								_						
Flow patt 100% recirculating vortices in all steps					Flow patt	100%	recirc	ulatin	g vor	tices	in all	steps												 !

	12 13 14 15 16 17 18 19 20	3 3 3 3	2 2 2 2	3 3 3	2 2 2 2	2.5 2.5 2.5 2.5			air cavities, weak recirculating vortices, neither nappe nor skimming flow		12 13 14 15 16 17 18 19 20	5 5.5 5.5 5.5 5.5 5.5 5.5 5.5 5.5	4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	5 5.5 5.5 5.5 5.5 5.5 5.5 5.5 5.5	5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	4.8 5 5 5 5 5 5 5					12 13 14 15 16 17 18 19 20	4.5 4.5 4.5	3 3 3 3	.5 4.5 4.5 4.5	3 3 3 3	.8 3.75 3.75 3.8		
	11 01 6	3 3	2 2 2	5 3 3	2 2	3 2.5 2.5			ther nappe n		10 11	5 5	5 4.5 4.5	5 5	5 4.5 4.5	3 4.75 4.8			100% recir.vortices		10 11	6 5.5	3.5 3.5	6 5.5	3.5 3.5	3 4.75 4.5		_
	8 9	2.5 2.5	2 2	2.5 2.5	2 2	2.3 2.3		_	rtices,neit		8	5 5	4.5 4.5	5 5	4.5 4.5	4.8 4.8					8	6.5 6	5 3.5	6.5 6.	5 3.5	5.8 4.8		
	6 7	2.5 2.5	2 2	2.5 2.5	2 2	2.3 2.3			ulating vo		1 9	5 5	4.5 4.5	5 5	4.5 4.5	4.8 4.8			10%to40% vortex	-	L 9	6.5 7	5.5 5.5	6.5	5.5 5.5	6.3		
4 =34°32	4 5	3.5 2.5	3 2	3.5 2.5	3 2	3.3 2.3			eak recirc	$\alpha_2 = 52^{\circ}14^{\circ}$	4 5	6.5 6.5	9 9	6.5 6.5	9 9	6.3 6.3				$\alpha_3 = 38^{\circ}50$	4 5	5.5 6	4.5 5	5.5 6	4.5 5	5 5.5		
illways c	2 3	.5 3.5	3 3	3.5	3 3	3.3 3.3		_	avities, w	spillways o	2 3	.5 5	4 5	.5 5	4 5	.3 5			air cavities	spillways o	2 3	3.5 5	3 3.5	5 5	3 3.5	.3 4.3		
epped sp		4 3	3	4 3	3	3,5	_	45	S S		1	3.5 4	2.5	3.5 4	2.5	3 4		40	100% a	þ	T	4 3	3	4 3	3	3.5 3		8
SN Mano Disch. Width Disch. Slope of stepped spillways α,	perunit Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps,	Inception	length(cm)	Flow patt	Slope of steppe	Step nos.	Max.	Min.	Max.	0.04 Min.	Aver.(dwps,)	Inception	length(cm)	Flow patt	Slope of steppe	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)
h Disch.	perunit	(cum) spillw. length	<u>(b)</u>) cum/m) Max.			<u>-</u>		_	·- <u>-</u> -									· 									
h. Widt	of	a) spillw	ways	(b m)		•									08 0.2	_	ī		_					_				
10 Disc	(Q)		(m)				_		<u></u>						2.95 0.008	-												
SN Man	metre	reading	(x cm)											_	3 2.											*		

Disch. Width Disch. Slope of stepped spillways $\alpha_1 = 34^{\circ}32$? (Q) of perunit Step nos. 1 2 3 4 5 6 7 8 6 (cum) spillw. length Max. 5 5 4 3 3.5 3.5 3.5 3.5 (b m) cum/m) Max. 5 5 4 3 3 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 1nception length(cm) 45			pillways $\alpha_1 = 34^{\circ}32$ 2 3 4 5 5 4 3 3 3 2.5 2.5 2.5 5 4 3 3 3 3 2.5 2.5 2.5 4 3.3 2.8 2.8 cavities, weak recirr pillways $\alpha_2 = 52^{\circ}14$ 2 3 4 5 4.5 5 6 6	ays $\alpha_1 = 34^{\circ}32$ 3 4 5 4 3 3 2.5 2.5 2.5 2.5 2.5 2.5 2.5 3.3 2.8 2.8 es, weak recirc ays $\alpha_2 = 52^{\circ}14$	1, =34°32 4 5 4 5 3 3 3 3 2.5 2.5 2.8 2.8 2.8 2.8 2.8 2.8 2.8 4 5 4 5 6 6	2.5.5.3.3.3.5.5.5.5.5.5.5.5.5.5.5.5.5.5.	[- <u></u>	3.5 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3	3.5.5.2.2.2.2.5.3.3.3.3.3.3.3.3.3.3.3.3.	1	68		2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3	878 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8	5.5	3 2 2 2 3 3 2 2 2 3 3 3 3 3 3 3 3 3 3 3	16 16 16 5.5	17	18 18 5.5	91 19 5.5	20 20 20 25 25 25 25 25 25 25 25 25 25 25 25 25
0.0	Min. Max 0.05 Min. Aver	Min. Max. Min. Aver.(d _{wps})		4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4	2,4 4,5 8,4 8,8 8,9 8,9 8,9 8,9 8,9 8,9 8,9 8,9 8,9	5.5 6 5.5 5.8	5.8 5.8 5.8 5.8 5.8 5.8 5.8 5.8 5.8 5.8	8 P P P	3 3 3 3	2 2 2 2	10	5.5 5.8 5.65 5.65 5.8 5.8 5.8 5.8 5.8 5.8 5.8 5.8 5.8 5.	5.5.8 5.7 5.7 5.7 5.7 5.7 5.7 5.7 5.7 5.7 5.7	5.5 5.8 5.8 5.8 5.5 5.5 5.7 5.65	8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8	\$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$ \$	5.3 5.3	5.5 5.3 5.3	5.5 5.3 5.3	5.5 5.25 5.25	5.5 5.5 5.25
	의[표] 55] 5		40 100% air cavities pped spillways α	air cavitii	vities ays α_3		40%to8(40%to80% vortex \$8°50'	ortex	100	100% recir.vortices	ir.vort	tices	- -	_	_ 	1 7	1	100	101	700
	ō ∑ ∑ ∑	Max. Min.	1 2 6 4	1 4 W 2	\bot		6.5	9 7	- 10 0 4	9	2 2 2	1 1 7 1	4					"	OT		3
	<u> </u>	Min. Aver.(d _{wps})		3.5 3 4	0 4 5	5.3	5.5		<u> </u>	0 0 0	0 0 00	9 W W	6 6 6 4.5 4.5 5.3 5.3	3 4.5	ų ω 4.	5 3.5 4.5					
	됩힐	Inception length(cm)	5				H														
	臣	Flow patt	100% r	ecirc	ulatin	lg voi	recirculating vortices in	in all	all steps			-									

	20	Γ	Γ				Γ	Ţ	Γ	П	8	6.5	5	6.5	3	15	Γ		I —	Γ_	18	1	Г				Ė	Ţ	\Box
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	18										18	6.5	5	6.5	5	5.8					18							1.0	
	17										17	6.5	5	6.5	S	5.8					17							1	
	16										16	6.5	5	6.5	5	5.8					16								
	15	4.5	3	4.5	co.	3.8					15	9	5	9	5	5.5	Г				- 15	9	4.5	9	4.5	5.3			П
	14	4.5	3	4.5	E.	3.75					14	9	5	9	5	5.5	-				14	9	4.5	9	4.5	5.25			
	13	4.5	3	4.5	3	3.75	-				13	9	5	9	5	5.5	\vdash				13	9	4.5	9	4.5	5.25	-	-	
	12	4.5	8	4.5	3	3.8	-		1		12	9	5	9	5	5.5	-				12	8.9	5	7	5	9	-	-	
	11	4	3	4	3	3.5	-	-			11	9	5	9	5	5.5	-		rtices		111	7	S	7	5	9	-		
	10	4	3	4	3	3.5	-				10	9	5	9	5	5.5	 -	-	cir.vo		10	7	5	7	3	9	-		
	6	4	3	4	3	3.5	-				6	9	5	9	5	5.5	\vdash		100% recir.vortices		6	7	5.5	7	5.5	6.3	_		
	8	4	3	4	3	3.5	-	_	ices		8	9	5.5	9	5.5	5.8			1(8	7	5.5	7	5.5	6.3		_	
	7	4	3	4	3	3.5	-	_	g vort		7	9	5.5	9	5.5	5.8			ortex		7	7	5.5	7	5.5	6.3			steps
	9	5	4	5	4	4.5	-	_	lating		9	9	5.5	9	5.5	5.8		_	40%to80% vortex		9	6.8	5.5	8.9	5.5	6.2			in all
=34°32'	5	5	4	5	4	4.5	-		ecircu	=52°14'	5	5.5	5.5	5.5	5.5	5.5			0%to8	=38°50'	5	6.5	5	6.5	5 ;	5.8	_		rtices
x ₁ =3,	4	5	4	5	4	4.5	-		air cavities, weak recirculating vortices	$\alpha_2 = 5$	4	5.5	5.5	5.5	5.5	5.5				α3 =3{	4	9	5	9	5	5.5			1% recirculating vortices in all
ays	3	9	4	9	4	5	L		ies,w	ays c	3	5.5	5.5	5.5	5.5	5.5			vities		3	5	4	5	4	4.5		-	ulatii
spillways α_1	2	9	5	9	5	5.5			cavit	spillways	2	4.5	4.5	4.5	4.5	4.5			air ca	spillways	2	4.5	4	4.5	4	4.3			recirc
뎟	1	9	5	9	5	5.5		20	No air		1	4.5	3	4.5	3	3.8		40	100% air cavities	P	1	5.5	4	5.5	4	4.8	-	5	100%
Disch. Width Disch. Slope of steppe	perunit Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt	Slope of steppe	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt	Slope of steppe	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt
isch.	:runit	ngth		cum/m) Max.											0.06 Min.	• •				_									
di D	ŭ	(cum) spillw. length	(g) s/											_	0.2			_											\dashv
W.	Jo	spil.	ways	(b m)																						. .			_
Disch	<u> </u>	(cum)													0.012														
ano	metre	reading	(x cm)				_	-			-				6.63														
SN Mano	Ē	ĕ	<u>×</u>	_					_						2														\dashv
[6]				نـــــــــــــــــــــــــــــــــــــ									_																

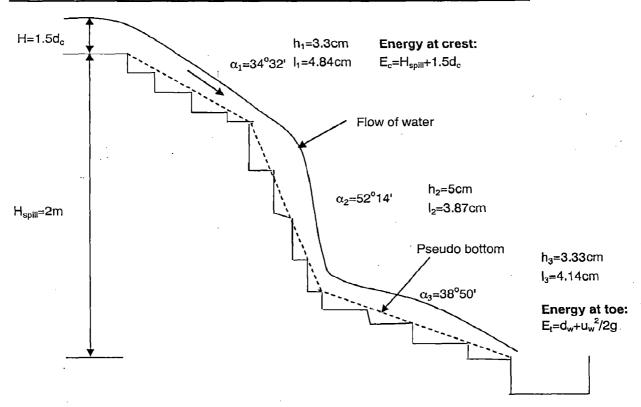
	20					Γ	Π			Γ	200	6.5	5.5	6.5	5.5	9	<u> </u>				707								
	19	\vdash		-	╁	<u> </u>	<u> </u>				19	6.5	5.5	6.5	5.5	9					19				-				
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	13	4	3	4	3	3.5					13	6.5	5.5	6.5	5.5	9					13	7	5.2	8.9	5	9			
	12	4	3	4	3	3.5					12	9	5.5	9	5.5	5.8	:				12	7	5.2	7	5	6.1			
	11	3.5	3	3.5	3	3.3					11	9	5.5	9	5.5	5.8					11	7.5	5.5	7.5	5.5	6.5			
	10	4	C	4	3	3.5					10	9	5.5	9	5.5	5.75					10	8	9	8	9	7	·		
	6	4	c	4	ς,	3.5					6	9	5.5	9	5.5	5.8			ွ		6	8	9	8	9	7	-		
	~	4	3	4	3	3.5			tices		8	9	5.5	9	5.5	5.8			100% recir.vortices		∞	8	9	8	9	7			S
	7	5	3	5	33	4	_	_	g vor		7	9	5.5	9	5.5	5.8	_		ecir.v		7	8	9	8	9	7			step
	9	5	3	5	3	4	-		ılatin		9	9	5.5	9	5.5	5.8	,		00% 1		9	7	5.5	7	5.5	6.3		-	in al
=34°32'	S	۲۷.	3.5	5	3.5	4.3			ecirc	=52°14'	5	9	5.5	9	5.5	5.8			1	=38°50'	5	6.5	5.5	6.5	5.5	9			rtices
		9	4	9	4	5			cavities, weak recirculating vortices	$\alpha_2 = 5$	4	5.5	5.5	5.5	5.5	5.5		lacksquare	ortex	α ₃ =3{	4	9	5	9	5	5.5			recirculating vortices in all steps
spillways α,	<u>, E</u>	9	4	9	4	5	_		ies,w	ays c	3	5	5	5	5	5			40% vortex	ays o	3	5	4	5	4	4.5			ulati
nil w	7	9	4	9	4	5				pillw	2	4.5	4.5	4.5	4.5	4.5			air 4	pillways	2	4.5	4	4.5	4	4.3			recirc
ned s	<u> </u> =	6.5	4.5	6.5	4.5	5.5		50	No air	s pad	1	4	3.5	4	3.5	3.8		30	100%	G 2	1	5	4	5	4	4.5			100%
Disch. Width Disch. Slope of stepned	nos.				·	Aver.(d _{wps})	tion	length(cm)		Slope of stepped spillways	nos.					Aver.(d _{wps})	tion	length(cm)		Slope of stepped	nos.					Aver.(dwps)	tion	n(cm)	
Slop	Step	Max.	Min.	Max.	Min.	Aver	Inception	lengt	Flow patt	Slope	Step nos.	Max.	Min.	Max.	Min.	Aver.	Inception	lengt	Flow patt	Slope	Step nos.	Max.	Min.	Max.	Min.	Aver.	Inception	length(cm)	Flow patt
Disch.	perunit Step nos.	ength	<u></u>	cum/m) Max.							-				0.07 Min.										`]		اشت		
Width	of p	(cum) spillw. length	ways ((b m)		<u> </u>									0.5		,									· 			
Disch.	<u> </u>		<u></u> -						-		-	_			0.014														\dashv
SN Mano		reading ((x cm)		_										9.03					-				•	-				\dashv
E	_=	<u> </u>	<u>ت</u>	\dashv			-	,							9	•													\dashv

	8	Ι			Γ	Γ-	_	<u> </u>	Π	_	ाठ	[V]	5	3	2	9	$\overline{}$	_	-	_	20		Γ.		Γ		Γ	· ·	
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	18										18	6.5	5.5	6.5	5.5	9					18								
	17										17	6.5	5.5	6.5	5.5	9					17							-	
	16								1		16	6.5	5.5	6.5	5.5	9			1		16								
	15	4.5	3.5	4.5	3.5	4					15	6.5	5.5	6.5	5.5	9					15	7.5	5.5	7.5	5.5	6.5			
	14	4.5	3.5	4.5	3.5	4					14	6.5	5.5	6.5	5.5	9					14	7.5	5.5	7.5	5.5	6.5			
	13	4.5	3.5	4.5	3.5	4					13	6.5	5.5	6.5	5.5	9					13	7.5	5.5	7.5	5.5	6.5			
	12	4.5	3.5	4.5	3.5	4					12	9	5.5	9	5.5	5.8	-				12	8	9	7	9	8.9			
	11	4.5	3.5	4.5	3.5	4					11	9	5.5	9	5.5	5.8					11	8	6.5	8	6.5	7.3			
	10	4.5	3.5	4.5	3.5	4				-	10	9	5.5	9	5.5	5.75					10	8	6.5	∞	6.5	7.25			
	6	4.5	3.8	4.5	3,8	4.2					6	9	5.5	9	5.5	5.8					6	8	6.5	8	6.5	7.3			
	8	5	4	5	4	4.5			ir cavities, strong recirculating vortices		8	9	5.5	9	5.5	5.8			Si		8	7.5	9	7.5	9	8.9			SC
	7	5	4	5	4	4.5			ing vo	·	7	9	5.5	9	5.5	5.8			20%vortex 100% recir.vortices		7	7	5.5	7	5.5	6.3			100% recirculating vortices in all steps
_	9	5	4	5	4	4.5			culati		9	9	5.5	9	5.5	5.8			recir.		9	7.5	5.5	7.7	5.5	9.9	_		s in a
=34°32	5	9	5	9	5	5.5			recir	=52°14'	5	9	5.5	9	5.5	5.8			100%	=38°50	5	6.5	5	6.5	5	5.8			ortice
	4	9	5	9	5	5.5			trong	$\alpha_2 = 5$	4	5.5	5.5	5.5	5.5	5.5			ortex	ၓ	4	9	4.5	9	4.5	5.3			y gri
spillways α_1	3	7	5	7	5	9			ities,s	spillways	3	5	5	5	5	5			20%v	spillways	3	5	4	5	4	4.5			rculat
spill	2	7	9	7	9	6.5			r cav	spilly	2	4.5	4.5	4.5	4.5	4.5			air	spilly	2	5.5	4	5.5	4	4.8			reci
padd	1	8	9	8	9	7		50	No ai		1	4	3	4	3	3.5		30	%06	pbed	1	6.5	4.5	6.5	4.5	5.5			100%
Disch. Width Disch. Slope of stepped	perunit Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)		Slope of stepped	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	Flow patt	Slope of stepped	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	$\overline{}$
Disch.	erunit	ength	<u></u>	cum/m) Max.					<u> </u>						0.08 Min.	•	·		•	_ _			<u> </u>	. 1	ر ت	. 7			
Width	of I	(cum) spillw. length	ways ((b m)											0.2				_	_				-			_		\neg
Disch.	<u> </u>													_	11.8 0.016														
SN Mano	metre	reading	(x cm)		i						-			-	11.8		-												
NS	<u> </u>	<u> </u>	<u> </u>		-									-,	7	_									_				\dashv
									_								_			_									

	20									[20	رب ا	1	3	6.5	Ŋ		Г			20		_			Ė			
												8.5	6.7	8.5		7.55					·								
	19										19	8.5	6.7	8.5	6.5	7.55					19					ĺ			
	18										18]	8.5	6.7	8.5	6.5	7.6		ì			18								
	17							-			17	8.5	6.7	8.5	6.5	9.7					17					-			
	16				_						16	8	9	8	9	7					16								
	15	5	4	5	4	4.5					15	8	9	8	9	7	•				15	7	5.5	7	5.5	6.3			
	14	5	4	5	4	4.5				-	14	8	9	8	9	7		-			14	7	5.5	7	5.5	6.25			
	13	5	4	5	4	4.5	_				13	8	9	8	9	7	_				13	7	5.5	7	5.5	6.25 6		-	
	12	5	4	5	4	4.5					12	8	9	∞	9	7	-	 			12	7.5	5.5	7.5	5.5	6.5 6	•		
	11	5	4	5	4	4.5					11	∞	9	8	9	7		_			11	8	5.5	∞	5.5	6.8		_	
	10	5	4	5	4	4.5		<u>. </u>			10	8	9	∞ ∞	9	7					10	8.2	6.2	8.5	6.2	7.28			
	6	5	4	5	4	.5	-				6	∞	9	8	9	7	_				6	8.2	6.2	8.5	7	7.3 7.			
	8	5	4	5	4	5 4			ices		8	6	4.	6	4.	7.2					· ∞	.5	6.5	8.5	6.5 6	7.5			
	7	5	4	5	4	5 4			y vort		7	7	5 5	7	5.5	6.8 7			ļ '		7	8 6	6.5 6	8.8	5.5 6	7.5 7			steps
	9	5	4	5	4	5.	_		lating		9	7	9 9	7	9	6.5 6					.9	6	6.5 6	8	6.5 5	7.8 7			ın all
32'	5	5	4	5	4	5.			circu	14.	5	٦.	5.5	6.5	3.	9 9		_	rtices	20,	5	7.5	9 9	7.5	9 9	∞			ices i
=34°32	4	7	.5	7	5.	.3 4			ong re	=52°14'	4	6 6.	5.	9 9	5.	∞.			cir.vo	=38°50'	4	7 7	5	7 7	5	6 6.			y vor
pillways α ₁	3	7	5 5.	7	5.5	.3 6	_		cavities, strong recirculating vortices	ys α ₂	3	7.	5 5	5.	5 5	.3			100% recir.vortices	ys α ₃	3	9	8.	9	.5	.3			recirculating vortices in all steps
illwa	2	6	7 5	6	7 5	9 8			avitie	pillways	2	5	5.	5 5	4.5	4.5 5	_	-		pillways	7	.5	5 4	<i>ن</i> ہ	5 4	.8		_	scircu
ed sp	1	6	7	6	7	8		20	No air c		1	4.5 4	4.5 4	4.5 4	4.5 4	4.5 4		30	80% air	ed sb	1	7.5 6	5.5	7.5 6	5.5	6.5 5			100% re
tepp	<u> </u>	_				(3				tepp			4	4	4	<u> </u>		_		tepp	_	7	5	7	5	_			
Disch. Width Disch. Slope of stepped s	perunit Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps	Inception	length(cm)	Flow patt	Slope of stepped s	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt	Slope of stepped s	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	Flow patt
sch.	runit	ngth		(b m) cum/m) Max.							1				0.09 Min.			٠.			,						,		
1th D	<u>g</u>	(cum) spillw. length	(b) s	n) Cn									_		0.2			-							•				\dashv
Wic	of	Spill	ways	(b n																									_
Disch	<u> </u>	(cmm)													0.01														
	metre	reading	(x cm)							1					14.92 0.018	•		-			,								\neg
SN Mano	Ĕ	Tea	<u>×</u>												8														\dashv
S					L																								

Z	Mano	Disch.	Wid	th Disch	h. Sic	SN Mano Disch. Width Disch. Slope of stepped	pped	spillways	ays ($\alpha_1 = 34$	=34°32'														
	metre	<u> </u>	oţ	perun	nit Ste	perunit Step nos.	1	2	3	4	5	9	7	8	9 1	10 1	1 12	2 13	14	15	16	17	18	19	20
	reading		spilly	(cum) spillw. length	h Max.	1X.	9.5	10	6	8	9	9	6 5.	5 5.	5.5	5.5	5.5	5.5	5.5	5.5					
	(x cm)		ways	<u></u>	Min.	n.	8	8	7	9	5	5	5	4	4	4	4	4	4	4					
			(p m)	cum/m) Max.	m) Ma	ıx.	10	10	6	8	9	9	6 5.	5 5.	5.5	5.	5 5.5	5.5	5.5	5.5					
					Min.	n.	8	8	7	9	5	5	5	4	4	4	4	4	4	4					_
		,		_	Av	Aver.(dwps)	8.9	6	8	7	5.5 5	5 5	.5 4	8:	4.8 4.75	4	8.4.8	3 4.75	4.75	4.8					
					Inc	Inception	,			-		-		<u> </u>	_	_		_	_	_					
					len	length(cm)	55			-	_			_	_	_			_						
					Fic		No air		ties,st	rong	ecirc	ılatin	cavities, strong recirculating vortices	ces											
					SI	Slope of stepped	pado	spillways		$\alpha_2 = 52$	=52°14'								:	ļ					
					Ste	Step nos.	1	2	3	4	5	9	7	8	9	10 1	1 12	13	14	15	16	17	18	19	20
					Max.	ıx.	4.5	4.5	5.5	9	6.5 6	3.	7	7	7 6.	5	5 6.5	7	7.5	7.5	7.5	7	7.5	7.5	7.5
					Min.	n.	4	5	5	5.5	5.5 5	5 5	9.	.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.	ıx.	5.5	4.5	5.5	9	9	9	9	9	9	5	5	5	5	5	5.5	4	5	5	5
9	18.42	0.02	0.7		0.1 Min.	'n.	4.5	4.5	5	5.5	5	5	5	5	5	4	4 4	4	4	4	4.5	5	4	4	4
					Av	Aver.(dwps)	4.6	4.6	5.3	5.8	5.8 5.	.8	.9 5.	.9 5.	9 5.2	.25 5.	3 5.3	3 5.38	5.5	5.5	5.8	5.3	5.5	5.5	5.5
					Inc	Inception						-	_			_	_	_							
					len	length(cm)	20									_			_						
					Fio	Flow patt	25% a	ir	00% 1	ecir.v	100% recir.vortices							1							
			_		Slo	Slope of stepped s	ped	spillways	ays c	$\alpha_3 = 38$	=38°50'														
				_	Ste	Step nos.	1	2	3	4	5	9	7	8	9 1	0 11	1 12	13	14	15	16	17	18	19	20
					Max.	ıx.	8.5	7	6.5	6.5	7.5 8.	5 9	.5	10 1	11 1	12 1	13 13	3 11.5	11	11					
					Min.	n.	6.5	5	5	5	5.5 5.	.5 6	.5	7 7.5	.5	8 8.5	5 8	7	7	7					
					Max.	×.	∞	7	9	6.5	6.5	7	8 8.	.5 8.5		8.6 8.7	7 9	7.5	7.5	7.5					
<i>,</i>			_		Min.	n.	5.5	5	4.5	5	5 5.	.5	6 6.	5 6.	5	6.8 6.8	8 7	5.5	5.4	5.4					
					Av	Aver.(dwps)	7.1	9	5.5	5.8	6.1 6.	9	7.5	8 8.	.4 8.85	1.6 5.1	1 9.1	7.88	7.73	7.7					
	•				Inc	Inception	ı										_								
	-	2.			len	length(cm)					$\left - \right $					<u> </u>									
\exists					윤	Flow patt	100%	recir	ulati	lg vo	recirculating vortices in all steps	in all	steps					1							

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 $\alpha = 38^{\circ}50^{\circ}$ and step sizes are taken.

Data:

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

Equations to be solved:

$z^{0.1}/ng^{0.5} = 0.25 + 19\log(\lambda/1) + 5.75\log(z^{0.6}/k) \dots \dots \dots \dots (1)$
$z=qn/(sina)^{0.5}(2)$
$y={qn/(sina)^{0.5}}^{0.6} \dots
v=q/y
k=h*cosa
$\lambda = (h^2 + l^2)^{0.5} \dots
$E_c = H_{spill} + 1.5 d_{c$
$E_t = d_w + u_0^2 / 2g \dots \dots \dots \dots (8)$
$\Delta E = E_c - E_{t_{m_1, m_2, m_3, m_4, m_4, m_4, m_4}}(9)$

Calculations:

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

q_w		$\mathbf{d}_{\mathrm{c}\;(\mathrm{m})}$		H _{spill}
0.1		0.10		2
h		1	λ (m)	
0.0	33	0.04	0.052	
α		$sin\alpha$	$\cos \alpha$	k(m)
38.	83	0.627	0.779	0.026
Sol	ving	Mann	ing's n	from eq.(1)
		,	0	
n		z	λ/Ί	LHS
		z	$\lambda / 1$	
n 0.0		z 0.006	$\lambda / 1$	LHS
n 0.0	5 0.6/	z 0.006	$\lambda / 1$	LHS 3.84802584
n 0.0 {z^ 1.8	5 0.6/ 62	z 0.006	$\lambda / 1$	LHS 3.84802584 log(λ/l)
n 0.0 {z^ 1.8	5 10.6/ 62 {z^(z 0.006 k}	$\lambda / 1$	LHS 3.84802584 log(λ/l) 0.11273541

```
Put different values of n & check whether LHS=RHS
         LHS
                 RHS
0.04
         4.704
                 3.498
        3.848 3.832
0.05
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
uw (m/s)
2.09
Change in energy between crest and toe of spillways: ∆E=Ec-Et
Ec =Hspill+1.5dc
                         Ec(m)
                         2.151
Et = d_w + u_w^2 / 2g
                         Et(m)
                         0.270
                         \Delta E(m)
                         1.881
Energy dissipated=\Delta E/Ec*100 =
                                           87.4 %
Residual head =Et =0.27m
(b) Chanson (1994) methods:
\alpha = 38^{\circ}50'; h = 3.33cm; l = 4.14cm.
Average equilibrium air concentration (Ce) =0.9*\sin \alpha
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
0.436
        -0.05
                 0.246 -0.1278747
                 e<sup>-x</sup>
        ex
                         ex-e-x
f
                                       ex+e-x
1
        0.88
                 1.136 -0.256447
                                       2.0164
fe
Uniform aereted flow depth, dwu = dc^* \{fe/(8\sin\alpha)\}^{1/3}
8sina dw
5.014 0.045
Characteristic depth (bulk depth), d_{90}=dc^*\{fe/(8(1-Ce)^3\sin\alpha)\}^{1/3}
8(1-Ce)<sup>3</sup>sina
                 d<sub>90</sub>(m)
0.415
                 0.102
But it has come 0.065m from experiment. So questionable?
Rate of energy dissipation;
\Delta H/Hmax = 1 - \frac{(fc/8sina)1/3*cosa+Ec/2(fc/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
∆H/Hmax
0.853
ie, rate of energy dissipation is 85.30%
Residual energy, Hres:
Hres/dc = (fe/8sina)^1/3 + Ec/2(fe/8sina)^-2/3
H<sub>res</sub>(m)
0.316
ie, energy lost by stepped spillways is:
```

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

H_{loss}(m) 1.835

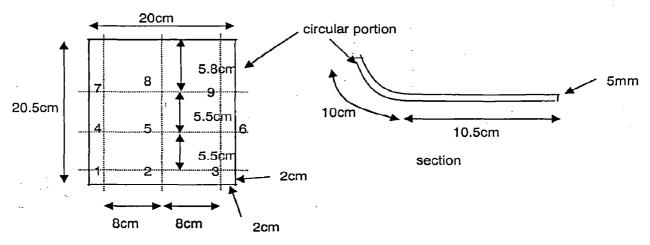
Result:

α	h	1	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:



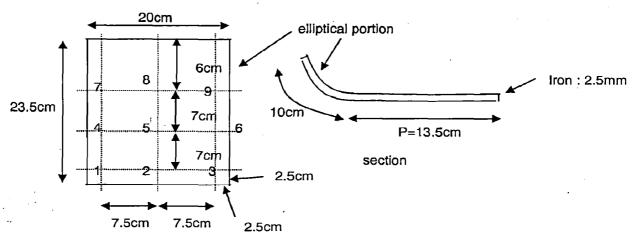
plan of circular suppressor plate

Uplift water pressure at circular suppressor plate:

Disch.	Points	1	2	3	4	5
(m3/s)	Piezom.					
	head (cm)	2.2	-2.5	2.7	1.5	0.5
0.004	Points	6	7	8	9	
	Piezom.					
	head (cm)	4.1	1	0.7	8.0	
	Points	1	2	3	4	5
- !	Piezom.					
0.006	head (cm)	2.4	-2.5	2.7	1.5	0.6
1	Points	6	7	8	9	
	Piezom.					
· .	head (cm)	4.1	1	1.5	1.7	
	Points	1	2	3	4	5
	Piezom.					
0.008	head (cm)	2.5	-2.5	2	1.5	0.5
!	Points	6	7	8	9	
l i	Piezom.					
	head (cm)	4.2	0.7	1.4	_1.5	
	Points	1	2	3	4	5
0.01	Piezom.					
	head (cm)	2	-2.5	2.4	1.5	0.5
1	Points	6	7	_8	9	
1	Piezom.					
	head (cm)	4.1	1	1.5	1.5	

	Points	1	2	3	4	5
0.012	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	
	Points	1	2	3	4	5
0.014	Piezom.					
	head (cm)	4.3	-2.1	2.1	1	0.5
	Points	6	7	.8	9	
	Piezom.				٠	
	head (cm)	4.5	0.7	1.5	1.5	
	Points	1	2	3	4	5
0.016	Piezom.					
	head (cm)	4.5	-2.3	1.7	1.7	0.7
, i	Points	6	7	8	9	
	Piezom.					
	head (cm)	4.5	0.8	1.5	1.4	
	Points	1	2	3	4	5
0.018	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	
	Points	1	2	3	4	5
0.02	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):



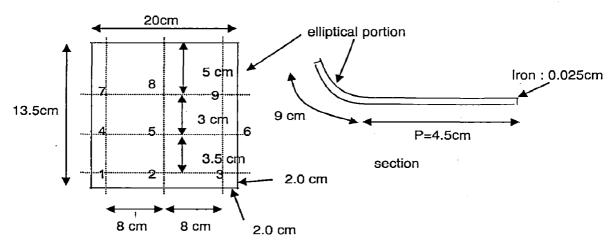
plan of elliptical suppressor plate

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

Disch.	Points	1	2	3	4	5
(m3/s)	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
	Piezom.					
0.008	head (cm)	-1	- 5.8	-2.9	1.8	1.9
	Points	6	7	. 8	9	
1	Piezom.					
	head (cm)	2	0.5	1	0.5	: !
	Points	1	2	3	4	5
0.01	Piezom.		:	. 4		
	head (cm)	-1	-6	-3.2	1.8	1.8
]	Points	6	7	8	9	
	Piezom.					
<u>L</u>	head (cm)	1.8	0.5	1	0.5	

Points	1	2	3	4	5
Piezom.			ž.		
head (cm)	0.9	-6	-3.2	2	2
Points	6	7	, 8	9	·
Piezom.			,		
head (cm)	2.1	0.5	1	0.5	
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	
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	•
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	
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	
	Piezom. head (cm) Points	Piezom. -0.9 Points 6 Piezom. -0.9 head (cm) 2.1 Points 1 Piezom. -1 head (cm) -1 Points 1 Piezom. -1 head (cm) -1 Points 6 Piezom. -1 head (cm) -1.5 Points 6 Piezom. -1.5 Points 1 Piezom. -1.5 Points 1 Piezom. -1.5 Points 1 Piezom. -1.5 Points 1 Piezom. -1.5 Points 6 Piezom. -1.5 Points 6 Piezom. -1.5	Piezom. -0.9 -6 Points 6 7 Piezom. -1 0.5 Points 1 2 Piezom. -1 -6.5 Points 6 7 Piezom. -1 -6.5 Points 1 2 Piezom. -1 -6.5 Points 6 7 Piezom. -1 -6.5 Points 1 2 Piezom. -1 -5.5 Points 1 2 Piezom. -1.5 -7 Points 6 7 Piezom. -1.5 -7.5 Piezom. -1.5 -7.5 Points 1 2 Points 1 2 Points 6 7 Piezom. -1.5 -7.5 Points 6 7 Piezom. -1.5 -7.5 Points 6 7 Piezom. -1.5 -7.5	Piezom. head (cm) -0.9 -6 -3.2 Points 6 7 8 Piezom. head (cm) 2.1 0.5 1 Points 1 2 3 Piezom. head (cm) -1 -6.5 -3.5 Points 6 7 8 Piezom. head (cm) 2 0.4 1 Points 1 2 3 Piezom. head (cm) -1 -6.5 -3.5 Points 6 7 8 Piezom. head (cm) -1 -6.5 -3.5 Points 7 8 Piezom. head (cm) -1 -6.5 -3.5 Points 7 8 Piezom. head (cm) 2.1 0.5 1 Points 1 2 3 Piezom. head (cm) -1.5 -7 -3.5 Points 6 7 8 Piezom. head (cm) -1.5 -7 -3.5 Points 6 7 8 Piezom. head (cm) -1.5 -7 -3.5 Points 6 7 8 Piezom. head (cm) -1.5 -7 -3.5 Points 6 7 8 Piezom. head (cm) -1.5 -7.5 3.8 Piezom. head (cm) -1.5 -7.5 3.8 Points 6 7 8 Piezom. head (cm) -1.5 -7.5 3.8 Points 6 7 8 Piezom.	Points 1 2 3 4 Piezom. head (cm) -0.9 -6 -3.2 2 Points 6 7 8 9 Piezom. head (cm) 2.1 0.5 1 0.5 Points 1 2 3 4 Piezom. head (cm) -1 -6.5 -3.5 2 Points 6 7 8 9 Piezom. head (cm) 2 0.4 1 0.4 Points 1 2 3 4 Piezom. head (cm) -1 -6.5 -3.5 1.8 Points 1 2 3 4 Piezom. head (cm) 2.1 0.5 1 0.5 Points 1 2 3 4 Piezom. head (cm) -1.5 -7 -3.5 2.1 Points 6 7 8 9

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



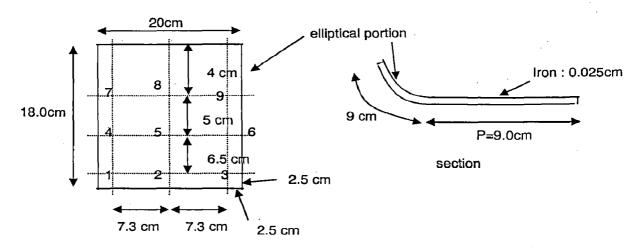
plan of elliptical suppressor plate

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

	Points	1	2	3	4	5
(m3/s)	Piezom.			·		
	head (cm)	-1.4	-7.5	1.6	-5	11
0.006	Points	6	7	8	9	
1	Piezom.					
	head (cm)	-1.1	1.1	2.1	3.5	
,	Points	1	2	3	4	5
•	Piezom.					
0.008	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
1	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.		, ,			•
l	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	l
"	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

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

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

	Points	. 1	2	3	4	5
0.012	Piezom.					-
Ì	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	
	Points	1	2	3	4	5
0.014	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	_
	Points	1	2	3	4	5
0.016	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	
	Points	1	2	_ 3	4	5
0.018	Piezom.					
	head (cm)	-1.2	-5	-3.5	0.5	2.4
	Points	6	7	8	9	
	Piezom.					
	head (cm)	4.1	\ o	0.9	O	
	Points	1	2	3	4	5
0.02	Piezom.			,		
	head (cm)	o	-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:

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Nappe to Transition (NA-TRA)
Transition to Skimming (TRA-SK) **Chanson (2001):** dc/h=0.89-0.4*h/l

Onset of Skimming (SK) dc/h=1.2-0.325*h/l ... Boes & Hager (2003): dc/h=0.91-0.14*h/l Critical depth(dc):

Table:1	Table: 1 (Theoretical)	tical)								
Ь	Slope	Step	Step	1/q	dc(m)	dc/h		dc/h (onset	t	Flow
(s/gm)	<u>(g)</u>	height	length			•	Cha	Chanson	Boes	regimes
		(h)m	(I)m				NA-TRA	TRA-SK	& Hager	ı
0.02	34032'	0.033	0.0484	0.682	0.034	1.043	0.617	0.978	0.815	SK
0.02	52014'	0.05	0.0387	1.292	0.034	0.689	0.373	0.780	0.729	TRA
0.02	38050'	0.0333	0.0414	0.804	0.034	1.034	0.568	0.939	0.797	SK
0.03	34032'	0.033	0.0484	0.682	0.045	1.367	0.617	0.978	0.815	SK
0.03	52014'	0.05	0.0387	1.292	0.045	0.902	0.373	0.780	0.729	SK
0.03	38050'	0.0333	0.0414	0.804	0.045	1.355	0.568	0.939	0.797	SK
0.04	34032'	0.033	0.0484	0.682	0.055	1.656	0.617	876.0	0.815	SK
0.04	52014'	0.05	0.0387	1.292	0.055	1.093	0.373	0.780	0.729	SK
0.04	38050'	0.0333	0.0414	0.804	0.055	1.641	0.568	0.939	0.797	SK
0.05	34032'	0.033	0.0484	0.682	0.063	1.922	0.617	0.978	0.815	SK
0.05	52014	0.05	0.0387	1.292	0.063	1.268	0.373	0.780	0.729	SK
0.05	38050'	0.0333	0.0414 0.804	0.804	0.063	1.904	0.568	0.939	0.797	SK
					İ					

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								i						, ,		
ĺ.,																
SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK	SK		
2	6	7	2	6		2	6	7	2	6	7	5	6			
0.815	0.729	0.797	0.815	0.729	0.797	0.815	0.729	0.797	0.815	0.729	0.797	0.815	0.729	0.797		
	_	_								_						
0.978	0.780	0.939	8/6'0	0.780	0.939	0.978	0.780	0.939	0.978	0.780	0.939	0.978	0.780	0.939		87
0.617	0.373	0.568	0.617	0.373	0.568	0.617	0.373	995.0	0.617	0.373	0.568	0.617	0.373	0.568		
2.170	1.432	2.151	2.405	1.587	2.383	2.629	1.735	2.605	2.844	1.877	2.818	3.050	2.013	3.023		
7.2	72	172	6/1	62	62	187	187	28	194	94	94	0.1	0.1	01		
0.072	0.072	0.072	0.079	0.079	0.079	0.087	0.087	0.087	0.094	0.094	0.094	0.101	0.101	0.101		
0.682	1.292	0.804	0.682	1.292	0.804	0.682	1.292	0.804	0.682	1.292	0.804	0.682	1.292	0.804		
ł																
0.0484	0.0387	0.0414	0.0484	0.0387	0.0414	0.0484	0.0387	0.0414	0.0484	0.0387	0.0414	0.0484	0.0387	0.0414		
Ω	, _	133	13		33	13		133	13		:33	13		133	,	
0.033	0.05	0.0333	0.033	0.05	0.0333	0.033	0.05	0.0333	0.033	0.05	0.0333	0.033	0.05	0.0333		
34032'	52014'	38050'	34032'	52014'	38050'	34032'	52014'	38050'	34032	52014	38050	34032'	14'	38050		
346	520	380	340	520	380	340	52c	380	340	520	380	340	52014'	380	·	
9	9	6	7	7	7	8	 ∞	8	6	6	6					
0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1]	
			. •													
											,					

Table:2 Observational:Without suppressor

	1						
		Step	Step	[/q	dc(m)	dc/h	Flow patterns
(m3/s)	(B)	height	length				
		(h)m	m())		•		
0.02	34032'	0.033	0.0484	0.682	0.034	1.043	Undulating skim flow, Invisible vortices, Inception length=45cm.
0.02	52014	0.05	0.0387	1.292	0.034	0.689	Strong undulating transition flow,full vortices at lower steps, Incept. L=60cm.
0.02	38050'	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	34032	0.033	0.0484	0.682	0.045	1.367	Undulating skim flow, Invisible vortices, Inception length=48cm.
0.03	52014	0.05	0.0387	1.292	0.045	0.905	Strong undulating skim flow,full vortices at lower steps, Incept. L=65cm.
0.03	38050'	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	34032'	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	52014'	0.05	0.0387	1.292	0.055	1.093	Strong undulating skim flow,full vortices at lower steps,Incept.L=90cm.
0.04	38050'	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	34032"	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	52014'	0.05	0.0387	1.292	0.063	1.268	Strong airmixed skim flow, full vortices at lower steps, Incept. L=90cm.
0.05	38050'	0.0333	0.0414	0.804	0.063	1.904	Full vortices in all steps, concave skim flow at junction, incept. L=60cm.
90.0	34032'	0.033	0.0484	0.682	0.072	2.170	Full vortices after step12, rests weak vortices, skim flow, incept. L=60cm.
90.0	52014'	0.05	0.0387	1.292	0.072	1.432	Full vortices after step12, rests weak vortices, skim flow, incept. L=90cm.
90.0	38050'	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	34032'	0.033	0.0484	0.682	0.079	2.405	Full vortices after step15, rests weak vortices, skimmingflow, incept. L=60cm.
0.07	52014'	0.05	0.0387	1.292	0.079	1.587	Full vortices after step12, rests weak vortices, skim flow, incept. L=120cm.
0.07	38050'	0.0333	0.0414	0.804	0.079	2.383	Full vortices in all steps, concave skimflow at junction, incept. L=70cm.
80.0	34032'	0.033	0.0484	0.682	0.087	2.629	Full vortices after step13, rests weak vortices, skimmingflow, incept. L=60cm.
0.08	52014'	0.05	0.0387	1.292	0.087	1.735	Full vortices after step12, rests partial, skim. flow, convexflow, Li=120cm.
0.08	38050'	0.0333	0.0414	0.804	0.087	2.605	Full vortices in all steps, concave skimflow at junction, incept. L=70cm.
0.09	34032'	0.033	0.0484	0.682	0.094	2.844	Full vortices after step13, rests weak vortices, skimmingflow, incept. L=60cm.
0.09	52014'	0.05	0.0387	1.292	0.094	1.877	Full vortices after step12, rests partial, skim. flow, convexflow, Li=120cm.
0.00	38050'	0.0333	0.0414	0.804	0.094	2.818	Full vortices in all steps, concave skimflow at junction, incept. L=70cm.
0.1	34032'	0.033	0.0484	0.682	0.101	3.050	Full vortices after step13, rests weak vortices, skimmingflow, incept. L=60cm.
0.1	52014'	0.05	0.0387	1.292	0.101	2.013	Full vortices after step12, rests partial, skim. flow, convexflow, Li=120cm.
0.1	38050'	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

			I				
b	Slope	Step	Step	h/1	dc(m)	dc/h	Flow patterns
(m3/s)	(g)	height	length				
·		(h)m	(I)m				
0.02	34032'	0.033	0.0484	0.682	0.034	1.043	Undulating skim flow, Invisible vortices, Inception length=45cm.
0.02	52014'	0.05	0.0387	1.292	0.034	0.689	Strong undulating skim flow, full vortices at lower steps, Incept. Li=60cm.
0.02	38050'	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	34032	0.033	0.0484	0.682	0.045	1.367	Undulating skim flow, Invisible vortices, Inception length=48cm.
0.03	52014'	0.05	0.0387	1.292	0.045	0.905	Strong undulating skim flow, full vortices at lower steps, Incept. Li=55cm.
0.03	38050'	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	34032'	0.033	0.0484	0.682	0.055	1.656	All steps had full vortices looked like a skim flows Li=45cm
0.04	52014	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	38050	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	34032'	0.033	0.0484	0.682	0.063	1.922	All steps had full vortices & looked like a skim flows, Li=45cm.
0.05	52014	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	38050'	0.0333	0.0414	0.804	0.063	1.904	Full vortices in all steps, concave skim flow at junction, incept. Li=35cm.
90.0	34032'	0.033	0.0484	0.682	0.072	2.170	All steps had full vortices & looked like a skim flows, Li=45cm.
90.0	52014	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	38050	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	34032	0.033	0.0484	0.682	0.079	2.405	Full vortices after step15, rests weak vortices, skimmingflow, incept. Li=60cm.
0.07	52014'	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	38050'	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	34032	0.033	0.0484	0.682	0.087	2.629	Full vortices after step13, rests weak vortices, skimming flow, incept. Li=60cm.
0.08	52014'	0.05	0.0387	1.292	0.087	1.735	Full vortices after step4, rests weak vortices, uniform skim.flow, incept.Li=20cm.
80.0	38050'	0.0333	0.0414	0.804	0.087	2.605	Full vortices in all steps, concave at junction, uniform skimflow, incept. Li=10cm.
60.0	34032	0.033	0.0484	0.682	0.094	2.844	Full vortices after step13, rests weak vortices, skimming flow, incept. Li=60cm.
60.0	52014	0.05	0.0387	1.292	0.094	1.877	Full vortices after step3, rests weak vortices, uniform skim.flow, incept.Li=10cm.
60.0	38050'	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	34032	0.033	0.0484	0.682	0.101	3.050	Full vortices after step13, rests weak vortices, skimming flow, incept. Li=60cm.
0.1	52014'	0.05	0.0387	1.292	0.101	2.013	Full vortices after 2ndstep, rest partial, uniform skim.flow, convexflow, Li=5cm.
0.1	38050'	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)

b	Slope	Step	Step h/1	[<u>F</u>	dc(m) dc/h	dc/h	Flow patterns
n3/s)		height	length		· · · · · ·		
		(h)m	(l)m				
0.03	34032'	0.033	0.0484	0.682	0.045	1.367	Undulating skim flow, Invisible vortices, Inception length=20cm.
0.03	52014'	0.05	0.0387	1.292	0.045	0.902	Strong undulating skim flow, full vortices at lower steps, fincepts
0.03	38050'	0.0333	0.0414	0.804	0.045	1.355	Full vortices in all steps, concave skim flow at junction, incept.
0.04	34032	0.033	0.0484	0.682	0.055	1.656	All steps had full vortices& looked like a skim flows, Li=20cm
0.04	52014'	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	38050'	0.0333	0.0414	0.804	0.055	1.641	Full vortices in all steps, concave skim flow at junction, incepta
0.05	34032'	0.033	0.0484	0.682	0.063	1.922	All steps had full vortices& looked like a skim flows, Li=25cm.
0.05	52014'	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	38050	0.0333	0.0414	0.804	0.063	1.904	Full vortices in all steps, concave skim flow at junction, incept:
90.0	34032'	0.033	0.0484	0.682	0.072	2.170	All steps had full vortices & looked like a skim flows, Li=30cm.
0.06	52014'	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	38050'	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	34032'	0.033	0.0484	0.682	0.079	2.405	Full vortices after step5, rests weak vortices, skimmingflow, incept. Li=35cm.
0.07	52014	0.05	0.0387	1.292	0.079	1.587	Full vortices after step5, rests weak vortices, nearly uniform skim. flow, incept.
0.07	38050'	0.0333	0.0414	0.804	0.079	2.383	Full vortices in all steps, concave at junction, non uniform skimflow, incept.
0.08	34032'	0.033	0.0484	0.682	0.087	2.629	Full vortices after step5, rests weak vortices, skimming flow, incept. Li=35cm.
0.08	52014'	0.05	0.0387	1.292	0.087	1.735	Full vortices after step4, rests weak vortices, nearly uniform skim. flow, incept.
0.08	38050'	0.0333	0.0414	0.804	0.087	2.605	Full vortices in all steps, concave at junction, non uniform skimflow, sucept.
0.09	34032	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	52014'	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	38050'	0.0333	0.0414	0.804	0.094	2.818	Full vortices in all steps, concave at junction, non uniform skim flow, incepts
0.1	34032'	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	52014'	0.05	0.0387	1.292	0.101	2.013	Full vortices after 4th step, rest partial, nearly uniform skim flow, convexflow,
0.1	38050'	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 Observa	tional:V	Table:5 Observational:With elliptical suppressor	ical sug	presso	r (P=90 mm)) mm (
d	Slope	Step	Step	l/1		dc/h	Flow patterns
(m3/s)	(a)	height	length				
		(h) m	(I) m				
0.03	34032'	0.033	0.0484	0.682	0.045	1.367	All steps had full weak vortices & skim flows, Li=15cm
0.03	52014'	0.05	0.0387	1.292	0.045	0.905	Air cavities at first few steps, nearly uniformdepth flow, full vortices at lower steps
0.03	38050'	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	34032'	0.033	0.0484	0.682	0.055	1.656	All steps had full weak vortices& skim flows, Li=18cm.
0.04	52014'	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	38050'	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	34032'	0.033	0.0484	0.682	0.063	1.922	All steps had full vortices looked like a skim flows, Li=20cm.
0.05	52014'	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	38050'	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	34032'	0.033	0.0484	0.682	0.072	2.170	Full vortices after step5, rests weak vortices, skimmingflow, incept. Li=25cm.
0.06	52014'	0.05	0.0387	1.292	0.072	1.432	Full vortices after step5, rests weak vortices, nearly uniform skim.flow,
0.06	38050'	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	34032	0.033	0.0484	0.682	0.079	2.405	Full vortices after step5, rests weak vortices, skimming flow, incept. Li=25cm.
0.07	52014'	0.05	0.0387	1.292	0.079	1.587	Full vortices after step4, rests weak vortices, nearly uniform skim flow, incept.
0.07	38050'	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	34032	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	52014	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	38050'	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.
0.00	34032'	0.033	0.0484	0.682	0.094	2.844	Full vortices after step 7, rests weak vortices, skimming flow, incept. Li=30cm.
0.00	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	38050'	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	34032'	0.033	0.0484	0.682	0.101	3.050	Full vortices after step13, rests weak vortices, skimming flow, incept. Li=40cm.
0.1	52014'	0.05	0.0387	1.292	0.101	2.013	Full vortices after 2ndstep, rest partial, uniform skim flow, convexflow,
0.1	38050'	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)

		•			,	,	
ď	Slope	Step	Step	1/4	qc(m) qc/h	qc/h	Flow patterns
(m3/s)	<u>ප</u>	height	length			_	
	-	(h) m	(I)m				
0.03	34032	0.033	0.0484	0.682	0.045	1.367	Undulating skim flow, Invisible vortices, Inception length=15cm.
0.03	52014'	0.05	0.0387	1.292	0.045	0.902	Strong undulating skim flow,full vortices at lower steps, Incept.
0.03	38050'	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	34032'	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	38050'	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	34032'	0.033	0.0484	0.682	0.063	1.922	All steps had full vortices& looked like a skim flows, Li=25cm.
0.05	52014'	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	38050'	0.0333	0.0414	0.804	0.063	1.904	Full vortices in all steps, concave skim flow at junction, incept. Li=0cm.
90.0	34032'	0.033	0.0484	0.682	0.072	2.170	All steps had full vortices& looked like a skim flows, Li=30cm.
90.0	52014	0.05	0.0387	1.292	0.072	1.432	Air cavities at first few steps, uniform depth flow, full vortices at lower steps,
90.0	38050'	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	34032	0.033	0.0484	0.682	0.079	2.405	Full vortices after step5, rests weak vortices, skimmingflow, incept. Li=35cm.
0.07	52014	0.05	0.0387	1.292	0.079	1.587	Full vortices after step5, rests weak vortices, uniform skim. flow, incept.
0.07	38050	0.0333	0.0414	0.804	0.079	2.383	Full vortices in all steps, concave at junction, uniform skimflow, incept. Li=0cm.
80.0	34032'	0.033	0.0484	0.682	0.087	2.629	Full vortices after step5, rests weak vortices, skirnming flow, incept. Li=38cm.
0.08	52014	0.05	0.0387	1.292	0.087	1.735	Full vortices after step4, rests weak vortices, uniform skim. flow, incept.
0.08	38050	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	34032'	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	52014	0.05	0.0387	1.292	0.094	1.877	Full vortices after step 5, rests weak vortices, uniform skim.flow, incept.
0.09	38050	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	34032'	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	52014	0.05	0.0387	1.292	0.101	2.013	Full vortices after 4th step, rest partial, nearly uniform skim.flow, convexflow,
0.1	38050'	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:

 $\alpha = 37^{\circ}34'$; h = 5cm; l = 6.5cm; No.of steps = 40 nos.

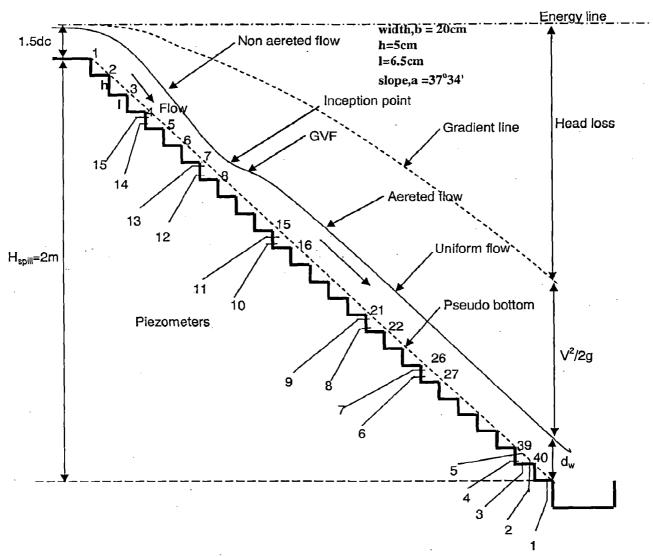
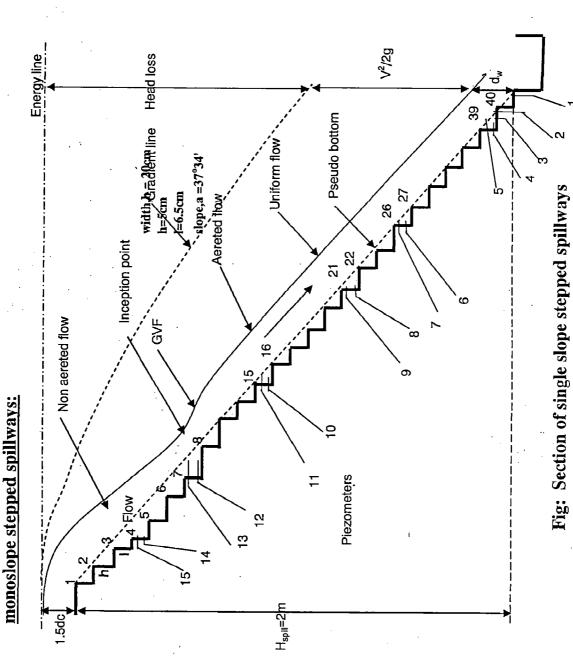


Fig: Section of single slope stepped spillways

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

spillways:Flow water depths: $\alpha = 37^{\circ}34'$; h = 5cm; l = 6.5cm; No.of steps = 40 nos SN Q (m3/s) Steps no. 5 6 7 8 10 11 12 13 14 15 $0.006 \, d_{\rm w} \, ({\rm cm})$ 3.5 2.8 2.72.6 2.8 2.8 3 2.6 2.6 3.5 3.8 2.6 2.6 2.6 2.6 Piezometer 0.4 2.3 9.5 -0.5 2.9 2.4 -0.5 -0.8 -0.8 2.3 -0.5 reading(cm) 1.4 1.3 1.6 -1 25 21 22 23 24 30 16 17 18 19 20 26 27 28 29 Steps no. 2.6 2.6 $d_w(cm)$ 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 37 38 39 40 Steps no. 31 32 33 34 35 36 2.6 2.6 2.6 2.6 2.6 2.6 2.6 2.6 2.6 2.6 $d_w(cm)$ 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 0.01 Steps no. 2 10 14 15 5 6 8 11 12 13 7 6 5 4.2 4.3 4.5 4.5 4.5 4.5 4.5 dw (cm) 4 4.5 4.5 4.5 Piezometer 8.3 2.3 13.4 reading(cm) -0.5 2.6 3.2 -0.8 4.2 -0.3 -0.1 3 -1 21 22 23 24 25 16 17 18 19 20 26 27 29 Steps no. 28 30 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 $d_w(cm)$ 4.5 4.5 4.5 4.5 4.5 4.5 Steps no. 31 32 33 34 35 36 37 38 39 40 dw (cm) 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4,5 Incept. length=35cm, vortex generated after 7th step and there was full vortices in all steps. Flow pattern 0.014 Steps no. 10 12 13 14 15 8 9 11 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 $d_w(cm)$ Piezometer 16.5 -0.7-1.1 4.6 0 5.5 0.7 reading(cm) 11 -0.52.8 3.1 -1.126 27 16 17 20 21 22 23 24 25 28 Steps no. 18 19 29 30 4.8 4.8 4.8 4.8 4.8 4.8 4.8 4.8 4.8 $d_w(cm)$ 4.8 4.8 4.8 4.8 4.8 31 32 33 34 35 36 37 38 39 40 Steps no. 4.8 4.8 4.8 4.8 $d_w(cm)$ 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. 0.018 Steps no. 10 12 13 14 15 11 6 9.5 5.5 5.5 5.8 5.8 5.8 5.8 5.8 5.8 10 5.8 dw (cm) 6 Piezometer -0.75.2 0.6 5.6 1.2 reading(cm) 13.4 2 18.1 -0.5 2.8 3 -0.6 3.5 20 22 23 24 25 26 30 16 17 18 19 21 27 28 29 Steps no. **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 $d_w(cm)$ Steps no. 31 32 33 34 35 36 37 38 39 40 5.8 5.8 5.8 5.8 5.8 5.8 5.8 5.8 5.8 5.8 $d_w(cm)$ Incept.length=60cm,0%vortex at first step,50% at 2nd step,aerated flow and full vortices Flow pattern from 3rd to last steps. 0.02 Steps no. 10 11 13 14 15 11 10 9 8.5 7.5 7 6 б 6.5 6.5 6.5 6.5 6.5 6.5 $d_w(cm)$ Piezometer reading(cm) 13.4 18.1 -0.6 -0.72.9 0.6 5.6 20 21 22 23 24 25 26 27 28 29 30 16 17 18 19 Steps no. 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 dw (cm) 40 36 38 39 Steps no. 31 32 33 34 35 37 6.5 6.5 6.5 6.5 6.5 6.5 6.5 6.5 6.5 6.5 dw (cm) Incept.length=65cm,0%vortex at first step,50% at 2nd step,aerated flow and full vortices Flow pattern

from 3rd to last steps.



32

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

Data:				Energy at crest:	Energy at toe:
q _w =0.02cu	qw=0.02cum/0.2m=0.1cum/m	cum/m		$E_c=H_{spill}+1.5d_c$	$E_t=d_w+u_w^2/2g$
Equations	Equations to be used:				
$z^{0.1}/ng^{0.5} = ($	$z^{0.1}/ng^{0.5} = 0.25 + 19log(1/1) + 5.75log(z^{0.6}/k)$	/I)+5.75log	$(z^{0.6}/k)$	(1)	
z=qn/(sina) ^{0.5}) ^{0.5}	(2)			
$y=\{qn/(sina)^{0.5}\}^{0.6}$	•	(.3)			*
v=q/y		(4)			
k=h*cosa	:	(5)			
$\lambda = (h^2 + l^2)^{0.5}$	5	(9)			
$E_c=H_{spill}+1$	E _c =H _{spill} +1.5d _c (7)	(<u>)</u>			
$E_1=d_w+u_o^2$	$E_1 = d_w + u_o^2/2g$	(8)			
ΔE=E _c -E _i	ΛΕ=Ε _c -Ε _c (9)	(6)			
Calculations:	tions:				
Critical d	Critical depth $(dc)=(q_w^2/g)^{1/3}$, 2/g) ^{1/3}			
ď	d _{c (m)}		$ m H_{spill}$		
0.1	0.10		7		
h		γ (m)			
0.05	0.065	0.082			
ಶ	sina		k(m)		
37.566667	0.609	0.793	0.040		
Solving M	Solving Manning's n from eq.(1)	rom eq.(1	<u> </u>		
n	z	×	THS		
0.06485	0.008307	1.26163	3.0493		
$\{z^{0.6/k}\}$			log(l/l)		
1.4240046			0.1009		
$log\{z^{\circ}0.6/k\}$	₹		RHS		
0.1535114			3.0504		
Put differe	Put different values of n & check whether I.HS=RHS	n & check	whether	THS=RHS	
c c	LHS	RHS			
90:0	3.27	2.934			
0.06485	3.049	3.05			
Hence val	Hence value of n is 0.06485	6485			

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

ф (ш)

0.056

Uniform velocity,uw =qw/dw

Uw (m/s)

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

Ec(m) Ec =Hspill+1.5dc

2.151

0.216 Et(m)

 $Et = d_w + u_w^2/2g$

 $\Delta E(m)$

1.935

89.9 %

Energy dissipated=DE/Ec*100 =

Residual head =Et =0.22m

(b) Chanson methods(1994):

Average equilibrium air concentration (Ce) =0.9*sina

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

0.916281 1.09137 -0.175 2.008

0.456395

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

8sina

dwu 0.045711 4.875365

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

8(1-Ce)³sina

d₉₀(m) 0.10123

0.4487891

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

Rate of energy dissipation;

 $\Delta H/Hmax = 1 - [\{(fe/8sina)1/3*cosa + Ec/2(fe/8sina) - 2/3\}/(1.5 + Hdam/dc); where Ec=(N+1)^3/\{N^2*(N+3) + Ec=1.1 \text{ for } N=3.5; Hmax=Hdam+1.5*dc \}$ where N=3.5 to 4,

Ec=1.1 for N=3.5; Hmax=Hdam+1.5*dc {fe/(8sina)}-2/3 (1.5+Hdam/dc) 4.84275

[fe/(8sina)]1/3

0.4540938

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

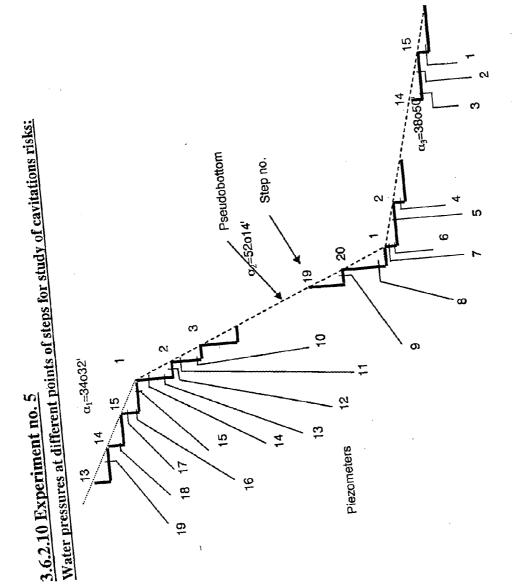
H_{res}(m)

0.3043631

ie, energy lost by stepped spillways is:

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

1.8466337



Experimental setup
Section of multislope stepped spillways showing the points in steps where the points of multislope stepped spillways showing the piezometric pressure head have been taken for cavitation risk study 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)	Piezo	metri	Piezometric reading of diff.points in steps(cm)	lo gu	diff.p	oints i	in ste	os(cm	_										ļ -
	. s/gm		2	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18	19
	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
_	9000	0.0	4.5	1.7	0	16	8.9	2.2	3	5.5	0	0	0	0.4	0	6.5	1.4	-2	2.1	7.5
_	800.0	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
+	0.01	1.4	9	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	-5	2.3	9.5
	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
	0.014	1.6	7.8	1.8	3.1	18.1	10.3	5.1	5.1	7.3	0	0	9.0-	0	0	12	2	-2	3.5	13.2
	0.016	1.6	9.8	1.8	3.8	19.5 11.4	11.4	5.8	5.2	8	-0.5	-0.2	-1.1	-0.5	0	11.5	2	-1.9	4	12.7
~	0.018	1.6	6.5	2	4.4	19.8 11.9		6.5	5.7	8.8	-1	-1.7	-1.8	-1.3	0	11.5	7	-1.8	4	12.6
	0.02	1.6	10	1.9	5	21.1	11.8	7	9	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):

	6	3	2	3	9	4	Ι Π	Ι Π	3	7
	19	4.3	×.	8.3	9.	13.4	13.1	13.	13	13.2
	18	2	2.1	2.6	3.1	3.5	4	4.1	4.3	4.5
	17	-1.9	-1.9	-2	-5	-2.1	-1.7	-1.7	-1.7	-1.6
	16	1.5	1.5	1.8	1.9	7	7	7	2	2.4
	15	3.6	7	7.3	8.2	11.2	11.8	11.3	11.5	12
	14	0.3	0.3	0.3	0.25	0.2	0.1	0	0	0
	13	0.4	0.4	0.4	0.3	0.2	0.1	0	0	0
	12	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4
	11	-0.9	6.0-	-0.9	6.0-	-0.9	-0.9	-0.9	6.0-	-0.9
	10	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4
<u> </u>	6	4.2	5.4	5.4	7	9.3	10.8	12.4	14.1	16.4
points in steps(cm)	8	es.	3.3	3.6	3.8	4.4	5.1	5.9	8.9	7.6
in ste	7	1.4	2.6	3.4	4	4.9	5.9	6.7	1.5	8.3
oints	9	5.1	6.8	7.9	8.8	10	11.5	13	15	17
diff.p	S	14	16.3	18	19.6	23.5	26	28	33.5	40
ng of	4	0	0.3	1.1	1.9	2.5	3	3.6	4.4	5.4
readi	3	1.6	1.55	1.5	1.5	1.8	1.7	1.7	1.7	1.8
metric	2	4.2	4.8	5.3	9	8.9	7.4	7.8	8.3	8.5
Piezometric reading of diff.	1	1.1	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4
Disch.(Q)	m3/s .	0.004	900'0	800.0	0.01	0.012	0.014	0.016	0.018	0.02
SN		1	7	3	4	5	9	L	8	6

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

ſ		- 20										20	c	2.5	3	2.5	2.8					20								
-		19										19	4.5	4	4.5	4	.25	-				19	_		-	r				
		18				_						18	4.5	4	4.5	4	4.25 4	-			i	18	-			-				
		17										17	4.5	4	4.5	4	4.25					17		-		-	-	_		
ł		16	-				-					16	4.5	4	4.5	4	4.25	_				16	-	-			-			
		15	7	2	2	7	2			-	1	15	5.5	4.5	5.5	4.5	5,	-				15	2.5	7	2.5	7	2.3			
		14	2	2	2	2	2			Me		14	5.5	5	5.5	5	5.25		-			14	2.5	7	2.5	2	2.25	_		
		13	2	2	2	7	2			ing flo		13	5.5	S	5.5	S	5.25	-	-			13	2.5	2	2.5	2	2.25			
		12	2	2	2	2	2			kimm		12	4	က	4	3	3.5		_	ortices		12	2.6	2	2.6	7	2.3			
		11	2	2	2	2	2	,		nor s		11	4.3	4	4.3	4	4.15			100% recir.vortices		11	2.8	2	2.8	2	2.4	_		
		10	2	2	2	2	2		-	lappe		10	4.5	4	4.5	4	4.25	-		00%		101	3	2	3	2	2.5	· · ·	П	
		6	2	2	2	2	2			ither 1		6	4.8	4.5	4.8	4.5	4.65					6	3.2	2.3	3.2	2.3	2.75			
		8	2	2	2	2	2			es,ne	ļ	∞	5	5	5	S	5			vortex		∞	3.3	2.6	3.3	2.6	3			ļ ,
		7	2	2	2	7	2			vortic		7	5.2	5	5.2	5	5.1			25%to75% vortex		7	3.5	2.7	3.5	2.7	3.1			steps
		9	2	2	2	7	2			lating		9.	5.3	5	5.3	S	5.2			25%tc		9	3.8	2.9	3.8	2.9	3.4			in all
	7.2	5	2	2	2	2	2			circu	4	5	5.4	5	5.4	5	5.2				,20,	5	4	3	4	3	3.5			rtices
1	=34-32	4	3	_ 2	3	2	2.5			eak re	=52°14	4	5.5	5	5.5	5	5.3				=380	4	3.8	2.8	3.8	2.8	3.3			oo gu
	ways α ₁	3	3	2	3	2	2.5			ties,w	ways α_2	8	5	4.5	5	4.5	4.75			cavities		3	3.5	2.5	3.5	2.5	3			culati
	III Wa	2	3	2	3	2	2.5			r cavi	illwa	2	3	2.5	3		2.75			_	illwa	2	2	1.8	2	1.8	1.9			recir
,	bea sh	1	3.5	3	3.5	3	3.25		30	No air cavities, weak recirculating vortices, neither nappe nor skimming flow	sed sp	1	2.5	2	2.5	7	2.25		35	100% ai	s pac	1	2.5	2	2.5	2	2.25		10	100% recirculating vortices
	Stope of stepped spilly	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt	Slope of stepped spilly	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt	Slope of stepped spillways α_3	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt
		perunit			cum/m)		_ •					•			ني-ن	0.03 Min.	<u> </u>	اخصا						<u> </u>					, <u></u>	
	n Dis	per	v. length	<u></u>												0.2					 -									4
	M IGI	jo	(cum) spillw.	ways	(b m)																	_		`						
-	Discn. width Discn.	<u>(</u>	(cnm)													1.66 0.006														
		metre	reading	(x cm)	_											1.66		-						_						
	SN Mano	Ĕ		<u>*</u>	_				-							,														\dashv
L	<u> </u>																													

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 13 14 15 13 14 15 13 14 15 13 14 15 13 13 13 13 13 13 13	ー	SN Mano	Disch.	Disch. Width Disch.	Disch.	Slope of stepped spill	ped sp	illways	ชื่	=34°32] -										
(c cm) spillw. [length Max. 4 3.5 3.5 2.5 2.5 2.5 2.5 2.5 3 3 3 3 3 3 3 4		metre	<u> </u>		perunit			2	3	4	5	9	7			11	12	13	14	15	16	17	18	19	20
(cm) ways (q) Min. 3 3 3 3 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2		reading		spillw.	length		4		5.	3.5	5	5	5	5 2.	5			3	3	3					
(b m) Max, 4 3.5 3.5 2.5		(x cm)			<u>Б</u>	Min.	3	3	ϵ	3	7	2	2		_			2	2	7					
Aver. (4 _{vec.}) 3, 3, 3, 2, 3, 3, 3, 3, 3, 3, 2, 3, 2, 3, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,				(p m)	cum/m)		4		5.		5		5	2				3	3	3					
Inception Signature Sign			_			Min.		3	33	3	2	7	2				_		2	7	_		-		
Inception Line						Aver.(dwps)	3.5	3.25	.25	6.	.25	3	6	3 2		2	<u> </u>	7	2.5	2.5	-		-		
Flow patt No air cavities, weak recirculating vortices, preither nappe nor skimming flow						Inception				_	_	_													
Elow patt No air cavities, weak recirculating vortices, neither nappe nor skimming flow Slope of stepped spillways $\alpha_3 = 32^{\circ}14^{\circ}$ Step nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 Max. 2.5 4 5 5 4 3 2.8 2.8 3 3.5 3.8 4.2 4.5 4.5 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 Max. 2.5 4 4.5 5 4 2 2.8 2.8 2.8 3.5 3.5 3.5 3.2 2.8 Min. 2 3.5 3.7 3 4 5 5 4 2 3 2.8 2.8 3 3.5 3.8 4.2 4.5 3 2.8 Max. 3 3.5 3.8 4.2 4.5 5 4 2 3.2 8 2.8 3.5 3.2 3.8 3.2 2.8 Min. 2 3.5 3.7 3 3.5 3.2 2.8 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5						length(cm)	45			-			_	-											
Stope of stepped spillways $c_2 = 52^{\circ} 14$ Step nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 Min. 2 3 4 4.5 5 4 3.5 3 3.5 3.8 4.2 4.5 4.2 4.5 14 3.5 Min. 2 3.5 4.5 5 4 3.5 3.2 2.8 3 3.5 3.5 3.5 3.5 3.5 2.6 Min. 2 3.5 4.5 5 4.5 5 4.5 3.5 3.5 3.8 4.2 4.5 4.2 4.5 3.5 4.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3						Flow patt	No air	r cavit	ies,wea	ık rec	irculat	ting vc	rtices	,neithe	er napt	oc nor	skimn	ning fl	OW O						
Step nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 Max. 2.5 4 4.5 5 4.5 4 3.5 3.8 4.2 4.5 4.2 4 3 Min. 2 3.5 4.5 5 4.5 5 4 3 2.8 2.5 2.8 3 3.5 3.5 3.2 3 2.8 Min. 2 3.5 4.5 5 4.5 3 4 3.5 3.5 3.8 4.2 4.5 4.2 4 3 Aver.(d _{wps}) 2.25 3.75 4.5 5 4.2 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5						Slope of step	ped sp	illwa	$rs \alpha_2 =$	52°14															
Max. 2.5 4 4.5 5 4.5 4 3.5 3.8 3.8 4.2 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5						Step nos.	1	2	60	4	5	9	7					13	14	15	16	17	18	19	20
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 Max. 2.5 4 4.5 5 4.5 3 4 3.5 3.5 3.8 4.2 4.5 4.5 3 5 1.0 3.5 3.5 3.5 3.8 4.2 4.5 3 2.6 Aver.(dwps.) 2.25 3.75 4.5 5 4.2 3.5 3.2 2.8 3.5 3.5 3.5 3.5 2.8 Inception length(cm) 40		_				Max.	2.5	4	4.5			_	5.	_	L	匚	<u> </u>	4.2	4	3	6	3	3	60	3
Max. 2.5 4 4.5 5 4.5 3.5		_				Min.	2		4.5	5	4	L		<u> </u>		<u> </u>		3.2	3	2.6	2.6	2.5	2.5	2.5	2.5
0.20 Min. 2 3.5 4.5 5 4.5 5 4.25 3.2 2.8 3.15 3.4 3.85 4 3.7 3.5 2.8 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 Inception 40 Flow patt 100% air cavities Step nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 Max. 3 2.5 4 4.2 4.4 4.5 4.5 4.5 4.3 3.2 3.8 3.2 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3	_					Max.	2.5	4	4.5		4.5		.5	ldash	_	匚		4.2	4	3	3	3	3	3	3
tion th(cm) 40 th 2.25 3.75 4.5 5 4.25 3.2 2.8 3.15 3.4 3.85 4 3.7 3.5 2.8 th(cm) 40 th 2 th 3 th 3 th 4 th 3 th 4 th 3 th 4 t		2.95	0.008)4 Min.			4.5	5	4			7			ᆫ	3.2	3	2.6	2.6	2.5	2.5	2.5	2.5
h(cm) 40						Aver.(d _{wps})		3.75	4.5	Ľ	25	ن.	7	_	3	├		3.7	3.5	2.8	2.8	2.75	2.75	2.75	2.8
hh(cm) 40						Inception					_														
of stepped spillways α ₃ =38°50· 25%to75% vortex 100% recir.vortices nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 nos. 1 2 3 4 2 4 4.5 4.5 4 3.5 3.2 3						length(cm)	40																		
nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 1 2.5 2.2 3 3.2 3.4 3.5 3.2 2.8 2.2 2 2 2 2.5 2.2 3 3.2 3.4 3.5 3.2 2.8 2.2 2 2 2 2.5 2.2 3 3.2 3.4 3.5 3.5 3.2 2.8 2.2 2 2 2 2.5 2.2 3 3.2 3.4 3.5 3.5 3.2 2.8 2.2 2 2 2 3.6 4 2 4 4 3 5 3 5 3 2 2 8 2 2 2 2 3.6 4 2 4 4 3 5 3 5 3 2 2 8 2 2 2 2 3.7 3 3 3 3 3 3 3 3 3.8 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3	_					Flow patt	100%	air ca	vities			5%to75	% vor	tex	100%	6 recir.	vortice	S							
nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 2.3 3.2.5 4 4.2 4.4 4.5 4.5 4 3.2 3.2 3 <						Slope of step	bed sp			38,20	_				!						;				
2.5 2.2 3 3.2 3.4 4.5 4.5 4.5 2.8 2.2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2						Step nos.	1	2	3	4	5	9	7			L	12	13	14	15	16	17	18	19	20
2.5 2.2 3 3.2 3.4 3.5 3.5 2.8 2.2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2						Max.	3			2	4.		5.	_			.3	3	3	3					
3 2.5 4 4.2 4.4 4.5 4.5 4.5 3.2 3.3 3 3 3 3 3 3 2.5 2.2 2.2 2.2 2.2 2 2 2 2 2 2 2 2 2 2						Min.	2.5							_				2	2	2	-			-	
2.5 2.2 3 3.2 3.4 3.5 3.5 3.2 2.8 2.2 2 2 2 2 2 2 2 3 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 2.0						Max.	3			L	4		3		L			3	3	3					
s) 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 2.5 2.5 2.5 2.5 2.5	_					Min.		2.2	<u> </u>	7			L	7	2			2	2	2					
) 8 100% recirculating vortices in all						Aver.(d _{wps})	_	2.35	3.		3.9	4		_	2		2	2.5	2.5	2.5					
) 8						Inception						-													
100% recirculating vortices in all						length(cm)	8																		
						Flow patt	100%	recirc	ulating	vorti	ces in		sd												

JISCH.	widin	Disch. width Disch.	Slope of stepped spillwa	bed st	illwa	iks a	=34°32'	. 7														
	of	perunit	Step nos.	1	2	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18 1	9 20
	(cum) spillw.	length	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		<u> </u>		
	ways	<u>(</u> b)	Min.	3	3	2.5	2.5	2.5	2	2	2	2	2	2	2	2	7	7				_
	(p m)	cum/m)	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	7	7	2	2	7	2	7		_	· 	-
			Aver.(d _{wps})	4	4	3.25	2.8	2.75	2.3	2.3	2.3	.25 2.	25 2	.25	2.25 2.	.25 2.	25	2.3				
			Inception				 			-		-							_	-	_	
			length(cm)	45												-			_	_		-
_	,		Flow patt	No air cavi	r cavi	ties, weak recirculating vortices	ak re	circul	ating	vortic	es						F 1	-				
-			Slope of stepped spillwa	bed st	illwa	iys α2	=52°1,	4														
1			Step nos.	1	2	6	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18 1	19 20
			Max.	2.5	33	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	3.5	3.5 3.	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	2.5 2	2.5	2.5 2.	2.5 2.5
			Max.	2.5	3.5	4	4.5	4	3.5	E.	3.2	3.4	3.5	4.2	4.5	4.2	4	3.8	3.5	3.5	3.5 3.	3.5 3.5
0.01	0.2		0.05 Min.	7	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	2.5 2	2.5	2.5 2.	5 2.5
			Aver.(dwps)	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	60	ε	3	3
			Inception							-	_											
			length(cm)	40								-							<u> </u>			
			Flow patt	2001	100% air cav.		25%to80% vort.	30% ve	_	.00%	100% recir.vortices	ortices							-		٠,	
			Slope of stepped spillways	bed sp	illwa	පි	=38,20	<u></u>														
			Step nos.	1	7	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18 1	19 20
			Max.	3.5	3	4	4.5	4.8	5	4.8	4.5	4	3.5	8	6	3	3	ω,				.
			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	2.5				-
			Max.	3.5	6	4	4.5	4.8	5	4.8	4.5	4	3.5	6	m	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	2.5	_	_		_
			Aver.(d _{wps})	3.25	2.75	3.5	3.9	4.1	4.3	4	3.8	3.4 3	3.05 2	2.75 2	2.75 2	2.75 2	2.75	2.8				
			Inception				-															5
			length(cm)	5									_	J								
			Flow natt	100%	recir	100% recirculating vortices in all stens	O VOT	i saut	o III c	tens								L				

SN Mano Disch. Width Disch. Width Disch. Width Disch. Slope of stepped spillways q, =34°22	l																									
reading (cum) Sign noss. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 reading (cum) Sign noss. 1 2 3 5 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 19 10 10 10 10 10 10 10 10 10 10 10 10 10	(7)	N Ma		isch.	Width	Disch.	Slope of step	bed sp	illwa	α_1	34°32	2.														
(cm) spillw. (ength Max. 6 6 6 5 5 5 4 4 4 4 4 4 4 4 4 4 4 4 4 4		me				perunit	Step nos.	1	2	3	4	5	9	7	8		1	$1 \mid 1$	1	1	1	16	17			8
(ccm) (bm) (dm, m) (dm		reac	_=	cum)	spillw.	length	Max.	9	9	9	5	5	5	4	4	4										
(b m) Cum/m) Max. 6 6 6 5 5 5 4 4 4 4 3 3 3 3 3 3 3 3 3 3 3 3 3		×		-	ways	<u>(b)</u>	Min.	5	5	4	4	4	4	3	3	3										
Min. 55 5.4 4.4 4.4 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3						cum/m)	Max.	9	9	9	S	S	5	4	4	4										
Flow part No air cavities, weak recirculating vortices Single of stepped spillways c ₂ = 52°14 Single of stepped spillways c ₄ = 50°14 Single of single of stepped spillways c ₄ = 50°14 Single of single of stepped spillways c ₄ = 50°14 Single of single of stepped spillways c ₄ = 30°14 Single of single of stepped spillways c ₄ = 30°14 Single of single of stepped spillways c ₄ = 30°14 Single of single of stepped spillways c ₄ = 30°14 Single of single of stepped spillways c ₄ = 30°14 Single of single of stepped spillways c ₄ = 30°14 Single of single of stepped spillways c ₄ = 30°14 Single of s	<u> </u>	_	-				Min.	S	5	4	4	4	4	3	3											
Finception Fin			_				Aver.(dwps)	5.5	5.5	5	4.5		3.	.5		5 3	5 3	3,	3.	3	3					
Flow patt No air cavities, weak recirculating vortices Flow patt No air cavities Flow patt							Inception																			
Elow patt No air cavities, weak recirculating vortices Slope of stepped spillways $\alpha_1 = 52^{\circ}$ T 4 Step nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 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 4.5 4.5 4.5 4.5								50											_	_				_		
Slope of stepped spillways $c_2 = 52^{\circ} I4^{\circ}$ Siep nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 Max. 3.5 4.5 4.5 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 4.5 4.5 4.5 4.5								No aii	cavit	ies,we	ak rec	ircula	ting v	ortice	s											
Step nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 Max. 35 3.5 4.5 5 4.8 4.5 4.6 4.7 4.8 4.9 4.9 4.9 4.9 5 4.8 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5							Slope of step	bed sp	illwa	rs α ₂ =	:52°14										ļ					
Max. 3.5 3.5 4.5 4.8 4.5 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 4.5 4.5 4.5 4.5							Step nos.	1	7	3	4	5	9	7	<u></u>										19	20
6.63 0.012							Max.	3.5	3.5		5	4.8	5.		L	4 8	9 4.	4.			7					4.5
6.63 0.012 0.06 Min. 3 5.5 4.5 5 4.8 4.5 4.4 4.4 4.45 4.45 4.4							Min.	3	3.5	4	4.5	4.2	4	4	4	4	<u> </u>		4		ε					3.5
6.63 0.012 0.2 Min. 3 3.5 4 4.5 4.2 4.4 4.4 4.4 4.4 4.45 4.45 4							Max.	3.5	3.5		5	4.8	٠.	9	7.	∞.	.9 4.	4	6		4					4.5
tion 40 tion 40 tion 40 tion 40 40 40 40 40 40 40 40 40 4			6.63	0.012	0.2		Min.	3	3.5	4			4	4	4					3	G.	3		3		3.5
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4 3.5 4 5 5.8 6 6 5.5 5 4.75 4 4 4 4 3.8 3.5 3							Step nos.	1	7	3	4	5	9	7	8		_	1		1						8
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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 4.5 4 4 4 3.5 3 3 3 3 3 3 3 3 3 6.5 6 6 6 5 5 5 4 4 4 4 4 4 4		19 20										19 20	4	5 3.5	4	3.5 3.5	75 3.8					19 20							-
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Disch. Width Disch. (Q) of perunit Step nos.		13	4	3	4	3	3.5					13	5.5	4.5	5.5	4.5	5					13	3.5	3.5	3.5	3.5	3.5		
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Disch. Width Disch. (Q) of perunit length ways (q) (b m) cum/m) 3 0.014 0.2 0.07	Wavs	2	9	4	9	4	رح آ					-2	3.5	<u> </u>	3.5	<u> </u>		_	-		S	}				<u> </u>	25	_	-
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33	Width	Jo	spillw.	ways						_	-		-	-		0.2			,									-	
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	metre	<u>0</u>	of	perunit		Step nos.		2	3	4	5	9	7	8	9 10	0 11	12	13	14	15	16	17	18	19	20
	reading		(cum) spillw.	length		Max.	8	7	7	9	9	5	5	5 4.5	5 4.5	5 4.5	4.5	4.5	4.5	4.5					
	(x cm)		ways	<u>(b)</u>	2	Min.	9	9	5	5	5	4	4	4 3.8	8 3.5	5 3.5	3.5	3.5	3.5	3.5					
			(p m)	cum/m)		Max.	∞	7	7	9	9	5	5	5 4.5	5 4.5	5 4.5	4.5	4.5	4.5	4.5					
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					∀	Aver.(d _{wps})	7	6.5	9	5.5	2.5	4.5 4	4.5 4	.5 4.15		4	4	4	4	4					
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					<u>위</u>	length(cm)	20			_			_										-	-	
					H		No air c		avities, strong recirculating vortices	ng re	sircul	ating v	ortice	Š.											Γ
					N N	Slope of stepped spill	bed sp		ways α ₂ =	=52°14	<u>.</u>			ļ. 											<u> </u>
					S	Step nos.	1	2	3	4	5	9	7	8	9 10	11	12	13	14	15	16	17	18	19	20
				_	[2]	Max.	4	4.5	5.5	5	4.5	4.5 4	4.5 4	4.8	5 5.3	3 5.3	5.4	5.5	5.3	5	5	5	5	S	5
					Z	Min.	3.5	4.5	5	4.5	4.5	4 3	3.5 3	3.6 3.8	8	4.3	4.3	4.5	4.3	4	4	4	4	4	4
					Z	Max.	7	4.5	5.5	5	4.5	4.5 4	4.5 4	4.8	5.3	3 5.3	5.4	5.5	5.3	S	S	S	S	5	5
9		11.8 0.016	0.2		0.08 Min.	din.	3.5	4.5	2	4.5	4.5	4 3	3.	3.6 3.8		4 4.3	4.3	4.5	4.3	4	4	4	4	4	4
					\ V	Aver.(d _{wps})	3.75	4.5	5.25	4.8	4.5	4.3	4	4.2 4.4	4 4.65	4.8	4.85	5	4.8	4.5	4.5	4.5	4.5	4.5	4.5
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					国	Flow patt	90% air		20%vortex		10% re	100% recir.vortices	tices												
					S	Slope of stepped spill	ds pac		ways $\alpha_3 =$	=38,20,	_					:	;								
					S	Step nos.	1	2	3	4	5	9	7	8	9 10	11	12	13	14	15	16	17	18	19	20
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					Σ	Max.	6.5	5.5	5	9	6.5	7.7	7 7	7.5	8	8	7	7.5	7.5	7.5	_				Г
					Σ	Min.	4.5	4	4	4.5	5	5.5 5	5.5	6 6.5	5 6.5	6.5	9	5.5	5.5	5.5					
					∀	Aver.(d _{wps})	5	4.38	4.38	4.9 5	.25		5.7	6 6.25	5 6.05	9	5.5	5.33	5.25	5.3					
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1					H	Flow patt	100% re		circulating vortices in all steps	yvorti	ces in	all ste	sda												
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7	5.5	7	5.5	6.3		_	ng re	52°14	4	5	4	5	4	4.5		-	cir.vo	38,20	4	5	3.8	5	3.8	1 .	-	\vdash	1
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length	(b)	cum/m)											0.00				-										
spillw.					_			_	_				0.7							-				• •			-
(cum)													0.018														-
reading ((x cm)							1	•				14.92			-		-				-					_
	(cum) spillw. length Max. 9 9 7 7 4.5	(cum) spillw. length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) spillw. length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) spillw. length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) spillw. length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) spillw. length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) spillw. length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) spillw. length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) spillw. length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) spillw. length 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	(cum) spillw. length 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	(cum) spillw. length 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	(cum) spillw. length 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	(bm) spillw. length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(bm) spillw length (bm) (hmx, equ) 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) Spillw. length 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	(cum) spillw. length 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	(cum) spilltw. length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) spillw. length 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	(cum) spillor, length Max. 9 9 7 7 7 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5 4.5	(cum) spillw. length (bm) ways (q) Min. 7 7 4.5 <th< td=""><td>(cum) spillw. length 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</td><td>(cum) spillw length Max. 9 9 7 7 4 55 55 35 35 35 35 35 35 35 35 35 35 35</td><td>(cum) spillw. reigth Max. 9 9 7 7 4.5</td><td>(cum) spillw. [ength Max. 9 9 7 7 4.5</td><td>(cum) spillw length 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</td><td>(cum) spillw, length Max. 6 9 7 7 4 45 45 45 45 45 45 45 45 45 45 45 45 4</td></th<>	(cum) spillw. length 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	(cum) spillw length Max. 9 9 7 7 4 55 55 35 35 35 35 35 35 35 35 35 35 35	(cum) spillw. reigth Max. 9 9 7 7 4.5	(cum) spillw. [ength Max. 9 9 7 7 4.5	(cum) spillw length 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	(cum) spillw, length Max. 6 9 7 7 4 45 45 45 45 45 45 45 45 45 45 45 45 4

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	6]				_	\dashv	·	\dashv			61	9	2	9		5.	\dashv	\dashv			6]				_	\dashv		-	
	~	_					_				3 1	9	2	9		5 5	\dashv				8						_	_	
	18			-			1				18		"		4,	5.5					<u>~~</u>			!				- 1	
	17										17	9	5	9	5	5.5					17								
	16				,	\neg					16	9	5	9	5	5.5	\neg				16						_	\dashv	
	5	5	4	5	4	.5	\vdash				5	9	5	6	5	5.5	_				15	5	4	5	4	4.5	-		
	4 1	5	4	5	4	5 4	Н				14	9	5	9	5	5 5					4 1	5	4	5		5 4		[-
	1					4.					L					5					1					4			
	13	5	4	5	4	4.5					13	5.5	5	5.5	5	5.25					13	5.3	4	5.3	4	4.65	1		
	12	5	4	5	4	4.5					12	5.3	5	5.3	5	5.15					12	5.5	4.5	5.5	4.5	5			
	11	5	4	5	4	4.5					11	5	4.5	5	4.5	4.75					11	9	5	9	iS.	5.5		_	
	10	5	4	5	4	.5	_		•		10	5	ئ.	5	7.						10	.S.	5	5.	S			_	
	9	5	4	5	4	5 4					6	6	5 4	6	4	7 4.75					6	9 /		7	5	6 5.75			l
					_	4						4.9	4.5	4.9	4.5	4.					Ĺ			Ĺ					
	8	5	4	5	4	4.5			ices		8	4.7	4.5	4.7	4.5	4.6					∞	6.8	5	6.8	5	5.9			
	7	9	5	9	5	5.5			vortices		7	4.5	4.5	4.5	4.5	4.5					7	6.3	'n	6.3	3	5.7			steps
	9	9	5	9	5	5.5			recirculating		9	4.8	4.5	4.8	4.5	4.7					9	9	5	9	2	5.5			all
_	5	9	5	9	2	5.5			circul	_	5	5	4.5	5	4.5	4.75			rtices	_	5	5.5	4.5	5.5	4.5	5			100% recirculating vortices in
=34°32	4	8	9	8	9	7	_			$=52^{0}14$	4	5	1.5	5	5.	∞	_		100% recir.vortices	=38°50'	4	5	4	5	4	.5		_	vorti
$\alpha_1 = 1$	3	6	7	6	7	8	-		stroi	$\alpha_2 = 5$	3		5 4	5	5 4	5 4			% rec	α ₃ =3	3	5	4	5	4	5 4			ting
ays (2	0	~	0	~	_			ities	ays (L						<u> </u>	100	ys.	2	1.0				4			ıcı
) illw	7	10	~	1	ω	5			t cav	illw	7	4.7	4.5	4.7	4.5	4.6			air	illw	7	5.5	3.5	5.5	3.5	4.5			reci
ed si	1	9.5	8	9.5	8	8.75		55	No air cavities, strong	ed si	T	4.5	4.5	4.5	4.5	4.5		20	25% air	is pa	T	9	4	9	4	5			00%
Slope of stepped spillw	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)		tepl	Step nos.	Max.	Min.	Max.	0.1 Min.	Aver.(d _{wps})	Inception	length(cm)		Slope of stepped spillw	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt
نے															0.1														
Discl	perunit	lengt	<u> </u>	cum/m)																									
Vidth	of	pillw.	ways	(p m)											0.7														\neg
Disch. Width Disch.		(cum) spillw. length	_=	<u> </u>											0.05		-										<u> </u>		\dashv
	<u> </u>	<u>)</u> gı	<u> </u>			_							-			<u>.</u>					-								\dashv
SN Mano	metre	reading	(x cm)												18.42														_
SN															00														

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

	Serci Ollara Pro	711. VY 1.	7 	Disch. Width Disch.	Slope of stepped spillwa	ped sp	illwa	$ys \alpha_1$:	=34°32	~ 1			-												
metre	<u>0</u>	of	d	perunit	Step nos.	1	2	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18	19	20
d:	reading (cum)	n) spill	spillw. length		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					
(x cm)	(F)	ways		(b)	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				-	
		(p m)		cum/m)	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	-	\dashv	٠	\dashv	
1	_				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	_	-			
,		- 4			Inception													-			:	<u> </u>			
			<u> </u>	- 	length(cm)	15			-							_						H			
			_			No air cavi		ties, weak recirculating vortices, with skimming	ak re	circul	ating	vortic	es,wit	h skin	aming	flow				-					
					Slope of stepped spillwa	ped sp	illwa	ys α2:	=52°14	4			٠						-			-			
					Step nos.	1	7	3	4	5	9	7	∞	6	10	11	12	13	14	15	16	17	18	19	20
		_			Max.	co	4.5	5.5	9	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	S	5	5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3	3	7.	2	2	2
		-			Max.	co	4.5	5.5	9	5.5	5.5	5	4.5	4	4	4	4	4	4	3.5	3.5	3.5	3	3	3
τi	1.66 0.006		0.2	0.03	0.03 Min.	7	4	5.5	5	S	5	4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3	3		2		7
					Aver.(d _{wps})	2.5	4.25	5.5	5.5	5.25	5.3	4.5	43	3.75 3	3.75 3	3.75 3	3.75 3	3.75 3	3.75	3.3 3.	25	2.75	2.5	2.5 2	2.5
					Inception						<u> </u>										•	\dashv	_	-	
					length(cm)													<u> </u>		-				-	
						100%	air c	100% air cavities		35to10	85to10% air cav.	_	100% recir.vortices	cir.vo	rtices										- 1
					Slope of stepped spillwa	ped sp	illwa	ıys α3 :	=38,2	,20,											ı ,				
					Step nos.	1	2	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18	19	8
					Max.	2.5	2.5	4.5	5.5	9	5.5	5.5	4.5	4	4	3.5	6.5 3	.25 3	.25	3.3				-	
					Min.	7	2.5	3.5	4	4.5	4	3.5	3.5	3	3	2.5	2.5	7	2	2			_		,
			_		Max.	2.5	2.5	4.5	5.5	9	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	m	3	2.5	2.5	2	7	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	2.63 2.	63	2.6					
					Inception									{			-		-	\dashv	\dashv		+	\dashv	
		_			length(cm)				_								\dashv		_	\dashv	-	\dashv	\dashv	\dashv	٦
	_				Flow patt	100% recir	recir	culating vortices in all steps	IOV 2	tices 1	n all s	teps													

Step nos. 1 2 Max 5 5	ped spil	=	Ilway 22	<u>α</u> <u>ε</u> 4	=34°32'	- N N	3 3	8 6	9	10	11	3.5	13	35	3.5	16	17	18	19 2	12
	Min.	4	3.5	10		2	2.	2.	2.	2.	2.5	2.5	2.5		2.5	+-	+	+-	-	\top
\mathbf{Z}	Мах.	5	5	4	4	3.5	3 3	3	3	3	3.5	3.5	3.5	3.5	3.5	-				
\mathbf{Z}	Min.	7_	3.5	3	3 2	2.8 2.5	5 2.5	5 2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	_				
Ā	Aver.(d _{wps})	4.5	4.25	3.5	3.5 3.	3.15 2.8	8 2.8	3 2.8	2.75	2.75	3	3	3	3	3					
ŢUC	Inception			_											_		_			
len	length(cm)	28					_													
윤	Flow patt	No air	caviti	es,we	No air cavities, weak recirculating vortices	culatin	ng vor	tices												
S	Slope of stepped spillw	bed sp	illway	ays $\alpha_2 =$	=52°14'		 													Γ
St	Step nos.	1	2	<u></u>	4	5	2 9	8	6	10	11	12	13	14	15	16	17	18	19 2	20
Max.	, v	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	1 4	4	4	4.5	4.5	4.5	4.5	4.5	4.5	4	3	3	3
Max.	ر.	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
0.05 Min.		2.8	4.5	5	S	5,	4 4	4	4	4	4.5	4.5	4.5	4.5	4.5	4.5	4	3	3	3
Ave	Aver.(dwps)	3.15	4.5	5.25	5.3	5 4.5	5 4.5	4.5	4.5	4.5	5	5	5	5	5	5	4	3.5	3.5 3	3.5
Ince	Inception															-		_		
leng	length(cm)														_		_	-	_	
Flo	Flow patt	100% air	air cav.		75to5% air cav.	ir cav.	100%	100% recir.vortices	vortic	es		·								\Box
Se	Slope of stepped spillways	ds pad	dlway	క్ర	=38,20,															
St	Step nos.	ī	2	3	4	2	2 9	8 /	6	10	11	12	13	14	15	16	17	18	19 2	20
Max.	tx.	4	3.5	4.5	5.5 5	5.6	6 6.5	6.5	9	5.5	5	4.5	4	4	4				_	
Min.	n.	6	2.8	3.5	4	4.5	5 5	5	4.5	4	3.8	3.5	3	3	3					
Ϊ́Ξ	Max.	4	3.5	4.5	5.5 5	5.6	6 6.5	6.5	9	5.5	5	4.5	4	4	4	_				-
Min.	ij.	3	2.8	3.5	4	7,	5 5	5.	4.5	4	3.8	3.5	3	3	3			_		
A	Aver.(dwps)	3.5	3.15	4	4.8 5.1	5.05 5	.5 5.8	5.8	5.25	4.75	4.4	4	3.5	3.5	3.5				-	П
الحرا	Inception				-									-	\dashv	\dashv		\dashv	-	П
12	length(cm)										•			-	-	\dashv	\dashv	\dashv	\dashv	
Į,	Flow patt	100%	recirc	ulating	100% recirculating vortices in all steps	es in a	ll step	s							_	l				

	18 19 20										18 19 20	5 5 5	4 4 4	5 5 5	4 4 4	4.5 4.5 4.5			!		18 19 20								
	17									ļ	17	5.5	4	5.5	4	4.75					17								
	16										16	5.5	4	5.5	4	4.75					16				<u>-</u> _				
	15	4	3	4	3	3.5					15	5.5	4	5.5	4	4.8					15	4.5	4	4.5	4	4.3			
	14	4	3	4	3	3.5					14	5.5	4	5.5	4	4.75					14	4.5	4	4.5	4	4.25			•
	13	4	3	4	3	3.5					13	5.5	4	5.5	4	4.75					13	5	4.5	5	4.5	4.75			
	12	4	3	4	3	3.5					12	5.5	4	5.5	4	4.75					12	5.5	4	5.5	4	4.75			
	11	4	3	4	3	3.5					11	5.5	4	5.5	4	4.75					11	5.5	4.5	5.5	4.5	5			
	10	4	3	4	3	3.5					10	5.5	4	5.5	4	4.75					10	9	5	9	5	5.5			
	6	4	3	4	3	3.5					6	5.5	4.5	5.5	4.5	S			tices		6	6.5	5.5	6.5	5.5	9			
	8 /	4	3 3	4	3	3.5			tices		8	5.5	4.5	5.5	4.5	5			100% recir.vortices		8	7	5.5	7	5.5	6.3		_	
	2 9	4	5 3	4 4	3	3.5	_		g vor		1 9	5.5	4.5	5.5	5 4.5	5 5			% rec		2 9	7 7	9	7 7	9	3 6.5		L	
	5		5 3.5		.5 3.5	4 3.8			ulatin		5	5.5	5 4.5	5.5	5 4.5	5		_	1		5	5	5.5		5.5	6.3	_	_	
=34°32	4	5 4.5	3.5	5 4.	.5 3.	5			recirc	,14,	4	2	5 4.5	5.5	5.4				ir cav.	=38,20,	4	9	5.5	.5 6.5	5.5	5		L	
$\alpha_1 = 34$	3	5.	5 4.5	5.	4	5			No air cavities, weak recirculating vortices	$\alpha_2 = 52^{\circ}$	3	5.5	5	5.5	5	5 5.3		_	60to10% air cav.	$\alpha_3 = 38$	· E	5 5.5	4 4.5	2	4.5			L	
ways c	2	6 5.5	5 4.5	6 5.5	5 4.5	5.	_		vities,	ways c				نہ	3	.5				ways c	7	.5 4.5		.5 4.5	33	25 4.25	_	_	
	1	9	2	9	5	5		30	air ca	spilly	1	4	4	4 4.	4	4			100% air	spilly	<u>—</u>	(C)		3		4 3.2			
padd						5.5	_	3	2	padd	_	L	3.5		3.5	3.75	_	_	100	pbed	_	4.5	3.5	4.5	3.5			_	
Slope of stepped spil	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	Flow patt	Slope of stepped spill	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	Flow patt	Slope of stepped spill	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	
			-	n/m)		•									0.06 Min.					• <u> </u>		•	<u> </u>		<u> </u>				
Vidth I	ų.	illw.	ways ((b m)				•			•	•			0.5							-							
Disch. Width Disch.	(Q) of	(cum) spillw. length	3	<u>(1</u>	-					-			-		0.012														
SN Mano D		_	(x cm)		_							-			6.63 0.012														
ĮΫ	me	rea	<u>×</u>												4														

	L	19 20										19 20	5.5	5 4.5	5.5	5 4.5	5 5					19 20							
	L	18			_						!	18 1	5.5 5.5	4.5 4.5	5 5.5	5 4.5	5					18 1				_			
	L	17		_			_					17 1	5.5 5.	4.5 4	5.5 5.5	.5 4	2					17 1		_	_				
	L	16					_	_				16	5.5 5	4.5 4	5.5 5	4.5 4	5		_			16				_			
	ļ	15	4	3	4	3	.5		_			15	5.5 5	4.5 4	5.	4.5 4	5					[5]	5	4	5	4	.5		
	L	14	4	3	4	6	3.5 3.		_			14	5.5 5	4.5 4	5.5 5	4.5 4	5					14	5	4	S	4	4.5 4.		
	,	2	4	n	4	3	3.5					13	5.5	4.5	5.5	4.5	5					13	5	4	5	4	4.5		
	,	77	4	α	4	3	3.5					12	5.5	4.5	5.5	4.5	5					12	5.5	4.5	5.5	4.5	, 5		
		11	4	3	4	3	3.5					11	5.5	4.5	5.5	4.5	5			5.5		111	9	4.5	9	4.5	5.25		
	(2	4	3	4	3	3.5					10	5.5	4.5	5.5	4.5	5			100% recir.vortices from step		10	6.5	5	6.5	S	5.75 5		
	,	6	4	3	4	3	3.5					6	5.5	4.5	5.5	4.5	5		_	es fro		6	6.5	5.5	6.5	5.5	9		Г
	,	×	4	3	4	3	3.5			SS		8	5.5	4.5	5.5	4.5	5			vortic		8	6.5	5.5	6.5	5.5	9		
	ŀ	7	4	3	4	3	3.5			No air cavities, weak recirculating vortices		7	5.5	4.5	5.5	4.5	5		_	recir.		7	7	5.5	7	5.5	6.3		
		٥	4.5	3	4.5	3	3.8			ating		9	5.5	5	5.5	5	5.3			100%		9	6.5	5.5	6.5	5.5	9		
12		2	5	3.5	5	3.5	4.25			circul	14'	5	5.5	5	5.5	5	5.25			Г	<u>.</u>	5	9	5	9	5	5.5		
-2012	5	4	5	4	5	4	4.5			eak re	=520]	4	5.5	5	5.5	5	5.3			50to10%aircav.	$\alpha_3 = 38^{\circ}50^{\circ}$	4	5.5	4.5	5.5	4.5	5		
			5.5	7	5.5	4	4.75			ties,w	ıys α ₂	3		5	5	5	5			50to1	ays α_3	3	4.5	4	4.5	4	4.25		
		2		5	9	5	5.5			r cavi	oillwa	2	4.5	4.5	4.5	4.5	4.5			air		2	4	3.5	4	3.5	3.75		
nod e	lo mad	1	6	5	9	5	5.5		30	No a	bed sl	1	4	3	4	3	3.5			100% air	ped s	1	5.5	4.5	5.5	4.5	5		
Slope of stenned snilly	nobe or sech	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)	Flow patt	Slope of stepped spillways	Step nos.	Max.	Min.	Max.	fin.	Aver.(dwps)	Inception	length(cm)	Flow patt	Slope of stepped spillw	Step nos.	Max.	Min.	Max.	Min.	Aver.(d _{wps})	Inception	length(cm)
		Ħ		(b)	cum/m)		<u> </u>	<u>1 — </u>	<u>i — </u>	<u> </u>	<u> </u>	نما	15	<u> </u>		0.07 Min.	144	<u> </u>	<u>1 – </u>	1174	<u>دما</u>	<u>دۍ ا</u>		<u>14</u>	15	<u> </u>	1*	<u> </u>	<u>–</u>
Vidth IT	, 10111 v	ot	pillw. It	ways ((p m)		<u>. </u>									0.2				<u> </u>								_	
Diech Width Diech	115011	<u>ಿ</u>	(cum) spillw. length	<u>*</u>	<u> </u>	-	_									0.014										_	-		
Г		metre ((reading ((x cm)			_							_		9.03													
CN Mono	<u> </u>	Ē	ĭë	<u>×</u>	·											Ŋ				_							•		

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SN Mano		Disch. Width Disch.	Disch		Slope of stepped spilly	ed spi	llways	α	=34°32														
metre	<u>©</u>	of	perunit		Step nos.	1	2	3	4	5	9	7	8	9 1	10 1	$1 \mid 12$	13	14	15	16	17	18	19
CII)	reading (cum)	(cum) spillw. length	length	_	•	7	7.5	7	9	2	4	4	4	4	4	4 4	4	7	4				
	(x cm)	ways	<u> </u>	Min.		5	5.5	S	4	4	3.5 3	3.5 3	5.3	5.3	5.3	.5 3.5	3.5	3.5	3.5				-
		(p m)	cum/m)	n) Max.		7	7.5	7	9	S	4	4	4	4	4	4	4	4	4				-
				Min.		5	5.5	5	4	4	3.5 3.	3.5 3	.5	5.	5.3	5 3.5	3.5	3.5	3.5				
				Ave	Aver.(dwps)	9	6.5	9	S	4.5	3.8 3	3.8 3	ω. 	.75 3.75	5 3.75	5 3.75	3.75	3.75	3.8			<u> </u>	-
				Ince	Inception	-				,	\vdash	_	L			_					<u> </u>		
				leng	length(cm)	32					L		_										
	·	-		Flow	Flow patt	No air ca		es,strc	ng re	vities, strong recirculating	ting v	vortices	လ္လ									-	
				Slop	Slope of stepped spillways	ed spi	llway	$s \alpha_2 =$	$=52^{\circ}14$													•	
				Step nos.	nos.	П	2	3	4	5	9	7	<u></u>	9 1	10 1	1 12	13	14	15	16	17	18	19
	-			Max.		4.5	4.5	S	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	4.5 4	4.5 4.5	5 4.5	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	3.	5.5 5.	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5 5.5
-	11.8 0.016		0.2	0.08 Min.		3.5	4.5	4	4	4	4	.5 4		5.4.	5 4.5	5 4.5	4.5	4.	4.5	4.5	4.5	4.5	4.5 4.5
		-		Ave	Aver.(d _{wps})	4	4:5	4.5	4.5	4.5.	4.5	5	5	5	5	5 5	5	5	5	5	2	5	5
				Ince	Inception			_				_		_			_				_	-	<u> </u>
				leng	length(cm)							_	_						·				
				Flow	Flow patt	100to 109	120	r cav.	air cav. In step	1,2	6	10	% rec	ir.vorti	100% recir.vortices from	step	4 onward	Į Į					
				Slop	Slope of stepped spillways	ed spi	llway	క	=38,20	_													
				Step nos.	nos.	T	7	3	4		9	7	<u>∞</u>	9 1	10 11	1 12	13	14	15	16	17	18	19
				Max.		5.5	4.5	4.5	5.5	9	6.5	7	7.5	7 6.5	5 6.5	9	5.5	5.5	5.5				
	•	-		Min.		4.5	4	4.5	4.5	5 5	5.5	9 9	6.5	6 5.5	5.5	5	4.5	4.5	4.5		-	:	
				Max.		5.5	4.5	4.5	5.5	9	6.5	7 7.	3.	7 6.	5 6.	5 6	5.5	5.5	5.5	_	\vdash		_
				Min.		4.5	4	4.5	4.5	5.	5.5	9 9	ιζ.	6 5.	5.5	5	4.5	4.5	4.5				H
				Aver	Aver.(d _{wps})	5 4	4.25	4.5	5	5.5	9 9	5.5	9 /	5	9	6 5.5	5	3	5				
				Inception	ption								_										
	···			lengi	length(cm)		_				_												
				Flow	Flow patt	100% recirculating vortices in	ecirca	lating	vorti		all	steps											

				Discii. Widiii Discii.	Stope of stepped spillw	sed sp	illwa	ays α ₁ =	=34.32	_														
metre	<u> </u>	of	perunit		Step nos.	1	2	3	4	5	9	7	8	9 1	10 11	1 12	13	14	15	16	17	18	19	20
reading	_	(cum) spillw. length	length		Max.	6	10	8	7	9	5.5	5 4	.5 4	5 4.5	5 4.5	5 4.5	4.5	4.5	4.5					
(x cm)		ways	<u>_</u>	~	Min.	7	9	5.5	2	4.5	4.5	4 3	3.5 3.	3.5 3.5	5 3.5	5 3.5	3.5	3.5	3.5					
		(p m)	cum/m)		Мах.	6	10	8	7	9	5.5	5 4	5	4.5 4.5	4	.5 4.5	4.5	4.5	4.5					
					Min.	7	9	5.5	\$	4.5	4.5	4 3	5.3	.5 3.	.5 3.	.5 3.5	3.5	3.5	3.5					
				~	Aver.(dwps)	8	8	6.75	6 5	.25	5 4	.5	4	4	4	4 4	4	4	4					
				<u> </u>	Inception								-											
					length(cm)	38																		
				1,	Flow patt	No air	cavit	ies,str	No air cavities, strong recirculating vortices	ircula	ting v	ortice	S			. 1								
				<u>رس</u>	Slope of stepped spillways	ed sp	illwa	ဦ	=52°14												i			
				دما	Step nos.	1	7	8	4	5	9	7	8	9 1	10 1.	12	13	14	15	16	17	18	19	20
		·		<u> </u>	Max.	4.5	4.5	5	5	5	5	5 5	.5 5.	5	6 6.5	5 6.5	6.5	6.5	7	7	7	6.5	9	9
•				1=4	Min.	3.5	4.5	5	5	5	5	5	5	5	5.5	5.5	5.5	5.5	9	9	9	5.5	5	5
		_	-	1~	Max.	4.5	4.5	5	S	5	S	5 5	.5 5.	5	9 6.5	5 6.5	6.5	6.5	<i>L</i>	L	7	6.5	9	9
14.97	14.92 0.018	.8 0.2		0.09 Min.	Min.	3.5	4.5	5	s)	5	5	5	5	5	5 5.	5 5.5	5.5	5.5	9	9	9	5.5	2	5
				~	Aver.(d _{wps})	4	4.5	5	5	5	5	5 5	3 5.2	.25 5.5		9 9	9 _ 9	9	6.5	6.5	6.5	9	5.5	5.5
					Inception							_												
				<u> </u>	length(cm)																			
					Flow patt	100to5%		air cavities in	es in s	steps 1	,2,3		100	100% recir.vortices from step 4 onwards	r.vortic	es fron	n step	4 onwa	rds					
				<u> </u>	Slope of stepped spillw	ds pac	illwa	ays α3 =	=38,20	_														
				<u> </u>	Step nos.	τ	2	3	4	5	9	7	8	9 1	10 1.	1 12	13	14	15	16	11	18	19	20
				154	Max.	9	5	5	5.5	9	7	8	8 8	5 8.5	5 7.5	5 7.5	6.5	5.5	5.5					
					Min.	5	4	4	4.5	5	5.5	9	9 9	6.5 6.5		9 9	5.5	4.5	4.5					
			<u> </u>	155	Max.	9	5	5	5.5	9	7	<u>∞</u>	∞ ∞	8.5 8.5	5 7.5	5 7.5	6.5	5.5	5.5					
			:	<u> </u>	Min.	5	4	4	4.5		5.5	9	9 9	.5 6.5		9 9	5.5	4.5	4.5					
				<u> </u>	Aver.(d _{wps})	5.5	4.5	4.5	5	5.5	6.3	7	7 7	7.5 7.5	5 6.75	5 6.75	9	5	5					
				_	Inception																			
					length(cm)					H														
					Flow patt	100%	recir	ulatin	100% recirculating vortices in all steps	ces in	all ste	_ sda												

SN	SN Mano	Disch.	Disch. Width Disch.	Discl		Slope of stepped spilly	ed sb	illways	ช	=34°32'															
	metre	<u> </u>	of	perunit	-	Step nos.	17	2	3	4	5	9	7	8	9 1	10 11	12	13	14	15	16	17	18	19	20
	reading		(cum) spillw. length	length		Max.	6	6	∞	7	6.5	9	5	5	5	5 5	2	5	5	5					
	(x cm)	.	ways	<u>_</u>		Min.	. 7	6.5	9	5	5	4.5	4	4	4	4 4	4	4	4	4					
			(p m)	cum/m)		Max.	6	6	8	7	6.5	9	5	2	2	5 5	5	5	5	5					
						Min.	7	6.5	9	5	5	4.5	4	4	4	4 4	4	4	4	4					
						Aver.(d _{wps})	8	7.75	7	9	.75	5.3 4	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	cavit	No air cavities, strong recirculating vortices	ing rec	circul	ating v	/ortice	S.											
					102	tepl	ed sb	illways	$^{1}S \alpha_{2} =$	=52°14	<u>.</u>														
					ر ت	Step nos.	1	2	3	4	5	9	7	∞	9 10	0 11	12	13	14	15	16	17	18	19	20
					<u></u>	Max.	4.5	4.5	S	5	5	5	5 5	.5 7.	5 7.5	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	1.5	5) 9	9 9	9	9	9	9	9	9	9	9	9
		-			<u>~</u>	Max.	4.5	4.5	5	5	5	5	5 5	.5 7	.5 7.	.5 7.5	7.5	1.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
∞	18.42	0.02	0.7		0.1	Min.	4.5	4.5	4.5	4.5	4.5	4.5 4	4.5	5) [9	9 9	9	9	9	9	9	9	9	9	9
					_ ~	Aver.(d _{wps})	4.5	\vdash	4.75	4.8 4	.75	4.8 4	4.8 5	.3 6.7	5 6.7	5 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	, in ste	ep 1,2		101	100% reci	ir.vorti	recir.vortices from	n step	3 onward	ards						
					<u> </u>	Slope of stepped spilly	ed sb	illway	န္ထင္သ	=38,20	_	ļ ,					·					i			
			٠		1 	Step nos.	T	2	3	4	5	9	7	∞	9 10	0 11	12	13	14	15	16	17	18	19	20
				-	⊏.	Max.	7.5	9	5	5.5	9	7	8	.5	6	6 6	8.5	8.5	8	8					
						Min.	5.5	5	4.5	4.5	5	5.5	9 9	6.5	. 1	7 7	6.5	9	9	9	•			-	
						Max.	7.5	9	5	5.5	9	7	∞ ∞	5	6	6 6	8.5	8.5	8	8					
						Min.	5.5	5	4.5	4.5	5	5.5	9 9	6.5	, /	7 7		6.5	6	9					
				-		Aver.(d _{wps})	6.5	5.5	4.75	2	5.5	6.3	7 7	.5	∞	8 8	7.5	7.5	7	7					
					لڪ	Inception					\dashv			-		_								Ì	
					==1	length(cm)				_	•	\dashv	-	-	_										
	,					Flow patt	100% rec	recirc	irculating vortices	yvorti	ices 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

3	3 3 3 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5	2	3 3 3 2.5 2.5 2.	3 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	25 2.5 2.5 2.5 2.25 2.3 2.3 2.3 2.25 2.25		55	ities, weak	ays $\alpha_2 = 52$	8	3.5 4.5 5.	2 3 4.5 5.5 5 5 4.5 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 4.5 5.5 6 5.5 5 4 4	4.5 5.5 5 4.5 4 3.5 3.5 3	25 3.25 4.5 5.5 5.5 5.5 5 4.5 3.8 3.75 3.75 3.75 3.75 3.75 3.75 3.75 3.75			cavities	రో	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20		3 4.5 4.5	1	2	2.25 3.		
0 1	2.		S		2.			pe nor s				5 3.	ĺ	5 3				r.vortices			$ldsymbol{ld}}}}}}$		7		2		
	12		5.2		25 2.			ther nap				.5 3.		3.				00% reci		L_		3.5	3.	5	3.		
8		2	2.5	7	3			ces,nei		8	4		4	3.5	<u> </u>	· ·				8	5	4	5	4	4.5	_	
	2	L.	2		2			g vorti							<u> </u>			25%			2		S				
L	5 2	L	.5					culatir			Щ			Ľ.	i.	_				L	5 5		5.	iر.			_
4		2		7	5 2.			k recir	2°14'	4	.5		.5	نہ	5	_			8,20	4	5 5	1,	3	3	5		_
<u> </u>	3	7	3	7	3.			s,weal	ర	ı	5	.5	5		5	-		ities	రో	n		<u> </u>	<u></u>				
2	3	2	3	2				cavitie	Iways	7	· '			ł		_			lways	7	2.5	7	2.5	7			_
	3.5	3	3.5	3			25	No air	ed spil	1	L	2	2.5	7		-		100%	ed spi	<u> </u>	2.6	L.	2.6	1			۶.
Step nos.	Max.	Min.	Мах.	Min.	Aver.(dwps)	Inception	length(cm)		Slope of stepp	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	length(cm)	Flow patt	Slope of stepp	Step nos.	Max.	Min.	Max.	Min.	Aver.(dwps)	Inception	leneth(cm)
														0.03							*						
of	spillw.	ways (-	, -			-				0.2										-			
<u> </u>	(cum)													0.006	,												
metre (-	-									1.66													
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(b m) (c m) (b m) (c m) (b m) (d m)		reading	\sim	spillw	v. len		Max.	4	3.5	6.2	3	3	3	3	3	3	3	3	3	8	3	3	-		ļ. -		
(b m) cum/m) Max. 4 3.5 3.5 3.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2		(x cm)		ways			Min.	3	2.8	2			2.5					2.5	2.5	5	5		-	-		-	
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Inception Ince							Aver.(d _{wps})	1	3.15	3.15	2.8	2.75	2.8	2.8	<u>∞</u>							2.8			-	-	Π
Elow patt No air cavities, weak recirculating vortices, neither nappe nor skimming flow Slope of stepped spillways $\alpha_2 = 32^{\circ}14$ Slope of stepped spillways $\alpha_2 = 32^{\circ}14$ Max. 2.8 4.5 5.5 5.5 5.4 4 4 2.2 4.4 4.5 4.6 4.8 5 4.8 Max. 2.8 4.5 5.5 5.5 5.5 5.5 5.5 5.4 4 4 3.5 3.6 3.8 4 4 4 3.8 Slope of stepped spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the spillways of a series of the series of the spillways of a series of the series							Inception					-					-		-		_		\vdash				
Elow patt No air cavities, weak recirculating vortices, neither nappe nor skirmning flow Stepped spillways $\alpha_2 \pm 32^{\circ}14^{\circ}$. Slope of stepped spillways $\alpha_2 \pm 32^{\circ}14^{\circ}$. Max. 2.8 4.5 5.5 5.5 5.5 5.5 5.4 4 4.2 4.4 4.5 4.6 4.8 5 4.8 Min. 2.4 4.5 5.5 5.5 5.5 5.5 5.5 5.5 5.5 5.5 5							length(cm)	20					-			-		-					-				
Slope of stepped spillways $c_2 = 52^\circ 14^\circ$ Step nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 Max. 2.8 4.5 5 5.5 5.5 5 4.5 4 4 2.4, 4.4 4.5 4.6 4.8 5 4.8 Min. 2 4 5 5.5 5.5 5.5 5 4.5 4 4 3.5 3.6 3.8 4 4 4 4 3.8 Aver.(d _{wp}) 2.4 4.25 5 5.5 5.5 5 5 4.5 4 4 3.7 3.9 4.1 4.25 4.4 4.5 4.3 4.3 8.3 1.6 pto. Step nos. 1 1 2 3 4 5 6 6 5.5 5.5 5 5 4.5 4 4 3.7 3.9 4.1 4.25 4.4 4.5 4.3 4.3 8.3 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8								No air	cavi	ies,we	ak re	circul	ating	vortice	es,nei	ther n	appe	TOT Sk	immi	off gr		\vdash	1			1	
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2.95 0.008 0.2 0.04 Min. 2.8 4.5 5 5.5 5.5 5.5 5.4 4 4.2 4.4 4.2 4.4 4.5 4.6 4.8 5 4.8 Min. 2.8 4.5 5 5.5 5.5 5.5 5.5 5.5 5.5 5.5 5.5 5							Step nos.	1	2		4	5	9	7	8	6	10	11	12	13	14	15	16	17	18	19	20
Min. 2. 4 5 5.5 5.5 5.5 5.4 4 4 3.5 3.6 3.8 4 4 4 3.8 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 3.8 4 4 4 4 3.8 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 3.8 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4							Max.	2.8	4.5		5.5			5	4.5	4		4.2	4.4				5		4.5	4.5	4.5
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2.95 0.008 0.2 0.004 Min. 2 4 4.25 5.5 5.2 5.3 4.8 4.3 4 3.5 3.6 3.8 4 4 4 4 4 3.8 1.8 Aver.(d _{wps}) 2.4 4.25 5 5.5 5.2 5.3 4.8 4.3 4 3.75 3.9 4.1 4.25 4.3 4.4 4.5 4.3 Inception length(cm)						<u>.</u>	Max.		4.5	5	5.5	5.5			4.5	4	<u> </u>	4.2	4.4		9		5		4.5	4.5	4.5
tion h(cm) 2.4 4.25 5 5.25 5.25 5.25 4.8 4.3 4.3 75 3.9 4.1 4.25 4.3 4.4 4.5 4.3 4.3 4.3 4.3 4.3 4.3 4.3 4.3 4.3 4.3	7		0.00		7	0.04	Min.		4	5	5.5	5	5	4.5	4	4	5.		3.8	4	4	4	4	∞	3.5	3.5	3.5
h(cm) h(cm)							Aver.(d _{wps})		4.25	5	5.5	5.25			4.3	⊢	1.75	3.9	-	.25	3	4.	ا	4.3	4	4	4
hf(cm) hf(cm) patt 100% air cavities							Inception									_			<u> </u>			_	_		_	_	
e of stepped spillways α_3 =38°50¹ 50 to 80% air 100% recir.vortices nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 nos. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 nos. 3 3.6 4.5 6 6 5.5 5.5 4.5 4 3.8 3.5 3.5 3.5 3.5 1 3.8 3.5 4 4.5 4.5 4.5 4.5 4.5 4.5 3.8 3.5							length(cm)									_		-		_	-	_		-	_		
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() 5 100% rec						<u>. '</u>]	Inception																			_	
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	11	3	2.8	3	2.8	2.9					11	4.5	4	4.5	4	4.25					11	S	4	S	4	4.5						
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	6	3	2.8	3	2.8	2.9					6	4	3.5	4	3.5				100% recir.vortices		6	5.5	4.5	5.5	4.5	5	-		֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֓֡֓֓֡֓֓֓֡֓֡			
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	7	3	2.8	€.	2.8	2.9			vortic	i	7	S	4.5	5	4.5	4.8			%00		7	5.5	4.5	5.5	4.5	S			teps			
	9	4	3	4	3	3.5			eak recirculating vortices		9	5.5	5	5.5	5	5.3				İ	9	5.5	4.5	5.5	4.5	5			ng vortices in all steps			
.2	5	4	3	4	3	3.5			ircul	-	5	5.5	5.5	5.5	5.5	5.5			% air.	-0	5	5.5	4.5	5.5	4.5	5			ices i			
=34°32	4	4	3	4	3	3.5		-	ak re	=52°14'	4	5.5	5.5	5.5	5.5	5.5			60to 10% air.	-38,20	4	S	4	N	4	4.5	-		g vor			
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d spil	 	4.5	3.5	4.5	3.5	4		35	No air cavities,w	d spil	1	6	6	1	1	6			100% air cav.	d spil	-	4.8	3.8	4.8	3.8	4.3 3		5	100% recirculati			
eppe	\vdash							<u> </u>		eppe	_	-	-	-	-				1	eppe				H				_	1(
Slope of stepped spillways α_1	nos.					Aver.(d _{wps})	tion	length(cm)	patt	Slope of stepped spillways α ₂	nos.					Aver.(dwps.)	tion	length(cm)	Flow patt	Slope of stepped spillways α_3	nos.					Aver.(dwps.	tion	length(cm)	patt		•	
Slop	Step nos.	Max.	Min.	Max.	Min.	Aver	Inception	lengt	Flow patt	Slop	Step nos.	Max.	Min.	Max.	Min.	Aver	Inception	lengt	Flow	Slop	Step nos.	Max.	Min	Max.	Min.	Aver	Inception	lengt	Flow patt			
Ę.	nit	н.		(m/					,						0.05		*															
Disch.	perunit		<u> </u>	cum/m)											<u></u>		1												_			
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Disch. Width	_ ②	(cum)	<u> </u>	<u> </u>											0.01														-	 		
_	metre (reading ((x cm)									-			4.61			,								,						
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SN	SN Mano	Disch.	Disch. Width Disch.	Disch.	Slope of stepped spilly	ped sp	illwa	vays α_1 :	=34°32	-2														
	metre	<u>0</u>	Jo	perunit	Step nos.		2	3	4	5	9	7	8	9	10 11	<u> </u>	12 13	3 14	4 15	16	17	18	19	8
-	reading	(cnm)	(cum) spillw. length	length		5.5	5.5	5	4.5	4	3.5	3.5	3.5 3	i.	3.5 3.5	3	5.3	5 3.5	3.5					
	(x cm)		ways	<u>(</u> ъ	Min.	4.5	4.5	4	3.5	3	3	3	3	3	3	3	3	3 3	3 3					
			(p m)	cum/m)	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					
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		ı			Inception							-					_	·. 						
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					Slope of stepped spilly	ped sp	illwa	rays α2 =	=52°14	-									ļ ,			;		
					Step nos.	1	2	6	4	5	9	7	8	6	10 1	1 1	2 13	3 14	15	16	17	18	19	20
					Max.	3.5	4.5	5	5.5	4	4	4	4	4	.5	5	5 5.5	5 6	5 5	5	9	9	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	5 4.8	3 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	2	5.5	9 9	5 5	5	9	9	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.	3.5	3 3.5		4.4	5 4.8	3 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 3.7	75 3.7	75 4.25	4.	5	5 5.4	4.9	4.9	5.4	5.4	. 5	5
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					Step nos.		2	3	4	5	9	7	8	9 1	10 11	1 12	1	3 14	15	16	17	18	19	20
					Max.	5	4	4.5	5	5.5	9	9	9	9	6 5.8	8 5.5		5 4	1 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	9	9	9	9	6 5.	.8 5.5		5 4	t 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 5.1	5 4.75	4	5 3.75	3.8					
				_	Inception															·				
					length(cm)	5																		
					Flow patt	100%	recir	100% recirculating vortices in	g vort	ices ii	all	steps												

Slope of stepped spillw
1
9
4
9
4 4
5 4.
25
No air cav
Slope of stepped spillw
7
4
4.
4.
4.
4
100% air
Slope of stepped spillw
·
3.5
4
4
3.75
100% recirculating vortices in all

-	SN Mano	Disch.	Disch. Width Disch.	ı Dis		Slope of stepped spillways	ed sp	illwa	ซี	=34°32	.7														
	metre	<u>0</u>	ot	peru	perunit	Step nos.	1	2	3	4	5	9	7	8	6	10 1	11 1	2 1	3 1	4 15) 16	17	7 18	3 19	20
<u> </u>	reading		(cum) spillw.	. length		Max.	7	9	5.5	5	4	4	4	4	4	4	4	4	4	4 4					
<u> </u>	(x cm)		ways	<u> </u>		Min.	2	5.5	5	4	3.5	3.5	3.5	3.5 3	5.	3.5 3.	5 3.	.5 3.	.5 3.5	5 3.5	15			i	
			(p m)		cum/m)	Max.	7	9	5.5	5	4	4	4	4	4	4	4	4	4	4			_		_
-						Min.	5	5.5	Ñ	4	3.5	3.5	3.5	3.5 3	3.5 3	3.5 3.5	<u> </u>	3.5 3.5	5 3.5	5 3.5	15		_	Ŀ	
					, ,	Aver.(d _{wps})	9	5.75	5.25	4.5	3.75	3.8	3.8	3.8 3.7	75 3.	75 3.7	75 3.7	75 3.7	75 3.75	5 3.8					_
						Inception				-													1		
						length(cm)	25			_							_								
							No air ca	rcavit	vities, strong recirculating vortices	ong re	circul	ating	vortic	es											·
					<u> </u>	Slope of stepped spillways	sed sp	illwa	$VS \alpha_2 =$	=52°14	<u>_</u>														
					<u> </u>	Step nos.	1	2	3	4	5	9	7	8	6	10 1	1 1	2 1	3 14	4 15	16	17	7 18	3 19	20
					L==_	Max.	4	4.5	5	5.5	5.5	5.5	5	5	5 5	5.5	9	9	9	9 9	9	9	9	9	9
						Min.	3.5	4.5	5	S	ئ	5	4.5 4	4.5 4	.S.	4.5	9	5	5	5 5	5	5	ζ.	. 5	5
						Max.	4	4.5	5	5.5	5.5	5.5	5	5	5 5	5.5	9	9) [9	9 9	9 9	9	9 9	9 9	9
9	11.8	0.016	0.7	<u></u>	0.08 Min.			4.5	S	5	5	3	4.5 4	4.5 4	4	5.	9	5	5	ŀ				5 5	_
						Aver.(d _{wps})	3.75	4.5	5	5.3	5.25	5.3	4.8 4	4.8 4.75	75	5	6 5.	5 5.	5 5.	.5 5.5	5.5	5.5	5.5	5.5	5.5
					<u>-</u>	Inception																			
						length(cm)																			
						Flow patt	100% air		50% air		100% recir.vortices	cir.vo	rtices				 -							-	
						Slope of stepped spilly	ds pac	illways	ည်	=38,20	-0														
	-					Step nos.	7	7	3	4	5	9	7	8	6	10 1	1 1	12 1	$3 1^{2}$	4 15	16	17	7 18	3 19	20
						Max.	5.5	4.6	4.5	5	5.5	9	6.5	6.5 6	5.	6.5 6.	.5 6.	6.5	9 (9	9 9					
						Min.	5	4	4	4.5	4.5	5.	5.5 5	5.5 5	5.5 5	5.5 5.5		5.5	5 5	5 5					
						Max.	5.5	4.6	4.5	S	5.5	9	6.5	6.5 6	.5	6.5 6.	.5 6.	6.5	9	9 9	.=				
_						Min.	5	4	4	4.5	4.5	5	5.5 5	5 5	.5	5.5 5.	.5 5.	5.5	5 5	5 5					
					. 7.	Aver.(d _{wps})	5.25	4.3	4.25	4.8	5	5.5	9	9	9	9	9	6 5.	5 5.5	5.5					
					رح	Inception																			
*				1		length(cm)														Ц					
		_		_		Flow patt	100%	recirc	100% recirculating vortices in all	g vort	ices ir		steps												

z	SN Mano	Disch.	Disch. Width Disch.	Disch.	Slope of stepped spilly	ped sp	illways	8	=34°32	<u> </u>														Γ
	metre	<u> </u>	of	perunit	Step nos.	1	2	3	4	5	9	7	8	6	10 1	1 12	2 13		4 15	16	17	18	19	20
	reading		(cum) spillw. length	length	Max.	∞	9	5	4.5	4	4	4	4	4	4	4	4	4	4					
	(x cm)		ways	<u> </u>	Min.	9	5	4	4	3.5	3.5	3.5	3.5 3	3.5 3	5 3.	5 3.	5 3.	.5 3.5	3.5					
			(p m)	cnm/m)	Max.	8	9	5	4.5	4	4	4	4	4	4	4	7	4	4					
					Min.	9	5	4	4	3.5	3.5	3.5	3.5 3.	3	3.5 3.	3.	5 3.5	3.5	3.5					
					Aver.(d _{wps})	7	5.5	4.5	4.3 3	3.75	3.8	3.8	3.8 3.	3.75 3.	3.75 3.75	5 3.75	5 3.75	3.75	3.8					
					Inception						H				_	_	_	L						
				<u> </u>	length(cm)	30							_	<u> </u>	<u> </u>	_	L	_	_					
					Flow patt	No air ca	cavi	ies,str	vities, strong recirculating vortices	circul	ating	vortic	es] "	
	1				Slope of stepped spillways	ds pad	illwa	ಕ	=52°14															T
					Step nos.	1	2	3	4	5	9	7	∞	6	10 11	1 12	2 13	3 14	15	16	17	18	19	20
				,	Мах.	4	4.5	5	5.5	5.5	. 5	5	5	5 5	5.5	6 6.5	5 6.5	5 6.5	6.5	6.5	6.5	6.5	6.5	6.5
1					Min.	3.5	4.5	5	!	1	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
					Мах.	4	4.5	5	5.5	5.5	5	5	5	5 5	5.5	6 6.5	5 6.5	5 6.5	6.5	6.5	6.5	6.5	6.5	6.5
7		14.92 0.018	0.7		0.09 Min.	3.5	4.5				4.5 4	4.5	4.5 4.	5	4.5	ς.	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	5.25	4.8	4.8	4.8 4.75	75	5.5	_	9	9 9	9	9	9	9	9	9
					Inception								<u> </u>		_			L						
					length(cm)									-								T -		
-					Flow patt	100 to 10	10%	I		00% r	100% recir.vortices	ortice	·					ľ						
	_				Slope of stepped spillways	ds pac	llwa	ဗ်	=38°50'	_														
	_				Step nos.	1	7	3	4	5	9	7	<u>∞</u>	6	10 1	1 12	13	3 14	15	16	17	18	19	20
					Max.	9	5	4.8	5.5	9	6.5	6.5	6.5 6	8.9	7 6.8	8 6.5	5 6.5	9	9			-		
	_				Min.	5	4.5	4.2	4.5	5	5.5	5.5	5.5 5	5.5 5	5.5 5.5	5 5.3	3	5	S					
					Max.	9	5	4.8	5.5		6.5		6.5 6	8.9	7 6.8	8 6.5	5 6.5	9	9					
					Min.	5	4.5	4.2	4.5	5	5.5 5	5.5 5	5.5 5	5.5 5	5.5 5.5	5 5.3	3	5				-		
					Aver.(d _{wps})	5.5	4.75	4.5	5	5.5	9	. 9	6 6.15	15 6.25	25 6.15	5 5.9	5.75	5.5	5.5					
					Inception								_											
					length(cm)			Н	\vdash			_	\vdash											
ヿ					Flow patt	100%	recirc	ulatin	100% recirculating vortices in	ces in	all	steps												

\mathbf{z}	SN Mano	Disch.	Widtl	Disch. Width Disch.	Slope of stepped spilly	bed sp	illwa	vays \alpha_1	=34°32	121															
	metre	<u>©</u>	Jo	perunit	Step nos.	1	2	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18	19	20
	reading	(um)	(cum) spillw.	: length		01	∞	7	9	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
	(x cm)		ways	<u>(b)</u>	Min.	∞	9	9	S	4.5	4	4	4	4	4	4	4	4	4	4			-	_	
			(p m)		Max.	10	∞	7	9	5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5					
					Min.	8	9	9	5	4.5	4	4	4	4	4	4	4	4	4	4					
					Aver.(d _{wps})	6	7	6.5	5.5	4.75	4.3	4.3	4.3 4	1.25 4	1.25 4	1.25 4	1.25 4	.25 4	.25	4.3				Н	
	_				Inception						-		-	-											
-					length(cm)	30																			
	<u>.</u>				Flow patt	No air ca	r cavi	ties,st	rongı	ecircu	lating	vities, strong recirculating vortices	ces												
	_				Slope of stepped spillways	bed sp	illwa	ys α ₂	=52°14	4										[
					Step nos.	1	7	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18	19	8
					Max.	4.5	4.5	5	5.5	5.8	5.5	5	5	5	5.5	9	9	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	9	9	9	9	9
					Max.	4.5	4.5	5	5.5	5.8	5.5	5	5	5	5.5	9	9	6.5	6.5	6.5	7	7	7	7	7
80	18.42	0.05	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	9	9	9	9	9
				_	Aver.(d _{wps})	4.35	4.5	4.75	5.3	5.65	5.3	4.8	4.5 4	4.75	5	5.5	5.5	9	9	9	6.5	6.5	6.5	6.5	6.5
	_				Inception																				
					length(cm)								\vdash			-				_					
					Flow patt	100 to 25	25%	air	100%	100% recir.vortices	ortices	_													
	_				Slope of stepped spillw	ped sp	illwa	'S α ₃	=38°50	0.0															
	_				Step nos.	1	2	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18	19	20
					Max.	7	9	5.5	5.4	9	6.5	7.5	∞	∞	∞	7.5	6.5	9	9	9 .					
					Min.	9	2	4.5	4.5	5	5.5	9	6.5	6.5	9	5.5	5.5	5	5	2					
	_				Max.	7	9	5.5	5.4	9	6.5	7.5	8	8	8	7.5	6.5	9	9	9				_	
					Min.	9	S	4.5	4.5	5	5.5	9	6.5	6.5	9	5.5	5.5	5	5	5	_				
		_			Aver.(d _{wps})	6.5	5.5	5	5	5.5	9	8.9	7.3 7	7.25	7	6.5	9	5.5	5.5	5.5					
					Inception													-	-	-	\dashv		+	-	
					length(cm)	5						'								\dashv	\dashv		-	┪	Ţ
					Flow patt	100%	recir	culatin	10V gr	100% recirculating vortices in	all	steps											-		
1)																

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

dV²/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 σ =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

 $\alpha_1 = 34^{\circ}32'$; d1= 0.049m; V1=2.03m/s.(Knight&McDonold)

 $\alpha_2 = 52^{\circ}14'$; d2 = 0.045m; V2=2.24m/s.(Knight&McDonold)

 $\alpha_3 = 38^{\circ}50'$; 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
0.045	0.824	2.24	1	0.5115	0.25574	2.58579	against cavitations
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);

$$\begin{split} qw &= Q/b = 4 \text{ lps/20 cm} = 0.004 \text{ m3/s/0.2m} = 0.02 \text{ m3/s/m} \\ dc &= (qw^2/g)^{1/3} = (0.02^2/9.81)^0.333 = 0.034 \text{ m.} \\ qw &= Q/b = 8 \text{ lps/20 cm} = 0.008 \text{ m3/s/0.2m} = 0.04 \text{ m3/s/m} \\ dc &= (qw^2/g)^{1/3} = (0.04^2/9.81)^0.333 = 0.0546 \text{ m.} \end{split}$$

Table-1.

Qw(lps)	qw(Qw/0.2)	α (degree)	h(cm)	l(cm)	dc/h	h/l	0.05 <h l<="" th=""></h>
	m3/s/m						<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	7	ł

Table-2

Spillways	Upper limit of	Lower limit of	Onset of skimming	Flow
slopes	nappe flow	skimming flow	flow	regimes
,	regimes	regimes	dc/h=0.91-0.14	(NA,
	dc/h=0.89-0.4 *h/l	dc/h=1.2-0.325	* $\tan \alpha$	TRA, SK)
	(Chanson 2001)	*h/l	(Boes And Hager	(From
		(Chanson 2001)	2003)	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 $\alpha=34^{\circ}32'$ (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 $\alpha = 50^{\circ}14^{\circ}$, 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 (1st to 6th) 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 $\alpha = 38^{\circ}50^{\circ}$, 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)	α (degree)	h(cm)	l(cm)	dc/h	h/l	0.05 <h l<="" th=""></h>
	m3/s/m						<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	Upper limit of	Lower limit of	Onset of	Flow
slopes	nappe flow	skimming flow	skimming flow	regimes
	regimes	regimes	dc/h=0.91-0.14	(NA, TRA,
	dc/h=0.89-0.4 *h/l	dc/h=1.2-0.325	*tan \alpha	SK)
	(Chanson 2001)	*h/l	(Boes And Hager	(From table-
		(Chanson 2001)	2003)	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 $\alpha = 34^{\circ}32^{\circ}$ (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 $\alpha = 50^{\circ}14$ ' 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 $\alpha = 38^{\circ}50^{\circ}$ the flow was of concave nature at the junction point of 2^{nd} and 3^{rd} slopes ($\alpha = 50^{\circ}14^{\circ}$ and $38^{\circ}50^{\circ}$) and sprayed in the trajectory path to the D/S of the spillways. The inception point was short i.e. up to 2^{nd} 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

<u>Chapter-4</u> 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	1	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	Slope	Step	Step	h/l	dc(m)	dc/h		dc/h (onsc	t)	Flow
(m3/s)	(a)	height	length			-	Cha	nson	Boes	regimes
	· ·	(h) m	(l)m				NA-TRA	TRA-SK	& Hager	
0.02	34o32'	0.033	0.0484	0.682	0.034	1.043	0.617	0.978	0.815	SK
0.02	52014'	0.05	0.0387	1.292	0.034	0.689	0.373	0.780	0.729	TRA
0.02	38050'	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	52014'	0.05	0.0387	1.292	0.045	0.902	0.373	0.780	0.729	SK
0.03	38050'	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	52014'	0.05	0.0387	1.292	0.055	1.093	0.373	0.780	0.729	SK
0.04	38050'	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	52014'	0.05	0.0387	1.292	0.063	1.268	0.373	0.780	0.729	SK
0.05	38050'	0.0333	0.0414	0.804	0.063	1.904	0.568	0.939	0.797	SK

0.06	34032	0.033	0.0484	0.682	0.072	2.170	0.617	0.978	0.815	SK
0.06	52014'	0.05	0:0387	1.292	0.072	1.432	0.373	0.780	0.729	SK
0.06	380501	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	52014'	0.05	0.0387	1.292	0.079	1.587	0.373	0.780	0.729	SK
0.07	38050'	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	52014'	0.05	0.0387	1.292	0.087	1.735	0.373	0.780	0.729	SK
0.08	38050'	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	52014'	0.05	0.0387	1.292	0.094	1.877	0.373	0.780	0.729	SK
0.09	38050'	0.0333	0.0414	0.804	0.094	2.818	0.568	0.939	0.797	SK
0.1	34032'	0.033	0.0484	0.682	0.101	3.050	0.617	0.978	0.815	SK
0.1	52014'	0.05	0.0387	1.292	0.101	2.013	0.373	0.780	0.729	SK
0.1	38050'	0.0333	0.0414	0.804	0.101	3.023	0.568	0.939	0.797	SK

Calculations of cavitations no.:

d(m)	cosa	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
0.045	0.824	2.24	1	0.5115	0.25574	2.58579	against cavitations
0.048	0.824	2.09	1	0.4453	0.22264	2.26151	1

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 $\alpha_1 = 34^{\circ}32'$ 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 $\alpha_2 = 50^{\circ}14'$, which is steeper than first slope, and the third channel slope $\alpha_3 = 38^{\circ}50'$ 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.

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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=tan\alpha.

- 3. Calculate db flow depth at the brink of step.
- 4. Calculate nappe thickness at the impact with the receiving pool by the relation,

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

5. Calculate impact velocity of the nappe, by;

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

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;

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

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,

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

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;

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

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

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

$$\frac{Qair^{nappe}}{Qw} = 0.21(\frac{h - dp}{dp})^{1.03}$$
 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°<a<52°)

3.Location of the point of inception point;

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

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

4. Flow depth at the point of inception;

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

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;

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

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 $dc = \sqrt[3]{\frac{qw^2}{a}}$

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 $26^{\circ} < \alpha < 55^{\circ}$

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 $F = \left(\frac{fh}{8\sin\alpha}\right)^{\frac{1}{3}}\cos\alpha + \frac{Ec}{2}\left(\frac{fh}{8\sin\alpha}\right)^{\frac{-2}{3}}$

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 d₉₀(d_w) verses distance x graphs
- 2. Flow depth d₉₀ (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:

ន		Г		1	9	-	N			
		<u> </u>	_	L	126	1.6	15	_	_	
19					120	9.1	15			
18					113	8.6	16			
17					107	11	18			
16					101	11	18			
15		82	4.8	5.8	94	12	20	81	10	13
13 14		26	4.8	5.8	88	12	20	75	10	13
		70.3	4.8	5.8 5.8 5.8 5.8	82	13	20	70	11	14 14.1
12		64 7	4.8	5.8	75	13	21	65	11	14
11		59	4.8	5.8	69	14	22	59	11	14
10	_	52.7	4.8	5.8	63	14	22	54	11	14.3
6		46.9 52.7	4.8	5.8	99	13	21	49	11	14.4
8		41	4.9	5.9	20	13	21	44	10	13.2
7		35.1	5		43.5	11.9	19.4	38	10.3	9.47 8.5 8.02 8.99 11.4 11.7 13.2 13.2 14.4 14.3
9		29.3	5.3	6.5 6.4 6.07	38	12	19	32.9	9.1	11.7
2		23.4	5.4	6.5	31	10	17	27.6	8.9	11.4
4		17.6 23.4 29.3	7	8.5	24.9	5.6	15.5	16.9 22.3 27.6	7	8.99
က		11.7	8.6 8.25	10	12 18.5 24.9	8.13	8.5 7.5 13.3 15.5	16.9	6.25	8.02
N		5.9	8.6	10	12	5.2 6.8	7.5	12	7.4 6.6	8.5
-		0	6	11	5.9	5.2	8.5	6.32	7.4	9.47
Step no.		x(cm)	dw90cosa	(d _{w90})cm	x(cm)	0.1 dw90cosa	(d _{w90})cm	х(сш)	dw90cosa	mɔ(06^p)
	(s/ _c m)		=		<u></u> :	0.1				
cosa da			0.82			0.61			0.78	
	 		34032 0.82		_	52014 0.61			38050	7
Sn a	\neg		(4)	ل		1.5			<u>(1)</u>	\dashv

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	_		_	126	L.,		L	_	
19				120	10	16			
18				113	10	17			
17				107	11	18			
16				101	12	19			
15	82	4.5	5.8	94	12	20	81	10	13
4	9/	4.5	5.8	88	12	8	75	10	13
5	70.3	4.5	5.8	82	12	20	2	10	13.2
12	64	4.5	5.8	75	14	22	65	11	14
11	59	4.5	5.8	69	14	22	59	12	15
10	52.7	4.5	5.5	63	14	22	54	12	15.1
6	46.9	4.5	5.5	56	13	21	49	11	14.4
ω	41	4.5	5.5	20	13	21	4	11	13.5
7	35.1	4.5	5.46	43.5	11.6	19	38	10.4	13.3
9	29.3	4.5	5.5	38	11	18	32.9	9.8	12.5
S.	23.4	4.8	5.8	31	6.6	16	27.6	9.8	11.1 12.5
4	17.6	9	7.28	24.9	9.5	15.5	22.3	7	8.99
က	11.7	6.25	7.58	18.5	8.13	13.3	16.9	5.63	7.22
2	5.9	8	6.7	12	8.9	11	12	5.9	7.5
-	0	8	6.7	5.9	4.9	8	6.32	8.9	99.8
Step no.	x(cm)	dw90cosa	mɔ(06mp)	x(cm)	0.09 dw90cosa	шэ(^{06м} р)	x(cm)	dw90cosa	$(d_{\underline{w}90})$ cm
(6)					0.00				
cosα q _w (m3/s		0.82						0.78	
		34032		-	2 52014 0.61			38050 0.78	
Sn a		m			25	ب_		<u>w</u>	

8	Т	T	Τ	छ	4	4	Т	Т	Γ
	- -	↓_	<u> </u>	126	8.4		L	<u> </u>	<u> </u>
19			Ĺ	120	8.5	1.	1		
18				113	8.8	14			
17				107	8.6	18			
16				101	11	18	Γ		
15	82	4.3	5.8	46	11	20	81	6	12
14	76	4.4	5.8	88	11	18	75	6	12
13	70.3	4.4	5.8	82	11	18	70	6	11.6
10 11 12	49	4.3	5.8	75	13	20	65	8.6	14
Ξ	59	4	5.8	69	13	22	59	11	13
10	52.7	4	4.9	63	14	22	54	12	14.8
6	46.9 52.7	4	4.9	26	14	21	49	11	14
80	41	4.5	5.5	50	12	20	44	11	13.5
7	35.1	4.5	5.46	43.5	11.6	19	38	88'6	12.7
9	29.3	4.5	5.5	38	11	18	32.9	8.1	10.4 12.7
2	23.4	5.5	6.7	31	9.9	16	27.6	7.9	10.1
4	17.6 23.4	5.5	19.9	24.9	9.13	14.9	22.3	6.25	8.02
8	11.7	6.25		18.5	7.75	12.6	16.9	5.13	6.58
2	5.9	7.3	8.8 7.58	12	6.3	10	12	5.4 5.13	6.9 6.58
-	0	7.9	9.6	5.9	4.6	7.5	6.32	6.8	8.66
Step no.	x(cm)	dw90cosa	(d _{w90})cm	x(cm)	0.08 dw90cosa	(d _{w90})cm	x(cm)	dw90cosa	(d _{w90})cm 8.66
qw (m3/s)					0.08				
cosa qw (m3/s		0.82			0.61			0.78	
		34032 0.82		-	3 52014 0.61			38050 . 0.78	
Sυα	<u> </u>				n				

	1	_	-	<u> </u>	<u> </u>	آج،	_	1	
8				126	7.5	12		_	
19				120	7.5	12			
18				113	8.1	13			
17				107	6	15			
9				101	6	15			
15	82	4.2	5.8	24	9.3	15	81	9	7.7
14	76	4.2	5.8	88	10	17	75	9.9	8.5
13	70.3	4.2	5.8	82	11	19	70	7.4	11 9.47
127	64	4.2	5.8	75	12	19	92	8.3	•
Ę	59	4.2	5.8	69	13	77	59	8.5	11
10	52.7	4.2	5	63	13	17	54	8.5	10.9
6	46.9	4	4.9	99	13	21	49	9.3	11.9
8	41	4	4.9	20	12	19	44	9.3	11.9
2	35.1	4	4.85	43.5	11.4	18.6	38	8.5	10.9 11.9 11.9 10.9
9	29.3	4	4.9	38	11	17	32.9	8.1	10.4
Ω.	23.4	4	4.9	31	6.6	16	27.6	7.4	9.47
4	17.6 23.4	5		24.9	8.88	13 14.5	.22.3	9	7.7
က	11.7	5	6.1 6.07 6.07	18.5	7.95 8.88	13	16.9 22.3 27.6	4.63	5.94
2	5.9	5	6.1	12	6.3	10	12	4.6	5.9
_	0	5.4	6.5	5.9	4.4	7.1	6.32	5.5	7.06
cosα q _w Step no. (m3/s)	x(cm)	dw90cosa	(d _{w90})cm	x(cm)	0.07 dw90cosa	(d _{w90})cm	x(cm)	dw90cosa	(d _{w90})cm
qw (m3/s)					0.07				
cosa		0.82			0.61			0.78	
		34032 0.82			4 52014 0.61			38050 0.78	
Sn α					4				

													_			
8	T				126	5.8	9.4							20		_
5					120	9	8.6						ı	19		
18	7				113	6.5	11							18		
17	7	1			107	7.5	18		_					17		-
16	1	1	1		101	8	13							16		_
15	+	82	4.1	5.8	94	7.8	20	81	5.9	53			i	15	82	-; •
14	1	92	3.8	5.8	88	8.3	13	75	5.9	7.5				14	9/	
13		703	3.9	5.8	82	6	15	70	6.3	8.02				13	70.3	Ī
12	_	40	3.7	5.8	75	10	16	65	6.3	14				2	64	Ī
=		59	3.5	5.8	69	11	22	59	7	6				F	59	Ī
9		52.7	3.5	4.2	63	11	18	54	9.5	12.2				0	52.7	Ī
6		46.9	3.5	4.2	99	11	21	49	9.3	11.9				6	46.9	l
8	1	41	3.5	4.2	50	10	16	44	8.6	11.1		•		8	41	ŀ
7		35.1	3.5	4.25	43.5	101	16.3	38	∞.	10.3				7	35.1	
9		29.3	4.5	5.5	38	2	16	32.9	8.3	10.6				9	29.3	ŀ
2		23.4	4.5	5.5	31	9.9	16	27.6	6.3	8.02				2	23.4	ŀ
4		17.6	4.5	5.46	24.9	8.75	14.3	22.3	5.38	6.9				4	17.6	ŀ
8	-	11.7	4.5	5.46 5	18.5	7.5	12.2 1	16.9	4.65 5	5.97				က	11.7	L
7		5.9 1	5.5	6.7 5	12 1	5.9	9.6	12 1	4.5 4	5.8 5				N	5.9 1	L
-	\dashv	0	5.5	6.7		<u> </u>	7.3	丄	5.5	90:				-	0	l
<u> </u>	\dashv			<u> </u>	ᆫ	 	 _	9	ᄂ	7				<u> </u>	╄	ł
Step no.		x(cm)	dw90cosa	(d _{w90})cm	X(CIII)	0.06 dw90cosa	(d _{wen})cm	x(cm)	dw90cosa	(d _{w90})cm				Step no.	x(cm)	
ď.	(m3/s)		-			0.00								qw (m3/s)		
cosa d.			0.82			0.61		Γ	0.78					σοοσ		_
۴		-	34032		-			\vdash	38050					-	\vdash	_
8	_	_	346		_	5 52014		L	38					Sn α	1	_
Sn		l				٠,					1			l?	1	

		*										·														
_	П			126	8.8	4.6	_					8	7	_	\neg	126	8.4	6:7	\neg	$\overline{}$		٠				
+	1		-	120	9	8.6	7		٦		-	19	\dashv		7	120	8.4	7.7	十							
	1		_	113	6.5	11			\exists		٠.	18	1	_		113	2	8.2	1		┪					
-	┪			107	7.5	18						17				107	5.3	8.6	7							
	1			101	8	13						16	٦			101	5.3	8.6		7	\dashv					
	82	4.1	5.8	94	7.8	20	81	5.9	13			15	82	3.4	5.8	94	5.3	8.6	81	5	6.4					
_	92	3.8	5.8	88	8.3	13	75	5.9	7.5			14	76	3.4	5.8	88	5.5	6	75	N	6.4					
	70.3	3.9	5.8	82	6	15	70	6.3	8.02			13	70.3	3.4	5.8	82	9	8.6	2	5.4	6.9					
	64	3.7	5.8	75	10	91	9	6.3	14			12	64	3.4	5.8	75	6.8	11	65	6.1	14					•
	59	3.5	5.8	69	11	22	59	7	6			11	59	3.3	5.8	69	7.5		ш	6.3	8					
1	52.7	3.5	4.2	63	11	18	54	9.5	12.2			9	52.7	2.9	3.5	63	8.6		54	6.4	8.22					
	46.9	3.5	4.2	99	L	21	49	9.3	11.9			0	46.9	2.9	3.5	95	5.5	6	Ш	6.8	8.7					
	41	3.5	4.2	50	10	16	44	8.6	11.1			8	41	2.8	3.3	50	8.3	13	44	7.1	9.15		•			,
	35.1	3.5	4.25	43.5	10	16.3	38	8	10.3			7	35.1	2.9	3.52	43.5	œ.	13.1	38	6.53	8.38					•
	29.3	4.5	5.5	38	10	16	32.9	8.3	10.6			9	29.3	2.9	3.5	38	7.8	13	32.9	6.3	8.02					
	23.4	4.5	5.5	31	9.6	16	27.6	6.3	8.02			5	23.4	2.9	3.5	31	7.8	13	27.6	9	7.7		*			
	17.6	4.5	5.46	24.9	8.75	14.3	22.3	5.38	6.9			4	17.6	2.9	3.52	24.9	6.75	11	22.3	5.25	6.74					
	11.7	4.5	5.46	18.5	7.5	_	16.9	4.65	5.97			က	11.7	3.75	4.55	18.5	9	9.79	16.9	4.25	5.46					
	5.9	5.5	6.7	12	5.9		12	4.5	5.8			2	5.9	1	4.6	12	5	8.2	12	3.4	4.3					
	0	5.5	6.7	5.9	4.5	7.3	6.32	5.5	7.06			-	0	3.8	4.6	5.9	3.5	5.7	6.32	4.4	5.62					
	(1	as oo	(d _{w90})cm	2	cosa	(d _{w90})cm		.esoo	1			no.	2	cosa	(d _{w90})cm		ES OS	(d _w q ₀)cm	1 1	cosa	mɔ(06 ^m p)					
	x(cm)	dw90cosa	(d	x CED	0.06 dw90cosa	d _{w9}	x(cm)	dw90cosa	9			Step no.	x(cm)	dw90cosa	d M	X(CII)	0.05 dw90cosa	d d	x(cm)	dw90cosa	(d _{w90}					
(m3/s)												qw (m3/s)														
		0.82			0.61			0.78				cosa		0.82			0.61			0.78						
		34032			52014		T	38050						34032			6 52014			38050						
	-	<u></u>		<u></u>	5 5		Ь.	<u> </u>				Sn a	\dagger	m	—	<u> </u>	65		<u> </u>	3						
			_				_	_		•			_						_							

(2) d_w vs Fr graph:

Fr		3.54	3,64	3.52	3.72	3.60	3,7	148	3.68	3.66	3.8	3.73	3.75	48,€	3.76	3.80	16.5	3.76	3.83
3	(m)	0.033	0.02	0.032	98000	0.033	0.035	1,500	0.036	01039	Eho. 0	0.639	0.042	940.0	or 042	Show	640.0	Shora	8,000
$\sin \alpha$		0.57	0.79	0.63	0.57	0.79	0.63	0.57	0.79	0.63	0.57	0.79	0.63	0.57	0.79	0.63	0.57	0.79	0.63
α		34.5	52.2	38.8	34.5	52.2	38.8	34.5	52.2	38.8	34.5	52.2	38.8	34.5	52.2	38.8	34.5	52.2	38.8
ď	(m3/s)	0.05	0.05	0.05	0.00	0.00	0.00	0.07	0.07	0.07	0.08	0.08	0.08	0.0	0.0	0.09	0.1	0.1	0.1
Sn		1			2			3			4			5			9		

20				120 126		158			
19					7.7	154			
18				113	8.2	164			
17		-		101 107	6	180			
16				101	6	180			
15	82	5.8	176	94	6	180 180	81	6.4	194
14	9/	5.8	176	88	6	180	75	6.4	194
13	70.3	5.8	176	82	8.6	196	70	7	212
12	64	5.8	176	75	11	220	65	8	248 242 242
11	59	5.8	176	69	12	240	59	8	242
10	52.7	3.5	106	63	14	280	54	8.2	248
6	46.9 52.7	3.5	106	26	11	220	49	8.7	264
8	41	3.5	106	50	13	260	44	9.2	279
7	35.1	3.5	106	38 43.5	13	260	38	8.4	255
9	29.3	3.5	106	38	13	260	32.9	8	242
5	17.6 23.4 29.3	3.5	106	31	13	260	27.6	6.7	203
4	17.6	3.5	106	24.9	11	220	22.3	6.7	203
3	11.7	4.6	139	18.5	8.6	196	16.9	5.5	167
7	5.9	4.6	139 139	12	8.2	164	12	5.6 4.3	130
1	0	4.6	139	6.5	5.7	114	6.32	9.5	170
Steps	0.03 x(cm)	шо ^{06м} р	d _{w90} cm/h	0.05 x(cm)	d _{w90} cm	d _{w90} cm/h).03 x(cm)	d _{w90} cm	d _{w90} cm/h
h(п) Steps	0.03		-	0.05			0.03		
q _w m3/s		0.05		_					
ັ ຮ	34032			52014			38050'	1	

8				126	7.9	158			
19				120	7.7	154			
18	•			113	8.2	164			
17				107	6	180			
16				101	6	180			
15	82	5.8	176	94	6	180	81	13	388
14	76	5.8	176	88	6	180	75	7.5	229
13	70.3	5.8	176	82	8.6	196	70	8	243
12	64	5.8	176	75	11	220	65	14	424
11	59	5.8	176	69	12	240	59	6	370 272
10	46.9 52.7	4.2	129	£9	14	280	54	12	370
9	46.9	4.2	129	99	11	220	49	12	360
8	41	4.2	129	20	13	260	44	11	336
7	35.1	4.25	129	43.5	13	260	38	10.3	311
9	29.3	5.5	165	38	13	260	32.9	11	321
5	23.4	5.5	165	31	13	260	22.3 27.6	∞	243
4	17.6 23.4	5.46	165	24.9	11	220	22.3	6.9	209
3	11.7	5.46 5.46	165	18.5	8.6	196	16.9	5.97	181
2	5.9	6.7	202	12	8.2	164	12	5.8	175
F	0	6.7	202	5.9	5.7	114	6.32	7.1	214
Steps	x(cm)	mo _w p		0.05 x(cm)	д ^м ост	d _{w90} cm/h	0.03 x(cm)	d _{w90} cm	d_secm/h
h(m) Steps	0.03 x(cm			0.05			0.03		
qw m3/s		90.0		_					
α	34032			2 52014			38050		
Sn a				-2					

								•	
20				126	12	245			
19				120	12.2	245			
18				113	13.3	265			
17				107	14.7	294			
16	\vdash			101	14.7	294			
15	82	5.8	176	94	15	302	81	7.7	233
14	20	5.8	176	88	17	330	75	8.5	258
13	70.3	5.8	176	82	18.6	371	70	9.5	287
12	64	5.8	176	75	19	383	65	11	321
11	59	5.8	176	69	22	440	59	11	331
10	52.7	5	153	63	21.4	428	54	11	331
6	46.9 52.7	4.9	147	56	21	420	49	12	360
8	41	4.9	147	50	19.4	387	44	12	360
7	35.1	4.85	147	43.5	18.6	371	38	10.9	331
9		4.9	147	88	17.3	347	32.9	2	314
5	23.4	4.9	147	31	16.1	322	27.6	9.5	287
4	17.6 23.4 29.3	6.07	184	24.9	14.5	290	22.3	7.7	233
3	11.7	6.07	184	18.5	13	259	16.9	5.94	180
2	5.9	6.1	184	12	101	204	23	5.9	180
-	0	6.5	198	5.9	7.14	143	6.32	7.1	214
Steps	0.03 x(cm)	d _w ocm	d _{w90} cm/h	0.05 x(cm)	d _{w90} cm	dwocm/h	0.03 x(cm)	d _{w90} cm	Г
h(m) Steps	0.03			0.05			0.03		
Ф. m3/s		0.07							
	34032			52014			38050'		
Snα				m					

20			Π	126	14	273	İ		Г
19	+	-		00	6.	277 2	\vdash		├
ı	_	<u> </u>	ļ	120 1	13.9				
18				113	14.3	285			
17				107	18	360		İ	
16				94 101	17.9	359	-	ļ .	
14 15	82	5.8		8	20	400	81	12	l
14	92	5.8		88	18	367	75	12	350
13	64 70.3	5.8	176	.82	18.4	367	70	12	350
12	64	1 -	176	75	20	408	65	14	424
11	59	5.8	147 176	69	22	40	59	13	408
10	52.7	4.9	147	63	22.4	449 4	54	15	447
6	46.9 52.7	4.9	5 147 1	99	21	420	49	14	423
∞	41	5.5	165	20	19.6	392	44	13	408
7	35.1	5.5 5.46	165	43.5	19	379	38	12.7	-384
9	17.6 23.4 29.3		165	38	17.9	329	32.9	10	316
5	23.4	6.7	202	31	16.1	322	27.6	10	306
4	17.6	6.67	202	24.9	14.9	298	22.3 27.6	8.02	243
3	11.7	7.58	230	18.5	12.6	253	16.9	6.9 6.58	199
2	5.9	8.8	267	12	10	204	12	6.9	209
1	0	9.6	290	5.9	7.46	149	6.32	8.7	263 209
Steps	0.03 x(cm)	d _{w90} cm	d _{w90} cm/h	0.05 x(cm)	d _{w90} cm	d _{w90} cm/h	x(cm)	d _{w90} cm	d _{w90} cm/h
h(m) Steps	0.03			0.05			$0.03 \mathrm{x(cm)}$	-	
qw m3/s		0.08					-		,
	34032			4 52014 ¹			38050'		
Suα	Γ,			4			1		

_	Τ	,		1.2	1.2	-		1	
20				126	15	300			
19				120	16.3	326			
18				113	16.7	334			
17				107	18	360			
16	ľ			101	18.8	375	_		-
15	82		176	94	8	400	81	13	388
14	76	5.8	176	88	8	392	75	13	389
13	70.3	5.8	176	82	19.6	392	20	13	399 389
12	49	5.8	176	75	22	449	65	14	424
11	59	5.8	176	69	22	440	65	15	457 457
10	52.7	5.5	165	.63	21 22.4	644	54	15	
6	46.9 52.7	5.5	165	56	21	420 4	49	14	438
8	41	5.5 5.5 5.5	165	20	20.8	416	44	13	408
7	35.1	5.8 5.5 5.46	165	43.5	19	379	38	13 13.3	404
9	29.3	5.5	165	38 4	17.9	329	32.9	13	379
5	23.4	5.8	175	31		322		11	336
4	17.6 23.4 29.3	7.58 7.28	221	18.5 24.9	13.3 15.5 16.1	310	22.3 27.6	8.99	272
m	11.7	7.58	230	18.5	13.3	265	16.9	7.22	219
7	5.9	7.6	294	12	11	220	12	7.5	229
П	0	9.7	294	5.9	7.95	159	6.32	8.7	263
Steps	0.03 x(cm)	d _{w90} cm	d _{w90} cm/h	0.05 x(cm)	d _{w90} ст	d _{w90} cm/h	0.03 x(cm)	d _{w90} cm	d _{w90} cm/h
h(m) Steps	0.03			0.05		·	0.03		
qw m3/s		0.0							
	34032'			5 52014'			38050		
Sn a				S					

<u> </u>	1	т—	1	150	<u> </u>	<u> </u>	Г		_
20	L			120 126	15	300		L	<u> </u>
19			-	1	14.9	298			
18			`	113	15.9	318	1		
17				107	18	360			
16				101	18.4	367			
15	82	5.8	176	94	20	400	81	13	388
14	9/	5.8	176	88	20	400	75	13	389
13	70.3	5.8	176	82	20.4	408	07	14	428
12	64	5.8	176	75	21	424	65	14	424
11	59	5.8	176	69	22	440	65	14	428
10	52.7	5.8	175	63	22.4	449	54	14	433
6	46.9	5.8	175	56	21	420	49	14	438
∞ .	41	5.9	179	50	20.8	416	44	13	399
7	35.1	6.07	184	38 43.5	19.4	387	38	13.2	339
9	29.3	6.4	193	38	19	379	32.9	12	355
5	23.4	6.5	198	31	16.7	334	27.6	11	345
4	17.6	8.5	257	24.9	15.5	310	22.3	8.99	272
m	11.7	10	303	18.5	13.3	265	16.9	8.02	243
7	5.9	10	317	12	7.5	150	. 12	8.5	258
1	0	11	331	5.9	8.48	170	6.32	9.5	287
Steps	0.03 x(cm)	d _{∞90} ст	d _{ws0} cm/h	0.05 x(cm)	d _{w90} ст	d _{we} cm/h	0.03 x(cm)	d _{w90} cm	d _{w90} cm/h
h(m) Steps	0.03			0.05			0.03		
qw m3/s		0.1							
α	34032			6 52014'			38050		
Sn	<u>,</u>			9		!	<u> </u>		

(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

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

Calculations:

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

q_w	$d_{c (m)}$		$\mathbf{H}_{ ext{spill}}$
0.1	0.10		2
h	1	λ (m)	
0.033	0.0414	0.053	
a	sina	cosa	k(m)
38.83	0.627	0.779	0.026
Solvin	g Mannin	g's n fro	m eq.(1)
n	Z	λ/1	LHS
0.05	0.00632	1.2788	3.84801
$\{z^{0.6},$	/k}		log(l/l)
1.862			0.10681
$log{z^{*}}$	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 equivalent water depth, $d_w = {q_w n/\sin a^{0.5}}^{0.6}$

 $d_{w(m)}$

0.048

Uniform velocity, $u_w = qw/dw$

uw (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

 $\Delta E(m)$

1.881

Energy dissipated= $\Delta E/Ec*100 =$

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:

	out circular s			17	1-00(0 101)
x(cm)	dw90(Q=201p		dw90(Q=14lps)	x(cm)	
0	11	0	7	0	5
6	10	6	6	6	5
12 .	10	12	6	12	5
18	9 i	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	
230	9	230	8		6
236	11			230	7
		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=14lp	s)	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	б .
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):

20	_			126	5	100			
19				120	.5	100	-		
18				113	5	100			П
17	Π			107 113 120 126	2	100			
15 · 16				94 101	S	100	1		П
15	82	60	91	94	9	120	81	2	152
14	76	c	91	88	9	120	75	5	152
13	2	n	91	82	9	120 120 120 100	20	5	152
12	64	3	16	75	9	120	65	5	152
11	59	n	91	69	9	120	59	5	152
10	53	c	91	63	9	120	54	9	182
6	47	60	91	56	9	120 120	49	9	182
∞	41	c	91	50	9	120	44	9	182
7	35	3	91	44	9	120 120	38	9	182
9	59	3	16	38	9	120	33	9	182
5	23	3	91	31	9	120	28	9	182
4	17.6	3	16	25	9	120 120	22.3	5	121 121 152 152 182 182 182 182 182 152 152 152 152 152
ω	12 17.6	3	91	19	5	100	17	5	152
7	5.9	4	121	12	4	80	12	4	121
П	0	4	21	5.9	3	09	6.3	4	121
Steps	x(cm)	d _{w90} cm	dwoocm/h 1	0.05 x(cm)	mɔ ^{06^} p	d _{w90} cm/h	x(cm)	шэостр	d _{w90} cm/h
h(m) Stepa	0.033 x(cm)		J	0.02	_	Ĭ	0.033 x(cm)	Ť	
qw m3/s		0.05			_				
ರ	34032			52014			38050		

20				126	9	120			
19				120	9	120			
18	·			113	9	120			
17 18				107 113 120 126	9	120 120 120			
16				101	9	120			
15	82	4	121	94 101	9	120	81	9	182
14	76	4	121 121	88	9	120	75	9	182
13	70	4	121	82	9	120	70	9	182
12	49	4	121	75	9	120 120 120 120 120	65	9	182
11	59	4	121	69	9	120	65	7	212
10	53	4	121	63	9	120 120	54	7	212
9.	47	4	121	99	9	120	49	7	212
∞	41	4	121	20	9	120 120 120 120 120	44	7	212
7	35	4	121	44	9	120	38	7	212
9	62	4	121	38	9 .	120	33	9	182
5	23	4	121	31	9	120	28	9	182
4	17.6	5	152	25	9 .	120	22.3	9	182
33	12 17.6	5	152	19	5	100	17 22.3	5	152
7	5.9	5	152	12	5	100	12	4	121
Π	0	9	182	5.9	4	80	6.3	5	152
Steps	x(cm)	шэкмр	dwom/h 182 152 152 152 121 121 121 121 121 121 12	0.05 x(cm) 5.9	mo _{06w} p	d _{w90} cm/h	0.033 x(cm)	д ^м ост	d_oom/h 152 121 152 182 182 182 212 212 212 212 212 182 182 182 182 182
h(m) Step	0.033 x(cr			0.05			0.033		
q _w m3/s		0.07							
ಶ	34032			52014			38050'		

i			
	۰	d	

										-												
200				126	9	120		<u> </u>	_		ż											
19				120	9	120											`					
18				113	9	120			ï													
17				107	9	120																
16				101	9	120																
15	82	5	152	94	9	120	81	80	242													
3 14	76	5 5	152	88		12	7	8	242													
2 13	4 70	5 5	2 152	5 82	9 9	0 120	5 70	8 6	3 242													
11 12	9 64		2 152	9 75		0 120	9 65	5 6	3 273					,								
10 1	53 59	5	2 152	3 69		0 120	4 59	6	3 273													
9	47 5		2 152	6 63		0 120	49 54	8	2 273													
<u>∞</u>	41 4		2 152	50 56		20 120		8	2 242													
7	35 4		2 152	44 5		0 120	38 4	∞	2 242													
9	29 3		2 182	38 4	9 9	, ,	33 3	7	2 242													
2	23 2	9	2 182	31 3	9 9	LI	28 3	9	2 212													
4	<u> </u>		2 182	25 3		20 120		9	32 182													
·	12 17.6		2 212	19 2		120	17 22.3	9	82 182			:			٠							
2	5.9		73 242	12 1			12 1	9	7													
			73 273	5.9 1		100 100]	7	182													
	H	Ī	ı/h 273						ı/h 212													
Steps	x(cm	d _{w90} cm	d _{w90} cm/h	0.05 x(cm)	д ∞90сп	d _{∞90} ст/h	x(cm	d _{w90} cm	d _{w90} cm/h								-					
h(m)	0.033 x(cm)			0.05		_	0.033 x(cm)															
4 _w h	-	0.1				,																
	34032'	\dashv		52014'		\dashv	38050'	اء -	\vdash									•				
Snα	34,	l		652			<u>چ</u>															
	<u>. </u>							•					٠							•		

Graphs: Average flow depth $d_{\rm w}$ verses average velocity of flow Vw and flow rates $q_{\rm w}$:

Table of Calculations:

Table 1

Q (m3/s)	q (m3/s/m)	Slope (o)	h (m)	l/h	$V_{\rm w}$ (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
	<u> </u>	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°32¹	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):

20			126	3		
19			88 94 101 107 113 120 126	3		
18			113	3		
9 10 11 12 13 14 15 16 17			107	3		╗
16			101	3		\neg
15	82	2	94	3	81	6
14	20 76	2	88	4	75	3
13	70	2	82	4	70	3
12	64	2	75	4	65	3
11	59	2	69	4	59	3
10	53	2	63	3	54	3
6:	47	2	56	3	49	4
8	41	2	20	3	44	4
7	35	2	44	3.	38	4
9	29	2	38	æ	33	4
5	23	3	31	4	28	4
4	18	3	25	4	22	4
2 3 4	0 5.9 12 18	3	19	4	12 17	4
2	5.9	4	12	4	12	3
1	0	4	9	7	9	3
h(m) Steps	0.03 x(cm)	ф _{м90} сш	0.05 x(cm)	d _{w90} cm	0.03 x(cm)	d _{w90} cm
	0.03		0.05		0.03	
qw m3/s	= .	0.05	-			
מ	34032'		52014		38050	
Sn α			Ŧ			

			_				
	20			126	4		
ſ	19			120	4		
Ì	18			113	4		
	17			107	4		
Ì	9 10 11 12 13 14 15 16 17 18 19			75 82 88 94 101 107 113 120 126	4		
ļ	15	82	4	94	4	-81	4
	14	76	4	88	5	75	4
	13	70	4	82	5	70	. 4
	12	59 64 70	4	75	5	65	4 4 4
]	11	59	4	69	5	59	4
	10	53	4	63	5	54 59 65 70 75	4
		47	4	26	4	49	5
	∞	41 47 53	4	31 38 44 50	4	44	5
١	7	35	4	44	4	38	5
	5 6	29	4	38	4	33	5 . 5
	5	0 5.9 12 18 23 29	4	31	4	6 12 17 22 28 33	5
	4	18	5	12 19 25	5	22	4
	2 3	12	5	19	4	17	4
	2	5.9	5	12	m	12	3
	1	0	9	9	3	9	4
	Steps	$0.03 \mathrm{x(cm)}$	d _{w90} cm	0.05 x(cm)	d _{w90} cm	$0.03 \times (cm)$	d _{w90} cm 4
	h(m) Steps	0.03		0.05		0.03	
	qw m3/s		0.07				
		34032		2 52014'		38050'	
	Sn a			7			

	20			126	9		
	19			120	9		
	18			113	9		
ŀ	17 18			50 56 63 69 75 82 88 94 101 107 113 120 126	9		
ĺ	9 10 11 12 13 14 15 16			101	9		
	15	82	5	94	9	81	S
	14	76	5	88	9	75	5
Ì	13	64 70	5	82	5	70	5
	12	64	5	75	5	65	3
1	11	59	5	69	5	59	9
Ì	10	53	5	63	5	49 54 59 65 70 75	9
		47	5	56	5	49	9
	8	41	5	20	5	38 44	9
	7	35	9	44	5	38	9
	9	29	9	38	5	33	9.9
	5 6	0 5.9 12 18 23 29 35 41 47 53 59	9	12 19 25 31 38 44	5	6 12 17 22 28 33	5
	4	18	7	25	5	22	5
Ì	2 3	12	8	19	5	17	5
	2	5.9	6	12	5	12	5
	-	0	6	9	5	9	5
	Steps	0.03 x(cm)	d _{w90} cm	$0.05 \mathrm{x(cm)}$	d _{w90} cm	0.03 x(cm)	d _{w90} cm
	h(m) Steps	0.03		0.05		0.03	
	qw m3/s	-	0.1				
	sn α	34032		3 52014		38050	
	1.5	1		(1)			

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

20			126	4	•	
19		Ŀ_	94 101 107 113 120 126	4		
17 18			113	4		
17			107	4		
10 11 12 13 14 15 16			101	4		
15	82	3	24	5	81	4
14	72	3	88	2	75	4
13	20	3	8	5	2	4
12	64	3	75	5	65	4
11	59	3	69	5	59	4
10	53	3	63	5	54	5
6	47	3	56	5	49	5
<u></u>	41	3	20	5	4	9
7	35	3	44	5	38	9
9	29	3	38	5	33	9
2	23	3	31	2	28	5
4	18	4	25	5	22	5
6	12	4	19	5	12 17	4
7	5.9	4	12	5	12	3
Ħ	0	5	9	3	9	4
(m) Steps	0.03 x(cm)	d _{w90} cm	0.05 x(cm)	d _{w90} cm	0.03 x(cm)	$d_{w90}cm$
h(m)	0.03		0.05		0.03	
q.w m3/s		0.05	-			
ಶ	34032		52014		38050	
Sυ			1	_		

h(m) Steps	0.03 x(cm)	d _{w90} cm	0.05 x(cm)	d _{w90} cm	0.03 x(cm)	d _{w90} cm
	-	iii (<u> </u>	m 4		m S
1 7	5.9	9	6 12	5 1	6 12	4
w	0 5.9 12	5	19	2	17	4
4	18	5	19 25	5	22	5
N		4	31	5	28	9
2	23 29 35	4	38 44	5	33	9
7	35	4	44	5	38	9
∞	41	4	50	5	44	9
	47	4	56	2	49	9
10	53	4	63	5	54	9
11	59 64 70	4	69	5	S9 6S	5
12	64	4	75	5	65	
9 10 11 12 13 14 15 16 17 18 19	2	4	75 82	5	70	5
14	76	4	88	Š	75	5
15	82	4	94 1	5	81	5
16	-		01	5		\vdash
17			107	5		
18			88 94 101 107 113 120 126	5		
19			120	5		
20			126	5		

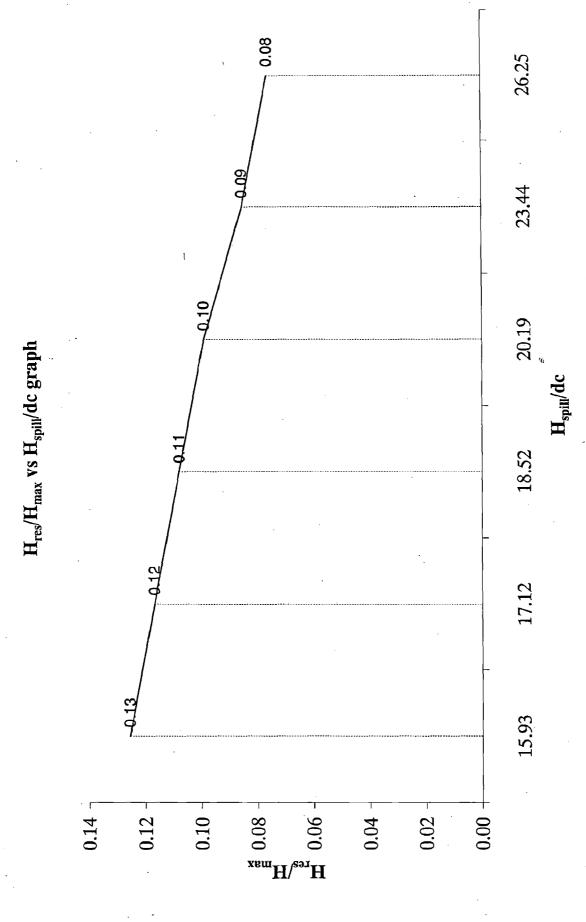
	_					_
20]		126	7		
19			120	7		
18			113	7		
17 18			94 101 107 113 120	7		
16			101	7		
15	82	S	94	7	81	7
14	20	5	88	7	75	7
13	2	2	8	7	70	8
12	64	5	75 82	7	65	8
11	59 64 70	5	69	7	59	8
9 10 11 12 13 14 15 16	53	5	63	7	54 59 65	8
	47	5	98	7	49	8
8	41 47	5	20	5		8
7	35	5	44	5	38 44	9
9	29	5	38	5	22 28 33	9
2	23	9	31	5	28	5
4	0 5.9 12 18	9	25	2	22	5
8	12	7	12 19	5	12 17	5
7	5.9	8	12	5	12	9
1	0	8	9	5	9	7
h(m) Steps	0.03 x(cm)	шообмр	$0.05 \mathrm{x(cm)}$	mo _{06w} p	0.03 x(cm)	dwoncm
	0.03		0.05		0.03	
qw m3/s		0.1				
ರ _	34032		52014		38050	
Sn a			3			

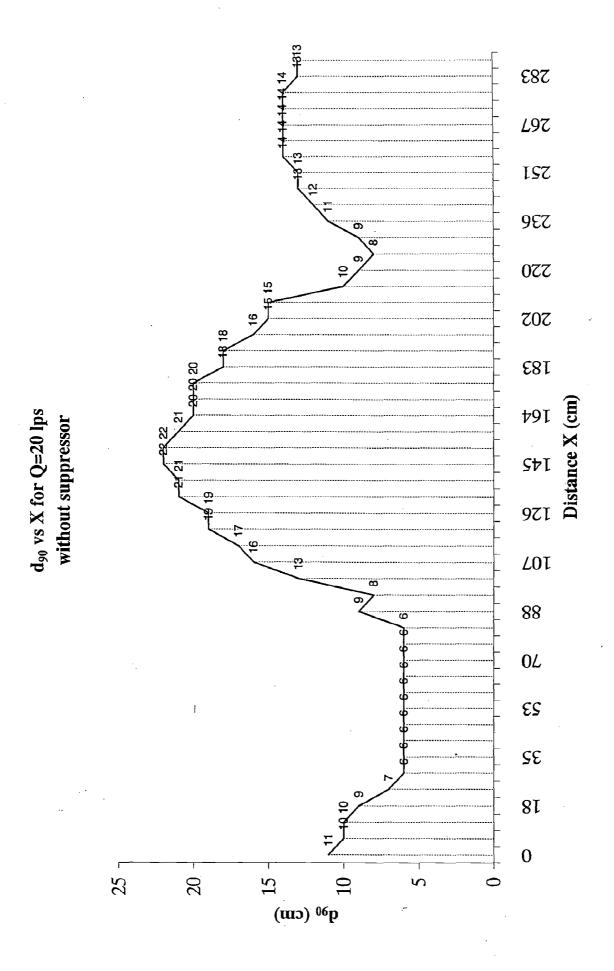
With elliptical suppressor plate P=135mm:

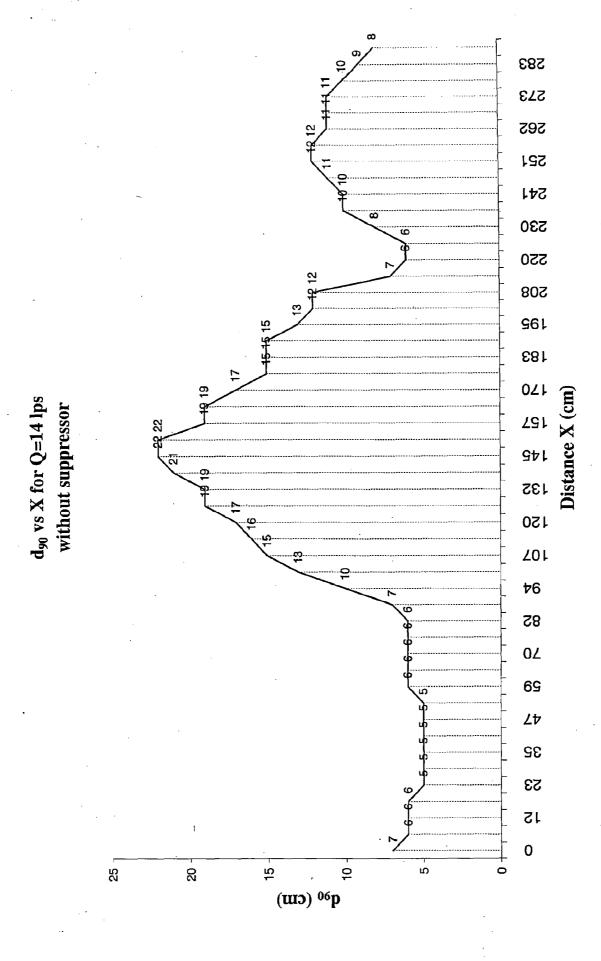
	emptical supp				L: 00(0, 10)
x(cm)	dw90(Q=20lps)	x(cm)	dw90(Q=14lps)		dw90(Q=10lps)
<u>0, </u>	9	0	6	0	4
6 12	9	6	5	6	4
12	8	12	5	12	3
18	7	18	5	18	3
23	6	23	4	23	3
23 29	6	29	4	29	12
35	6	35	4	35	2
41	5	41	4	41	2
47	5	47	4	.47	2
53	15	53	14	53	2
59	5	59	4	59	12
64	5	64	4	64	2
70	5	70	4	70	$\frac{\overline{2}}{2}$
76	5	76	4	76	$\frac{\overline{2}}{2}$
82	15	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		
145			4	138	3
143	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		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	15	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
262 267	6	267	4	202	3
207 273	_			267	3
273 278	6	273	4	273	3
	6	278		278	3
283	6	283	4	283	3
289	6	289	4	289	3

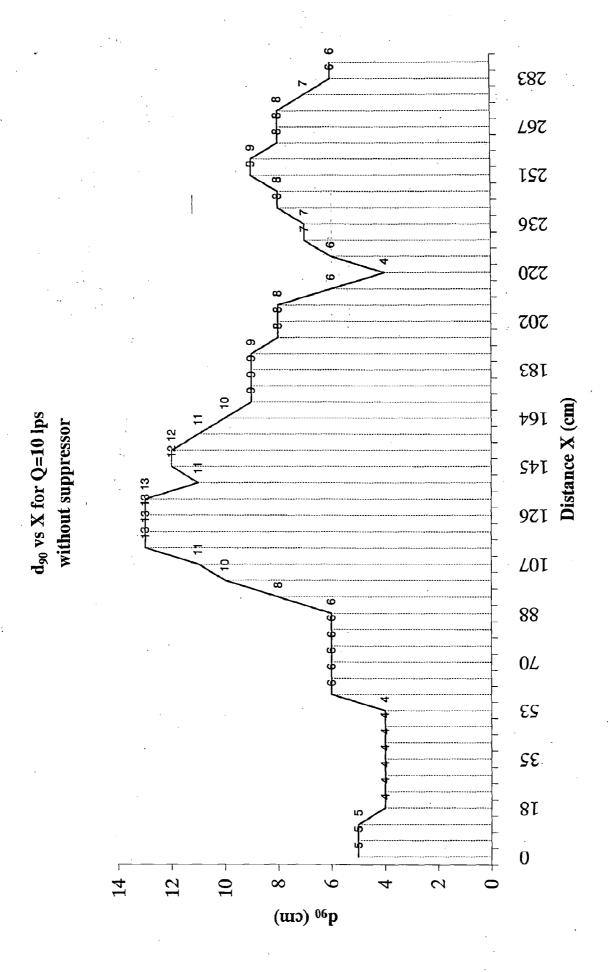
With elliptical suppressor plate P=90mm:

with elliptical suppressor							
x(cm) 0	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	14
23	6	1	23	4		23	3
29	5		29	4		29	13
35	5	i — —	35	4	i	35	3
41	5		41	4		41	3
47	15		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	$\frac{1}{3}$
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	15
120	5		120	5		120	5
126	5		126	5		126	5
132	5		132	5		132	15
138	7		138	5	•	138	5
145	7		145	5		145	5
151	 		151	5		151	5
157	 	-	157	5		157	5
164	 		164	5		164	5
170	7		170	5		170	5
176	7		176	5		176	5
183	7		183	-		183	4
189	7		189	5		189	4
195	 		195	5		195	4
202	7		202	5		202	14
208	7		208	5		202	
214	 		214	5		214	4
220	6		220	4		214	4
225	5		225	4		220 225	3
230	5		230	5		220	4
236	5		236			230	5
241	6		241	6		236	5
246				6		241	6
251	6 8		246	6		246	6.
251	10		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			5		278	4
283	7		283	5		283	4
289	7		289	5		289	4

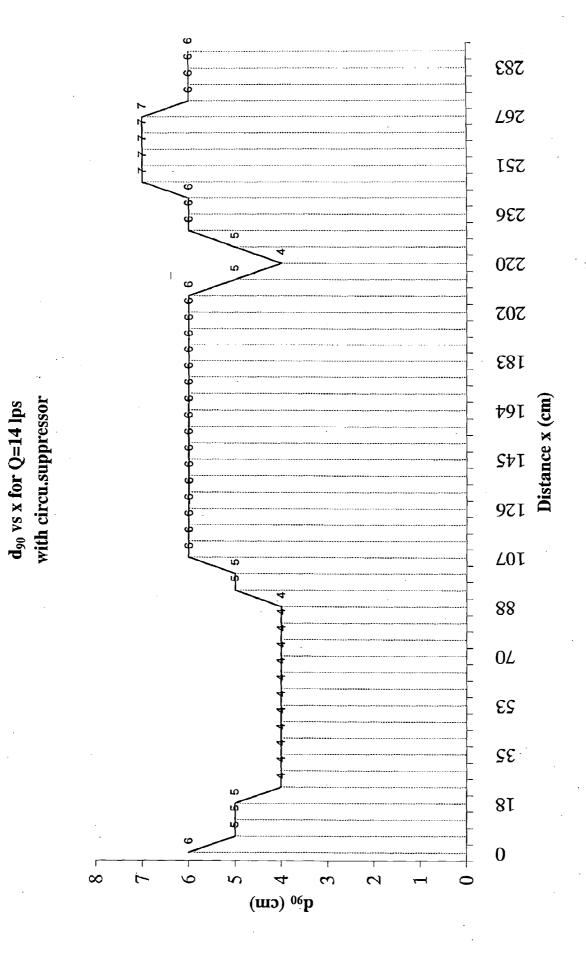




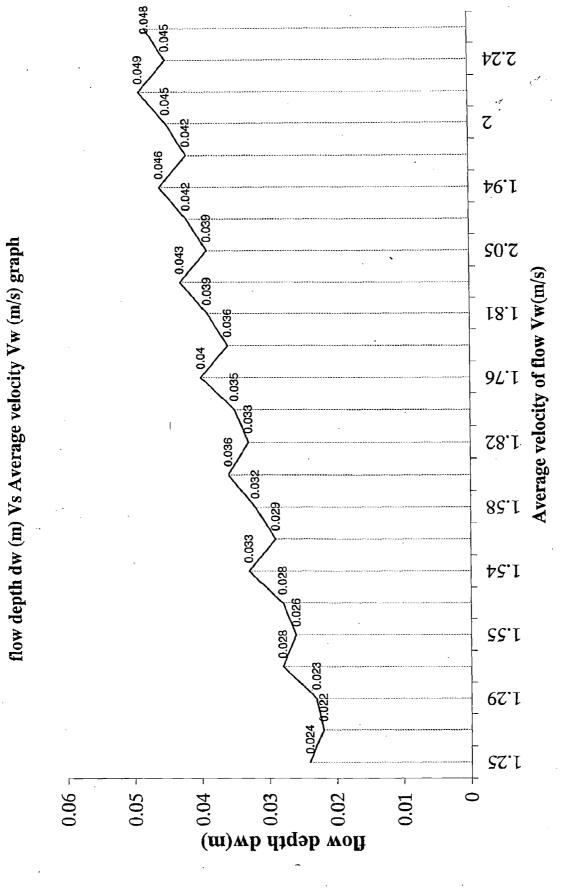




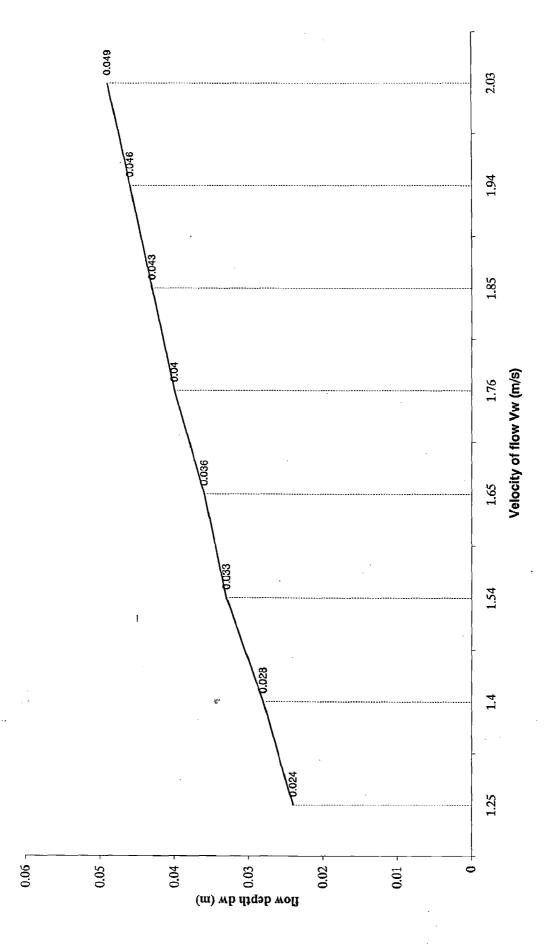
L97 £81 **Distance x (cm)** d_{90} vs x for Q=20 lps with circu.suppressor **L01** q⁰⁰ (cm)

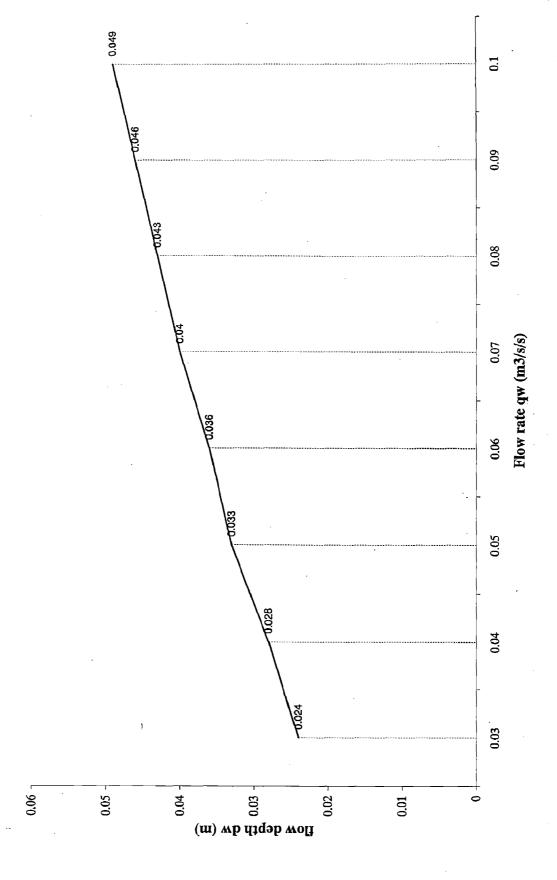


*L*97 d_{90} vs x for Q=10 lps with circu-suppressor Distance x (cm) **LO1** SE . (m2) _{0e}b 4 ω

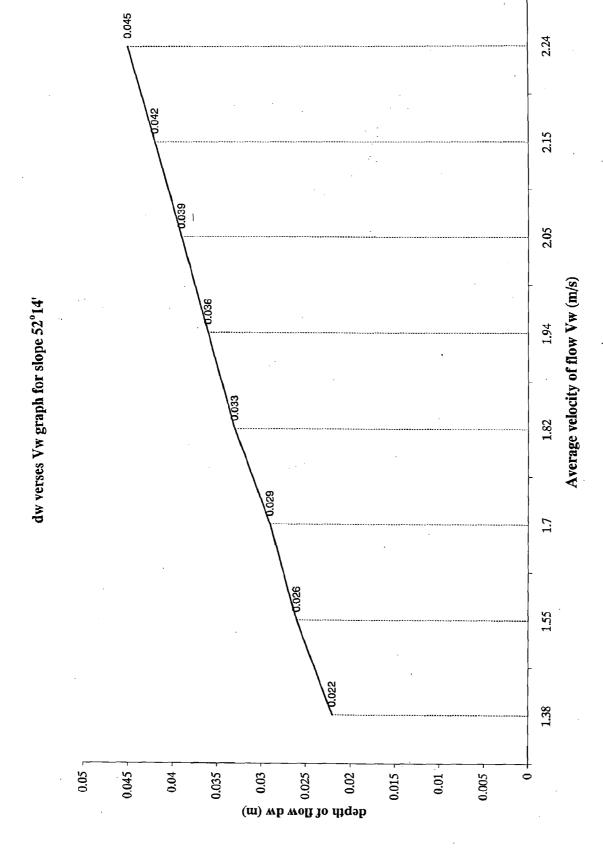


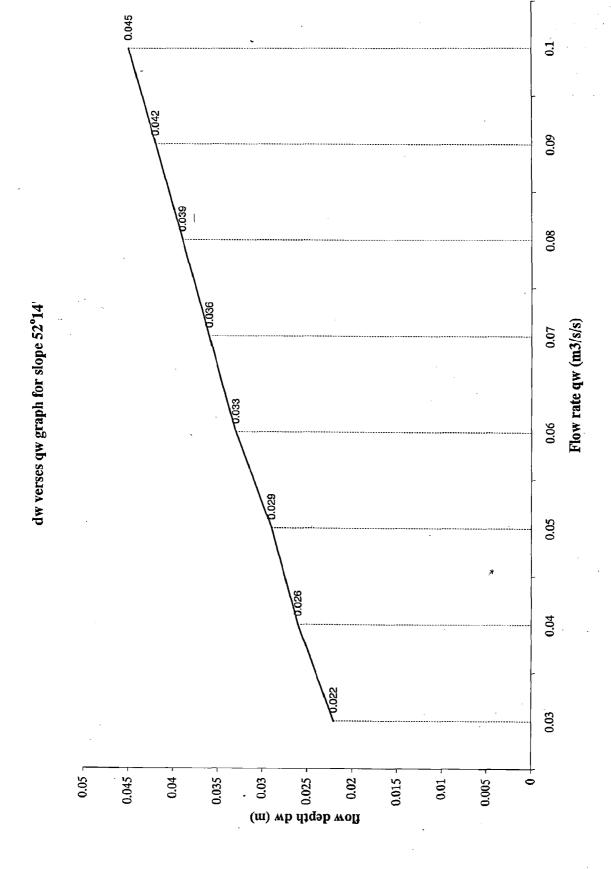
1.0 60.0 80.0 flow depth dw Vs Rate of flow qw graph Rate of flow qw (m3/s/m) 70.0 90.0 £0.0 **₽**0.0 £0.0 0.05 0.01

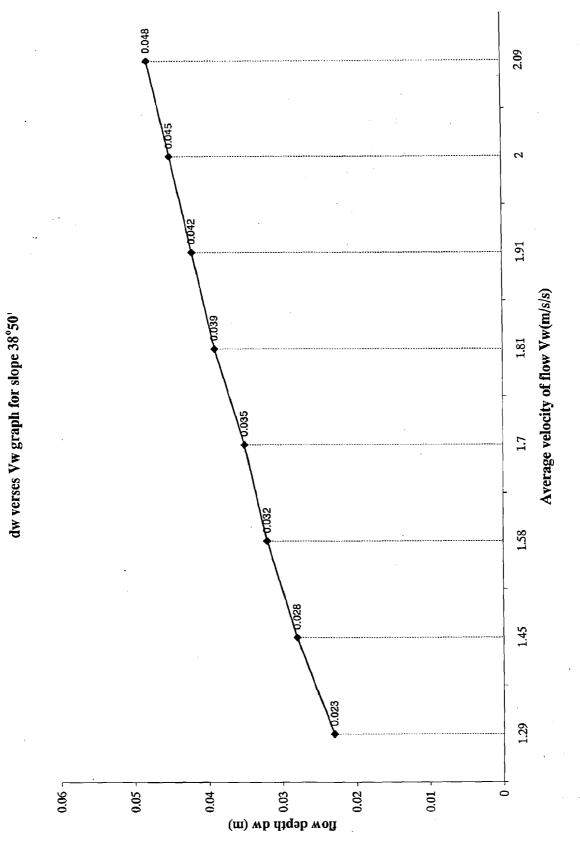


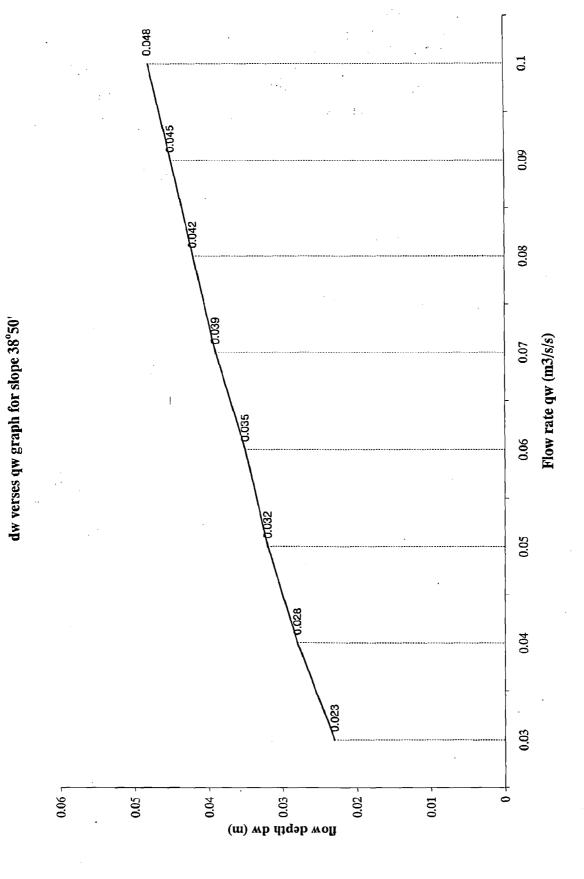


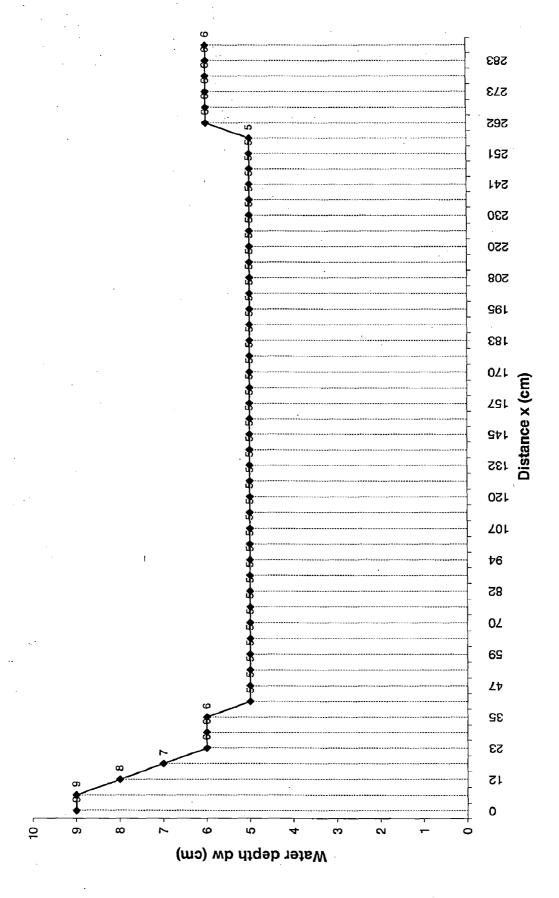
168



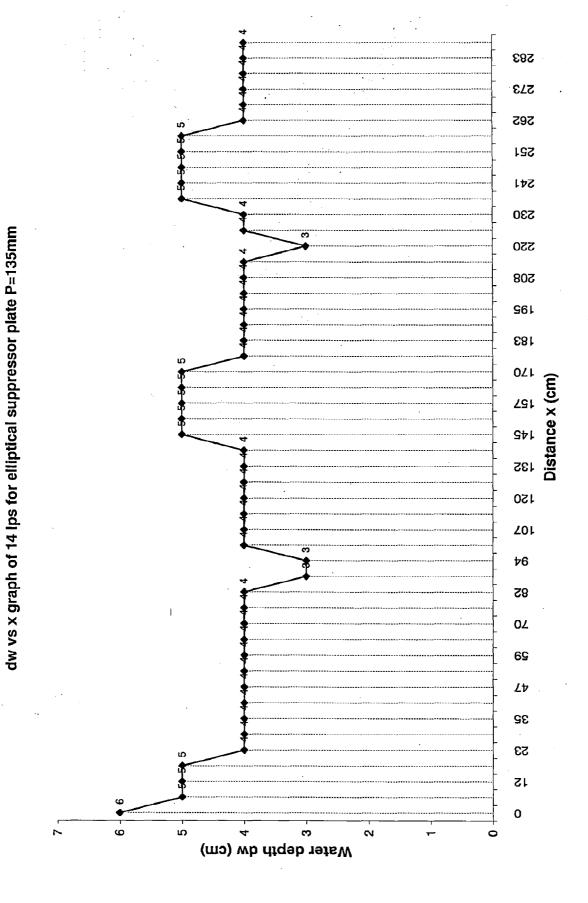


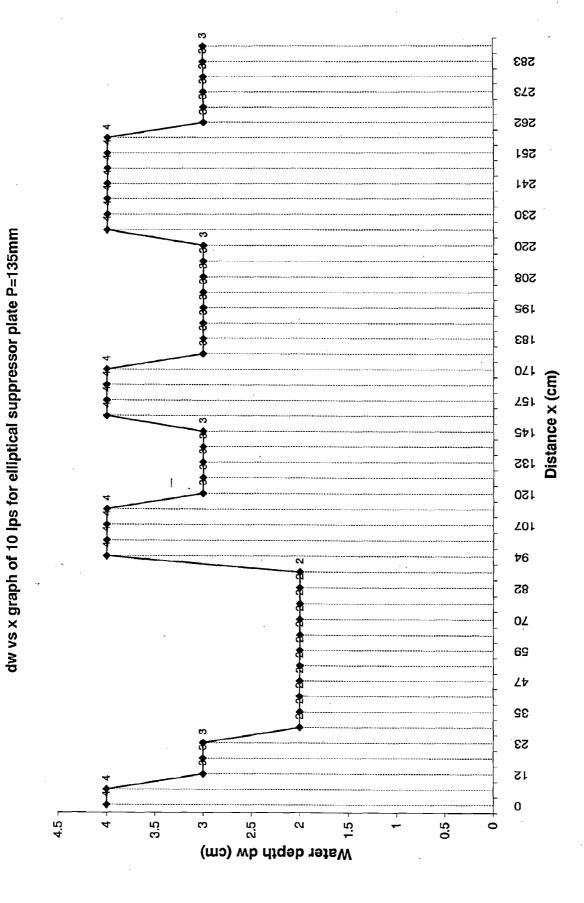


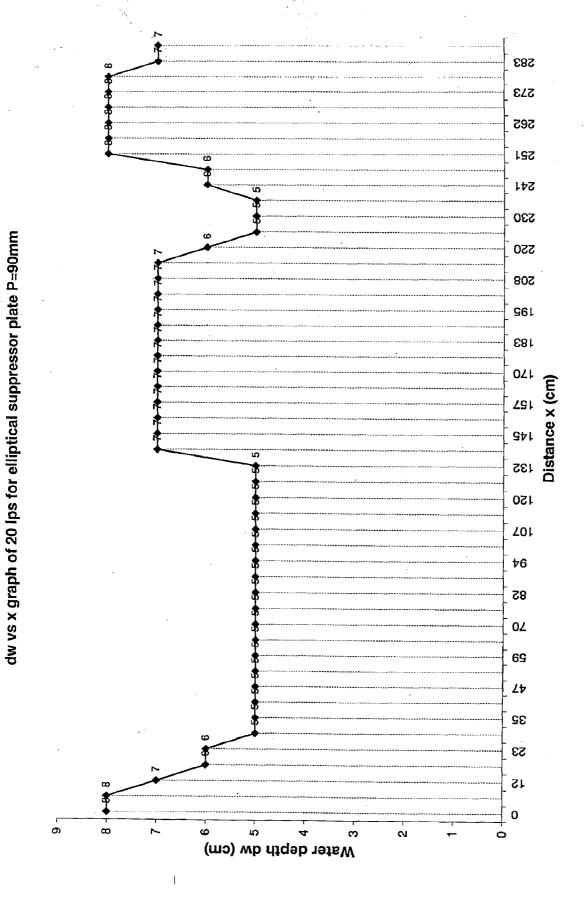


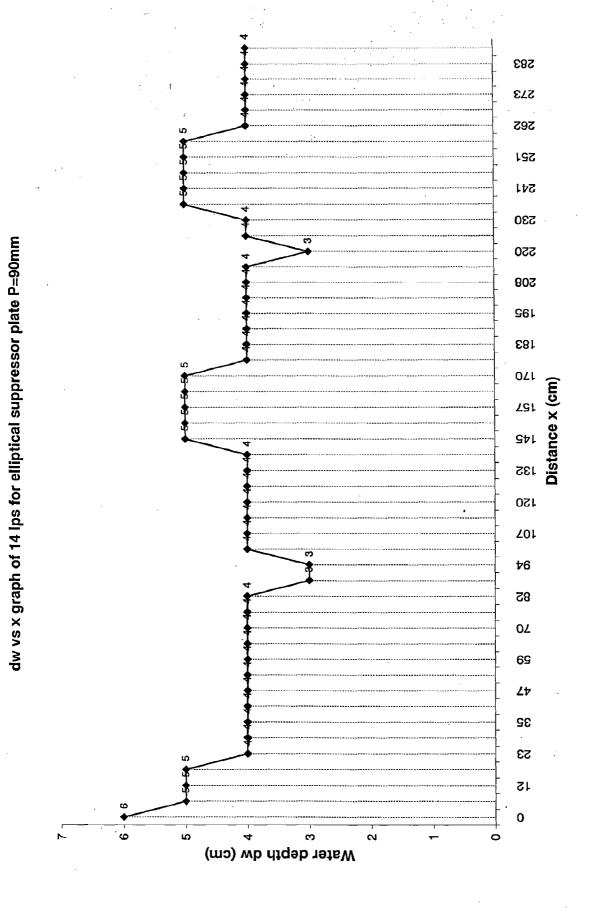


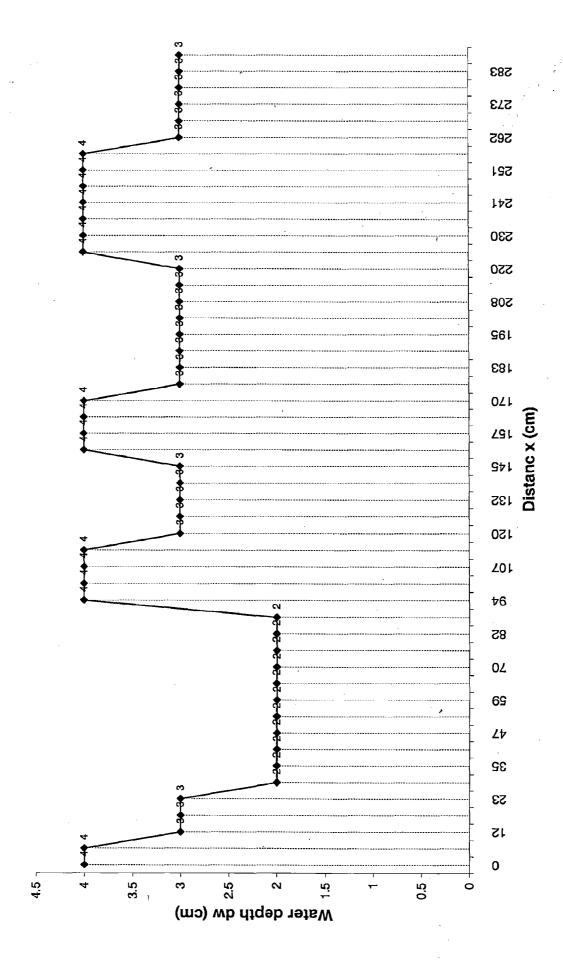
dw vs x graph of 20 lps for elliptical suppressor P=135mm



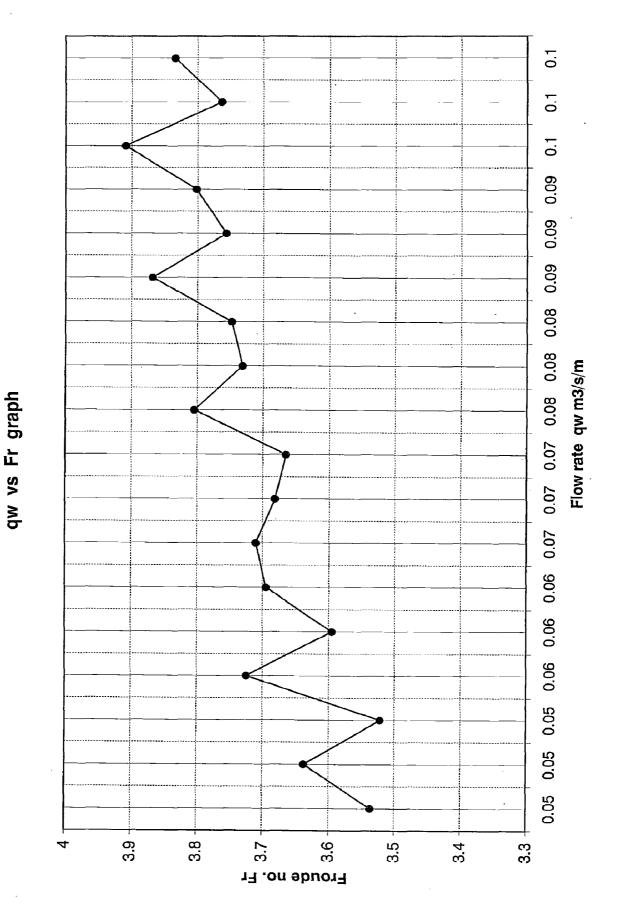








dw vs x graph for 10 lps for elliptical suppressor plate P=90mm



Appendix-C

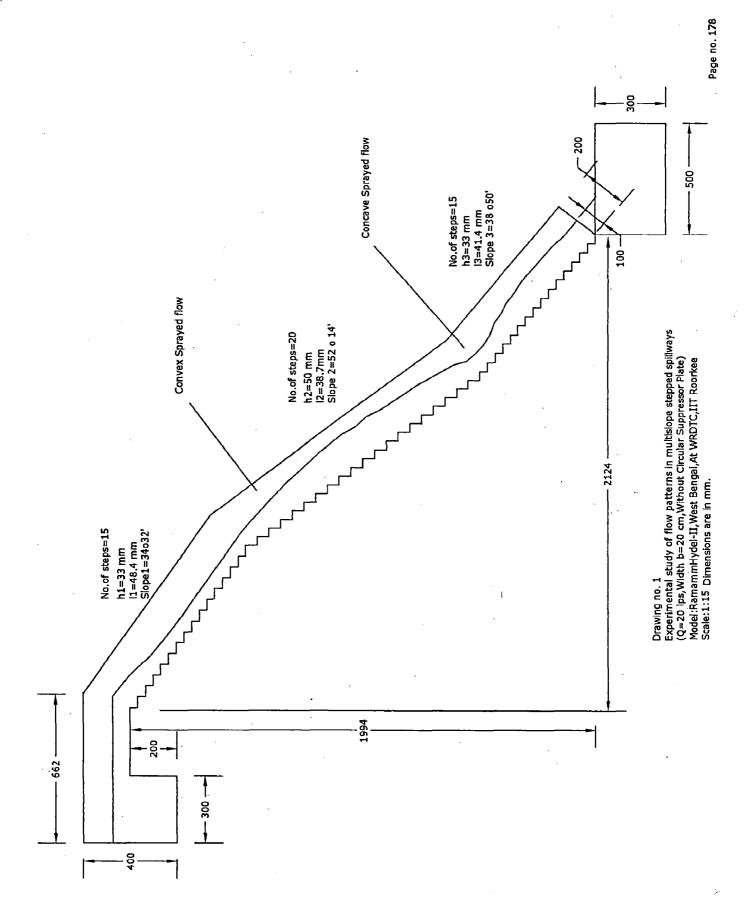
Drawings and Photographs:

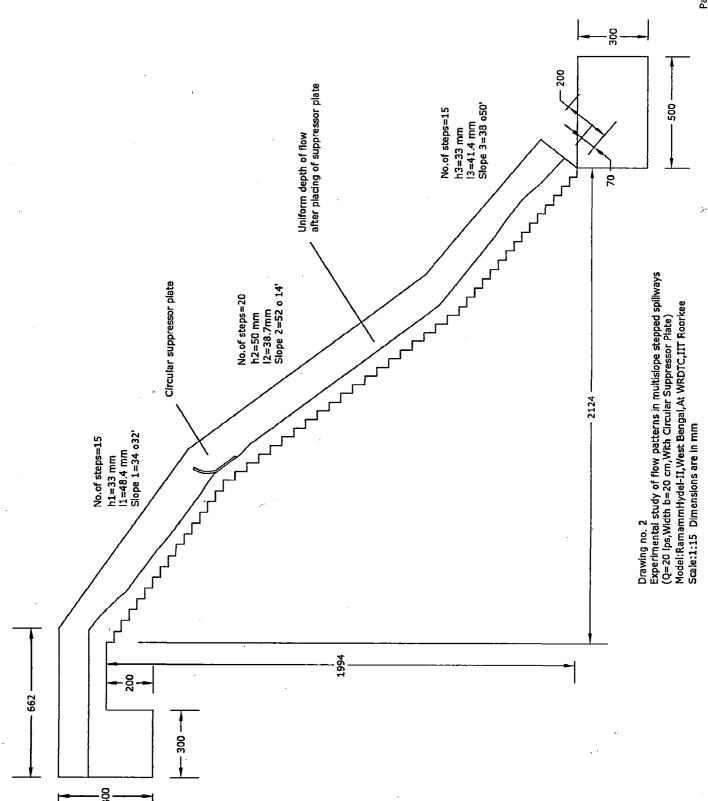
(a) AutoCAD drawings:

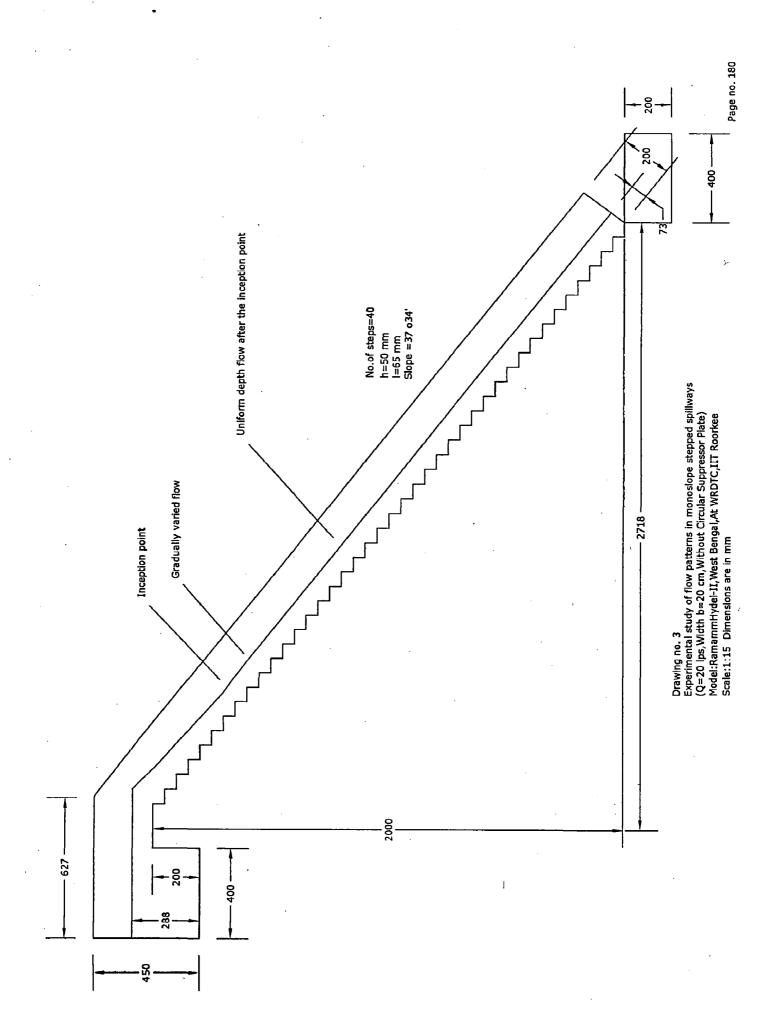
Drawings of flow patterns in multislope and monoslope stepped spillways model (width =20cm) for different discharges ranging from 6 to 20 lps.

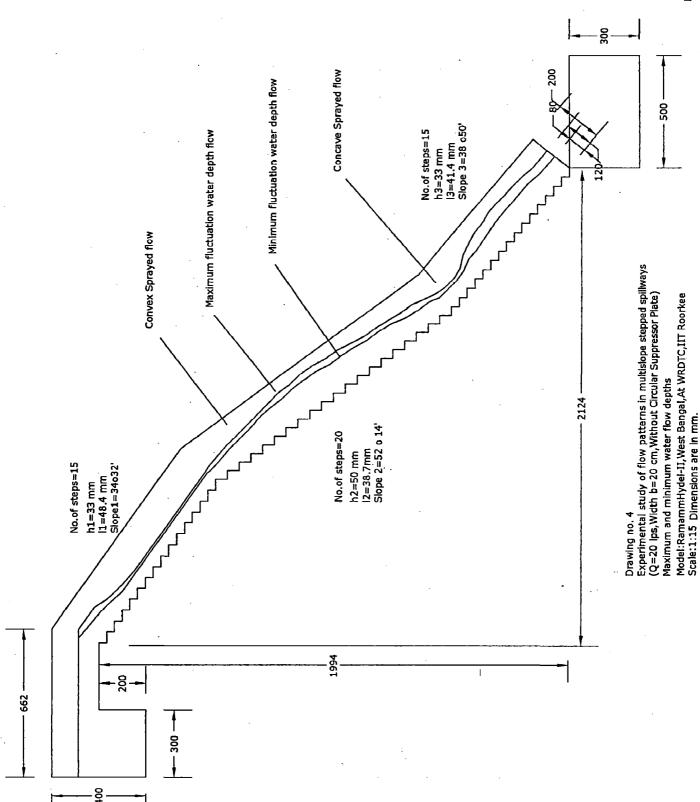
(b) Photographs:

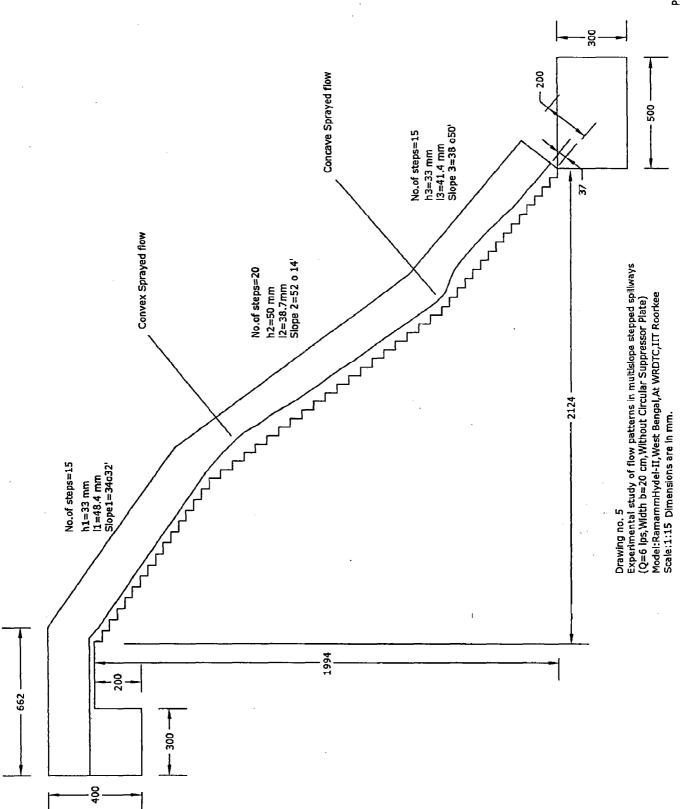
Photographs of flow patterns in the experimental setups with different discharges ranging from 6 to 20 lps.

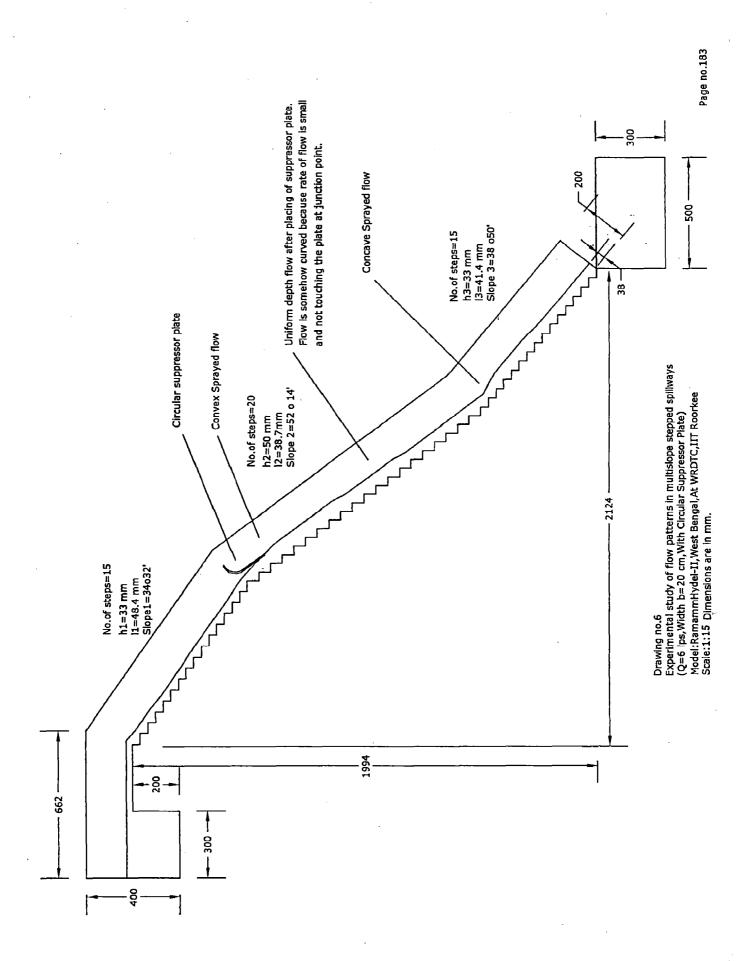


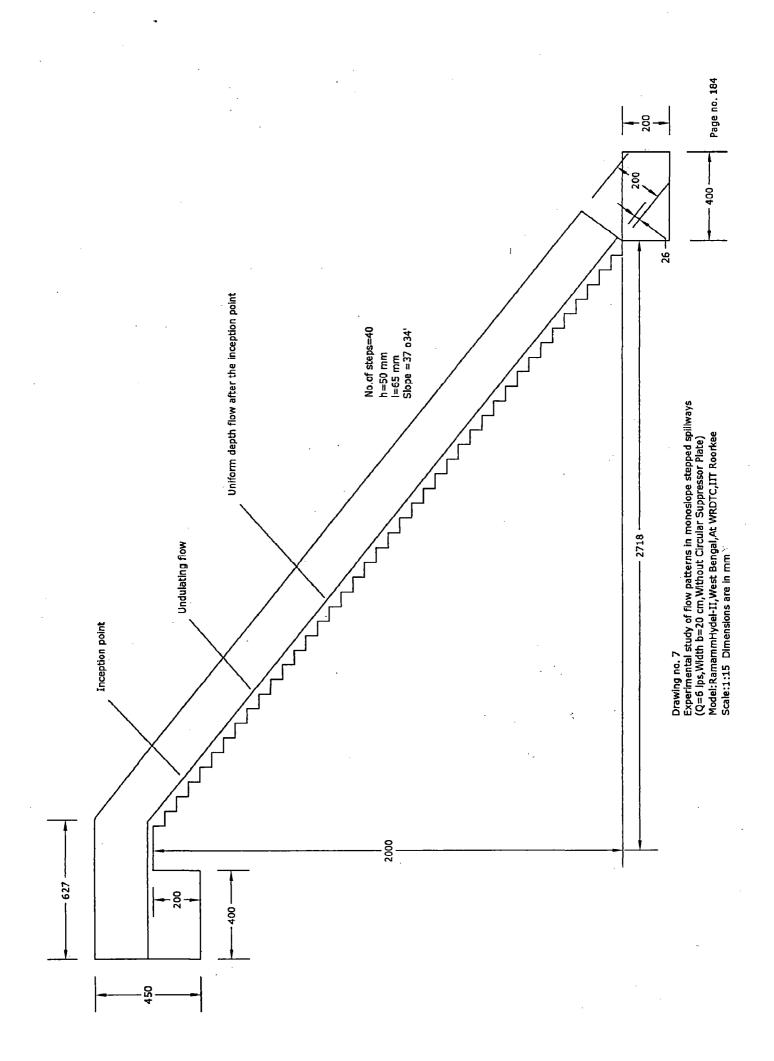


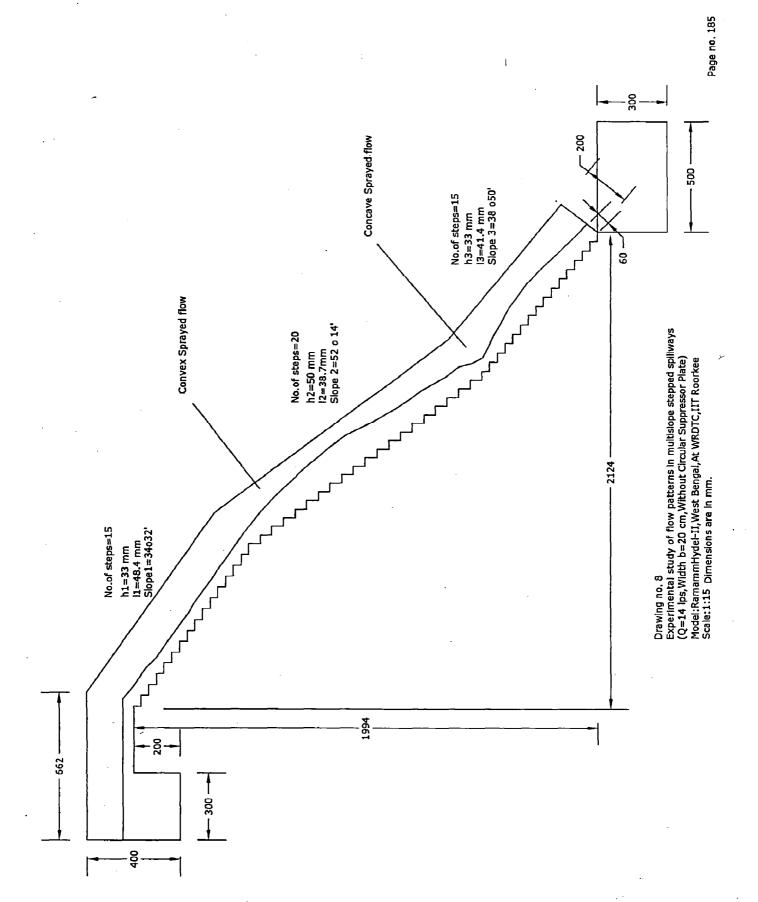


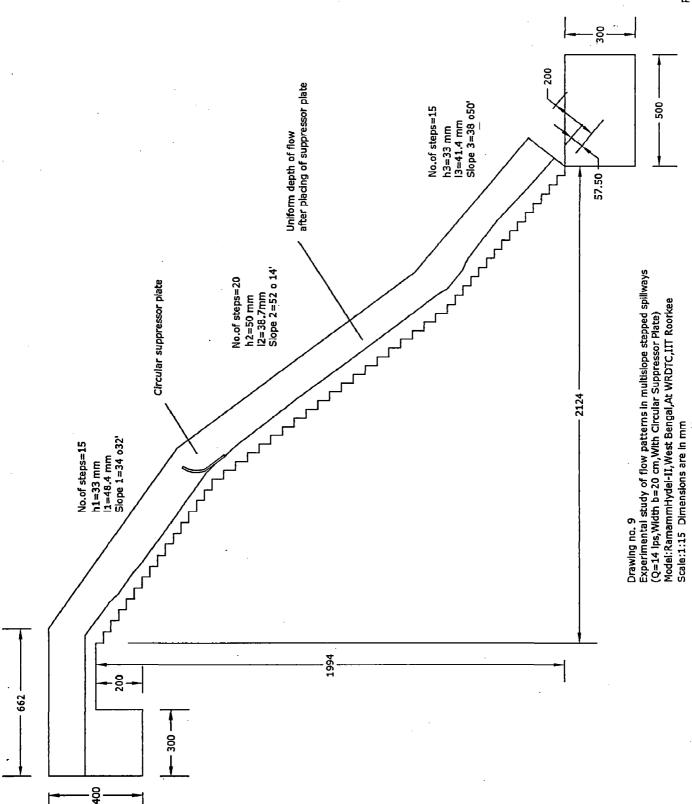


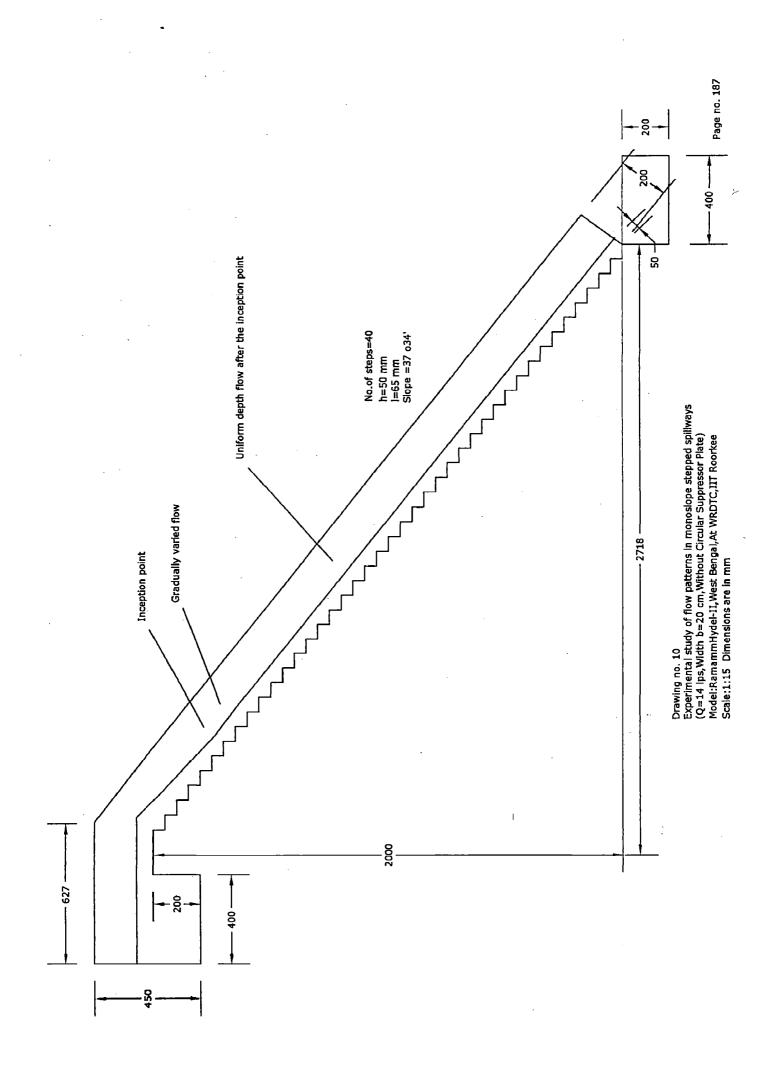


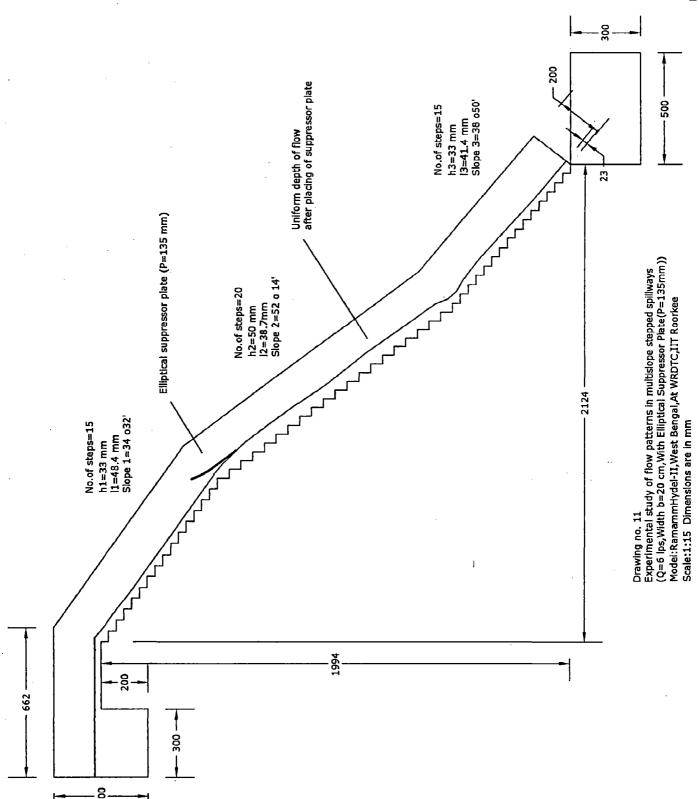


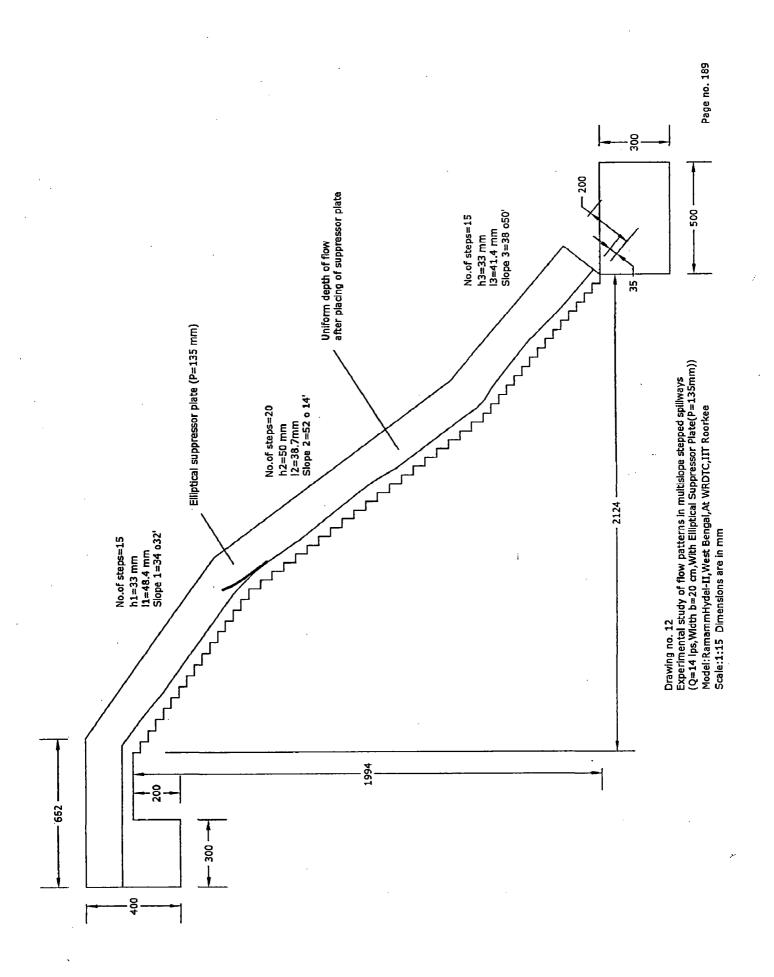


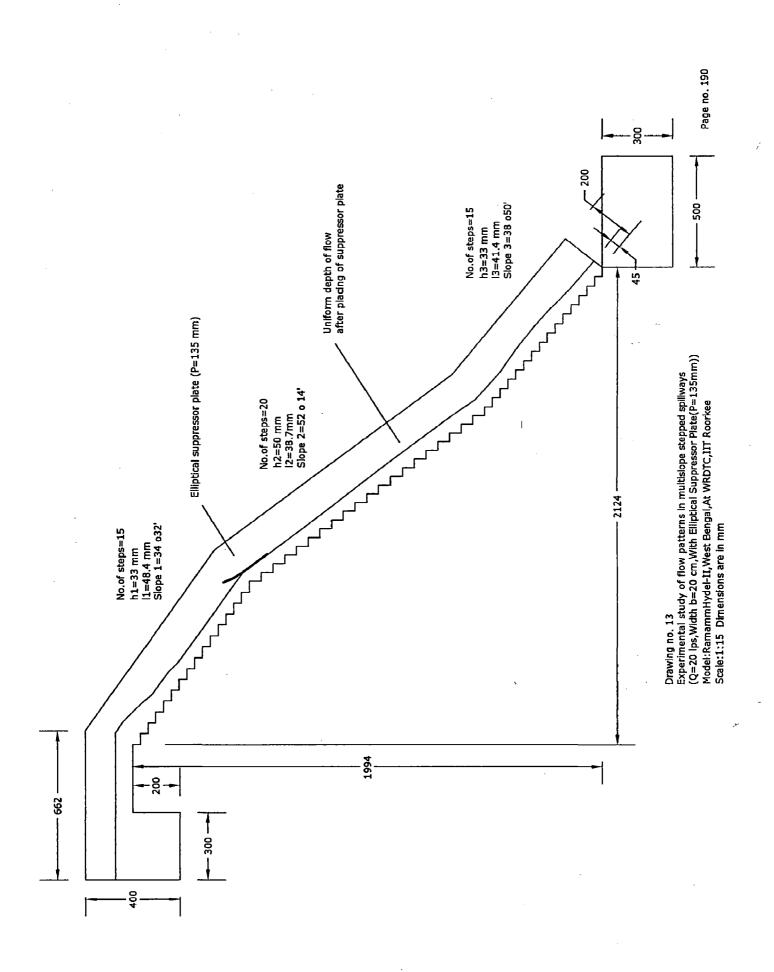


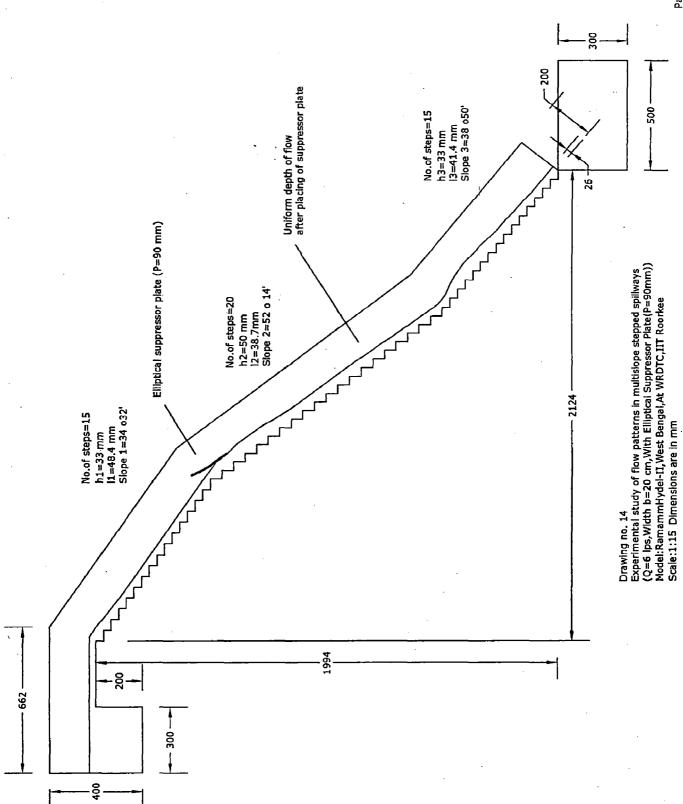


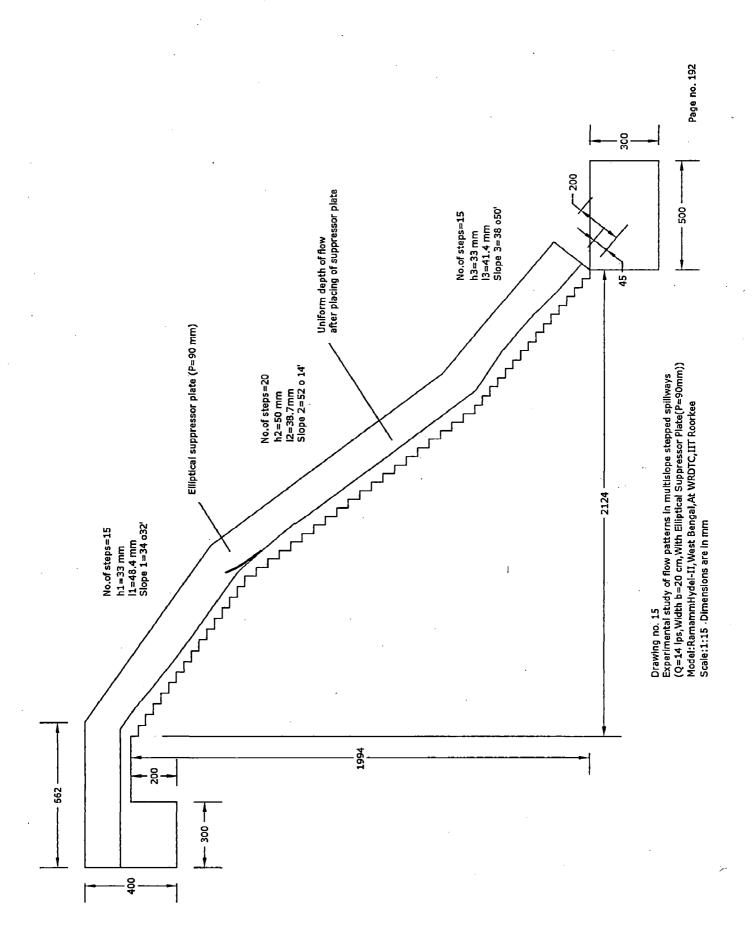


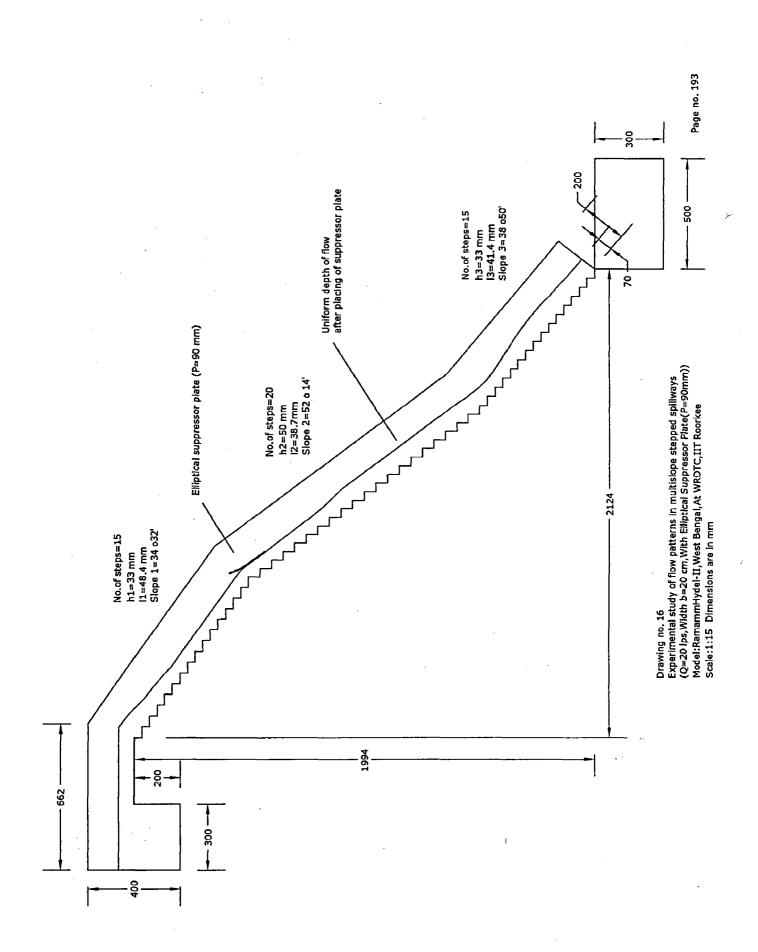


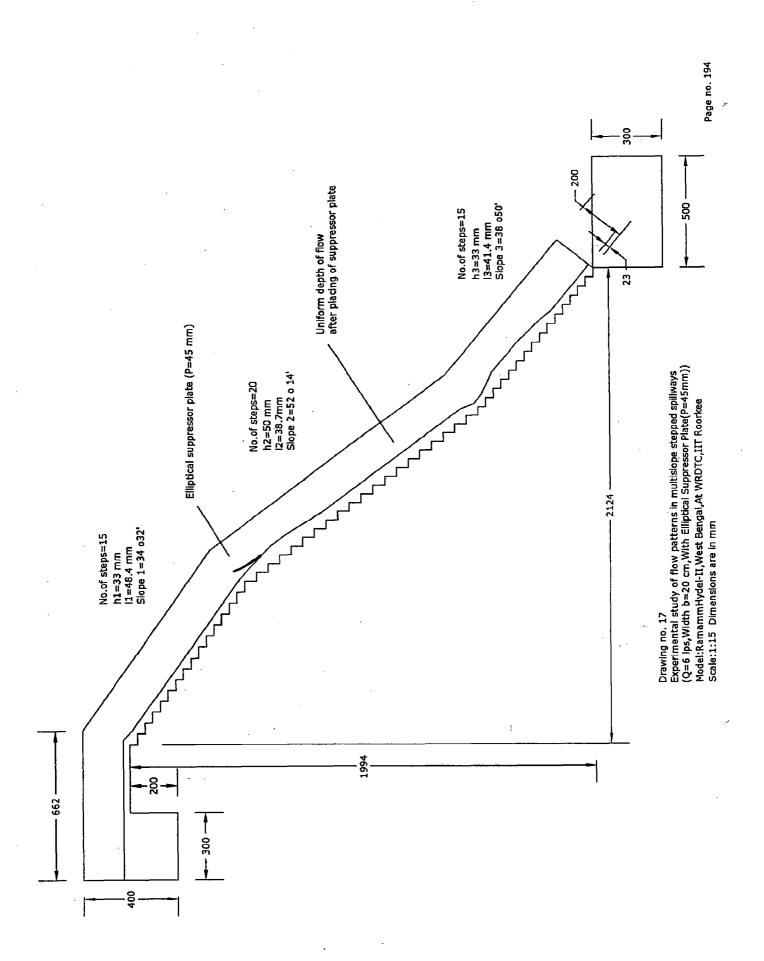


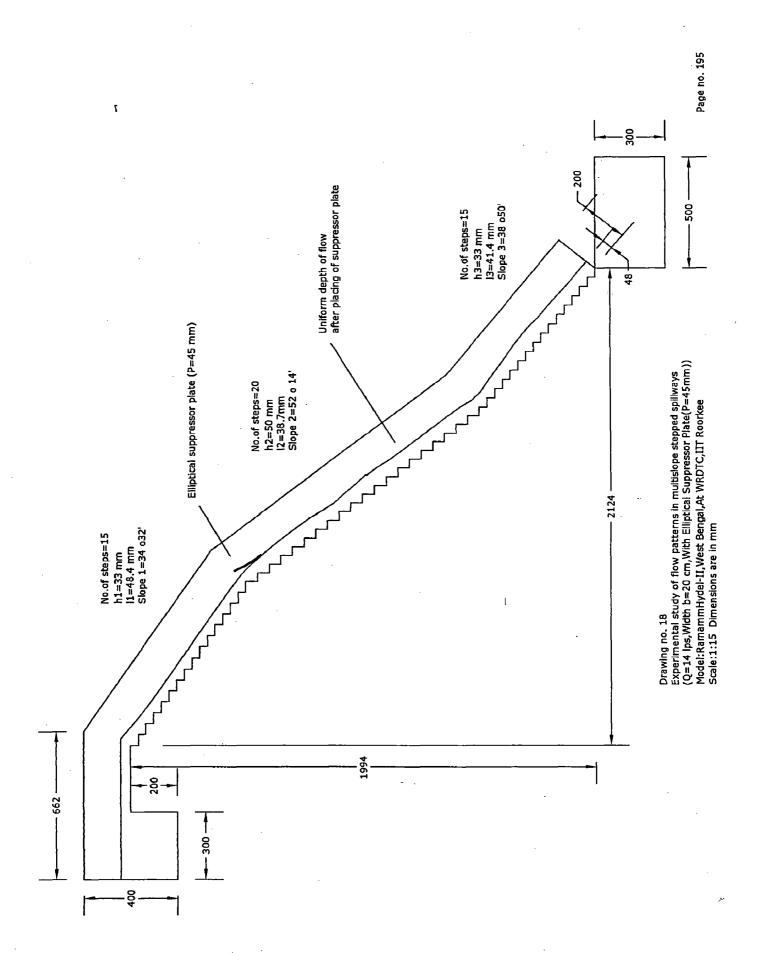


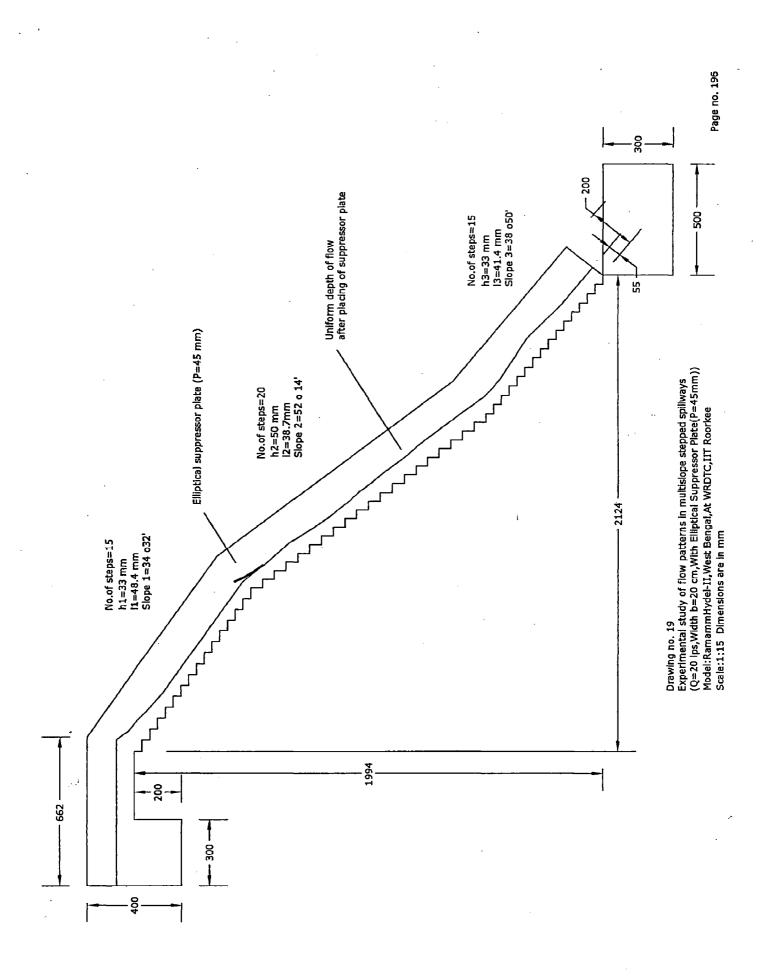












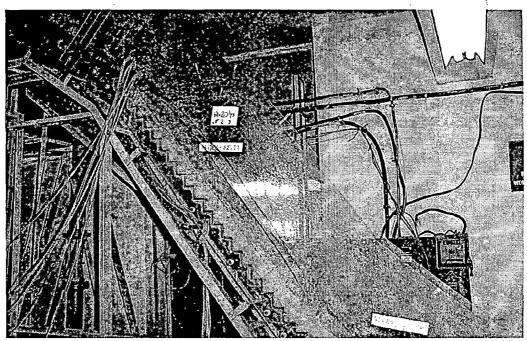


Fig. 1 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 20 lps per 20cm wide spillways.

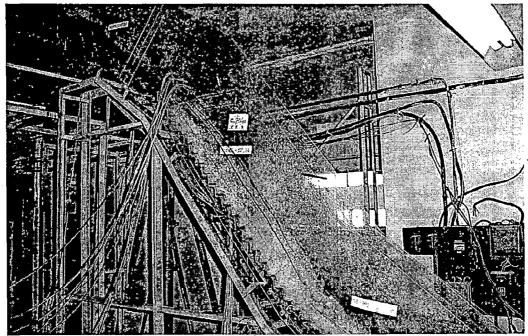


Fig. 2 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 20 lps per 20cm wide spillways.

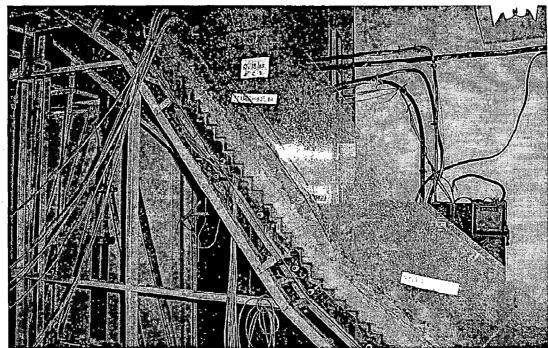


Fig. 3 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 18 lps per 20cm wide spillways

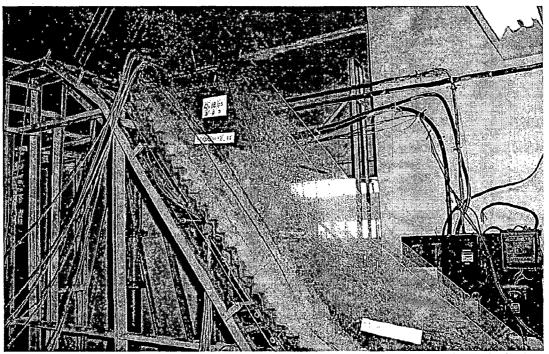


Fig. 4 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 18 lps per 20cm wide spillways

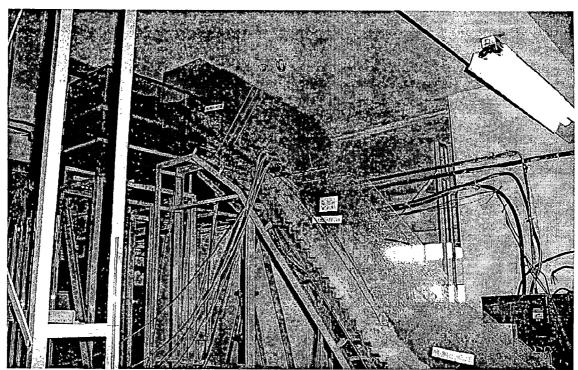


Fig. 5 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 14 lps per 20cm wide spillways



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

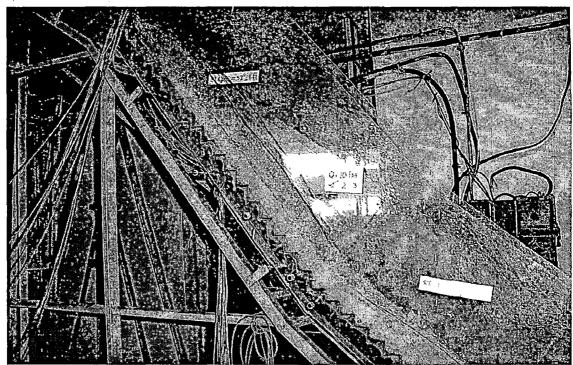


Fig. 7 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 10 lps per 20cm wide spillways

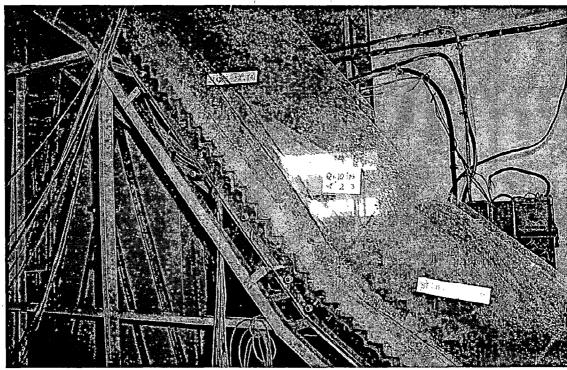


Fig. 8 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 10 lps per 20cm wide spillways

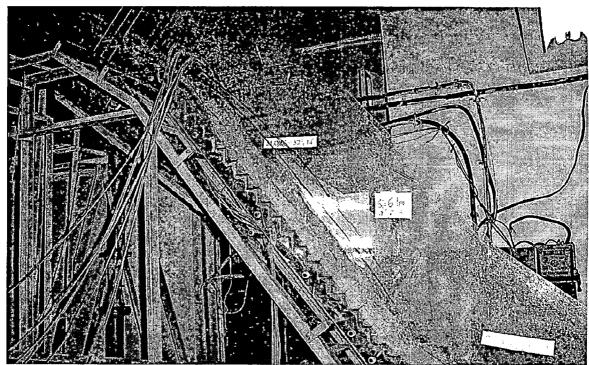


Fig. 9 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 6 lps per 20cm wide spillways

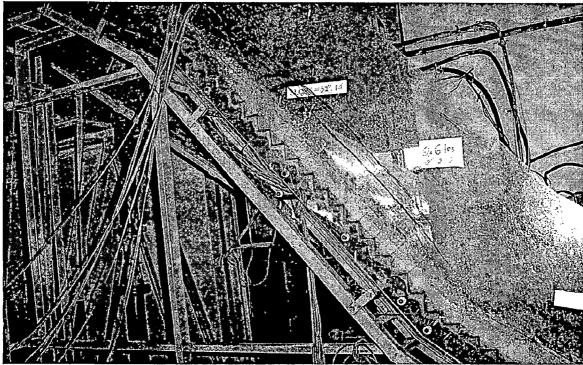


Fig. 10 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=135mm) at a discharge of 6 lps per 20cm wide spillways

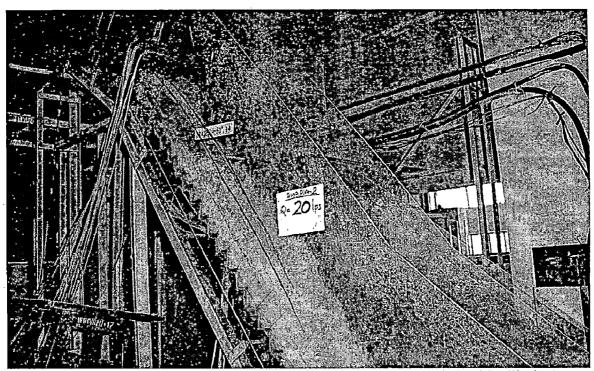


Fig. 11 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=90mm) at a discharge of 20 lps per 20cm wide spillways

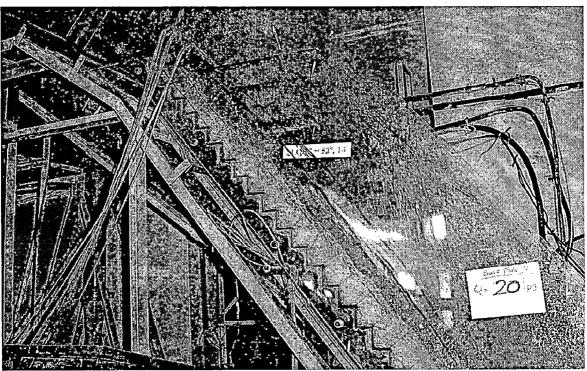


Fig. 11 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=90mm) at a discharge of 20 lps per 20cm wide spillways

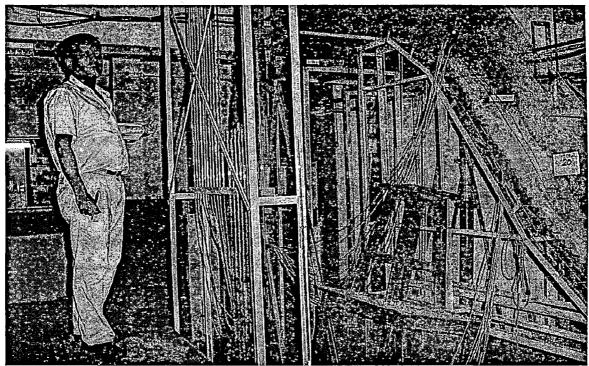


Fig. 12 Flow pattern in multislope stepped spillways in convex region with elliptical suppressor plate (P=90mm) at a discharge of 20 lps per 20cm wide spillways

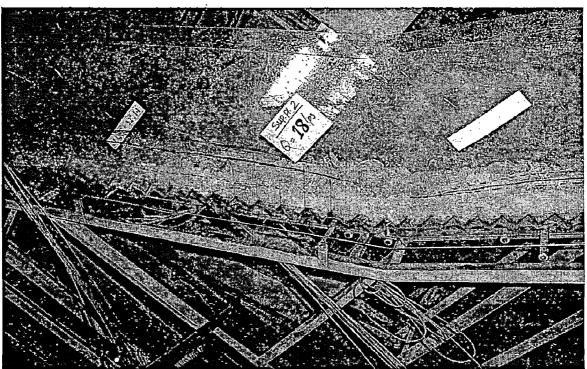


Fig. 13 Flow pattern in multislope stepped spillways in concave region with elliptical suppressor plate (P=90mm) at a discharge of 18 lps per 20cm wide spillways



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

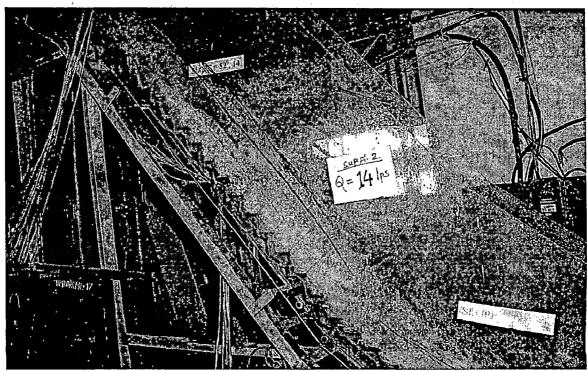


Fig. 14 Flow pattern in multislope stepped spillways in convex and concave region with elliptical suppressor plate (P=90mm) at a discharge of 14 lps per 20cm wide spillways

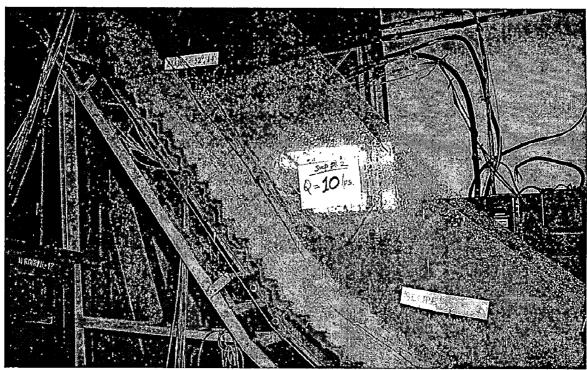


Fig. 15 Flow pattern in multislope stepped spillways in convex &concave region with elliptical suppressor plate (P=90mm) at a discharge of 10 lps per 20cm wide spillways



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

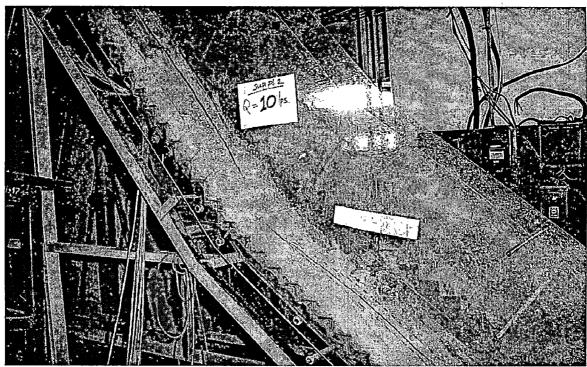


Fig. 17 Flow pattern in multislope stepped spillways in concave region with elliptical suppressor plate (P=90mm) at a discharge of 10 lps per 20cm wide spillways

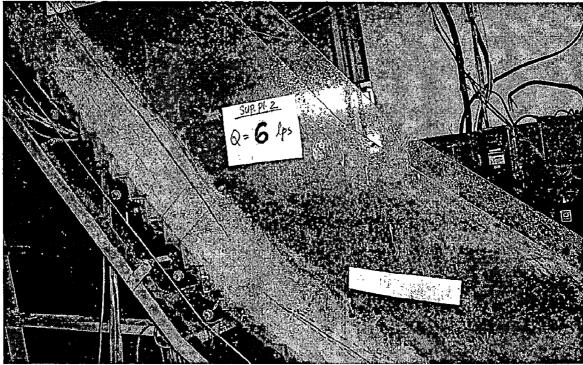


Fig. 18 Flow pattern in multislope stepped spillways in concave region with elliptical suppressor plate (P=90mm) at a discharge of 6 lps per 20cm wide spillways

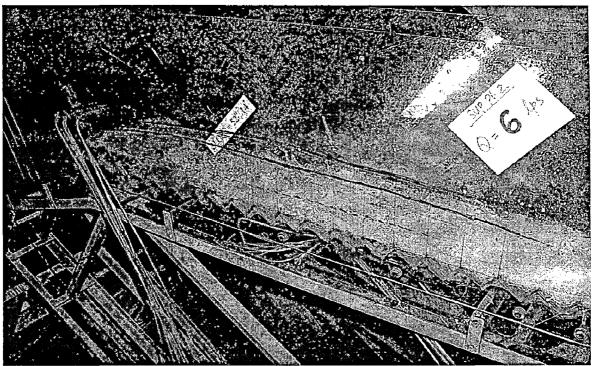


Fig. 19 Flow pattern in multislope stepped spillways in d/s of convex region with elliptical suppressor plate (P=90mm) at a discharge of 6 lps per 20cm wide spillways

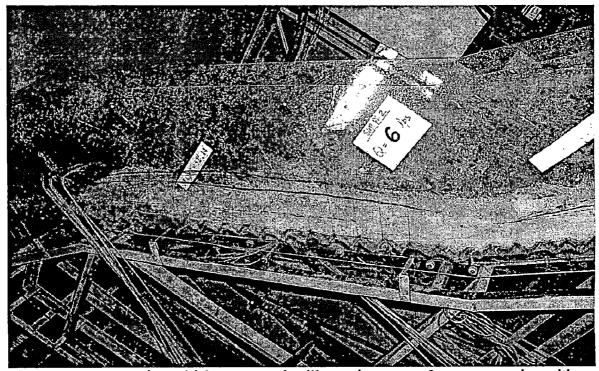


Fig. 20 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=90mm) at a discharge of 6 lps per 20cm wide spillways



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

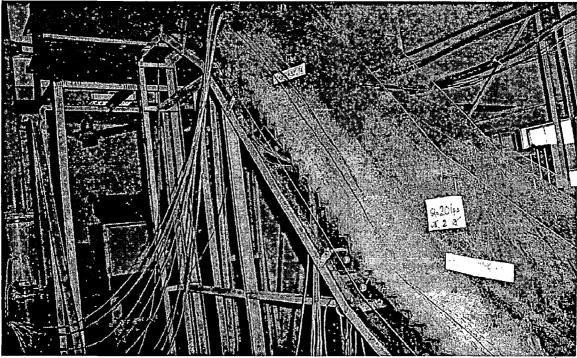


Fig. 22 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 20 lps per 20cm wide spillways



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

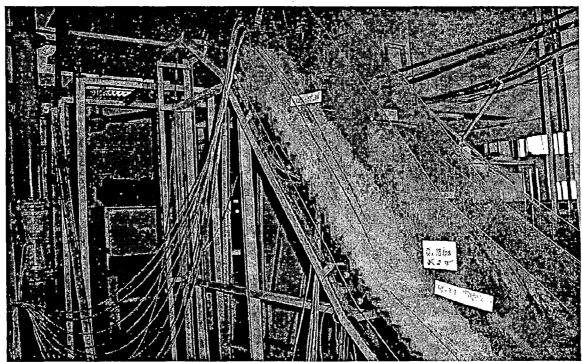


Fig. 24 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 18 lps per 20cm wide spillways

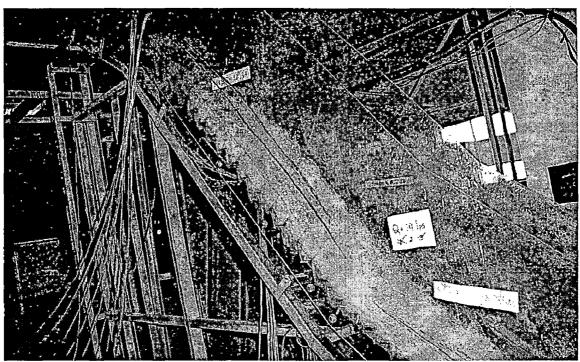


Fig. 25 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 14 lps per 20cm wide spillways



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

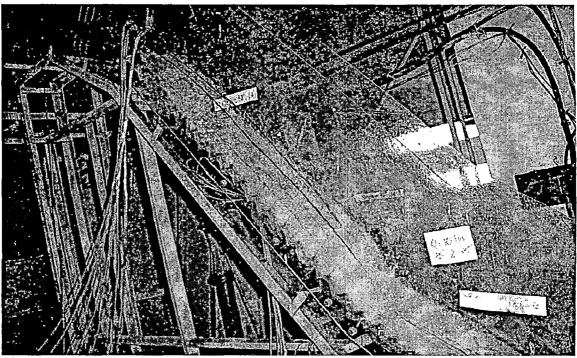


Fig. 27 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 10 lps per 20cm wide spillways



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

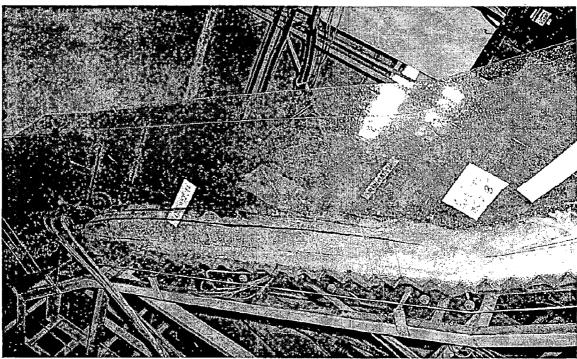


Fig. 29 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 6 lps per 20cm wide spillways

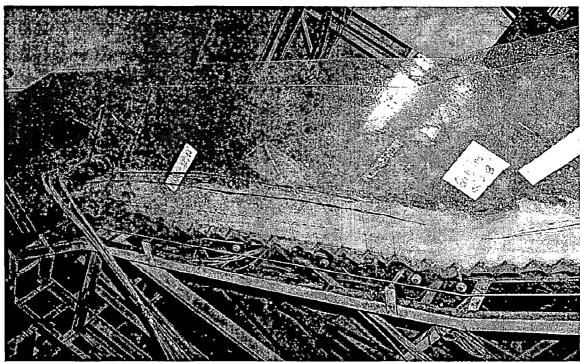


Fig. 30 Flow pattern in multislope stepped spillways in convex & concave region with elliptical suppressor plate (P=45mm) at a discharge of 6 lps per 20cm wide spillways

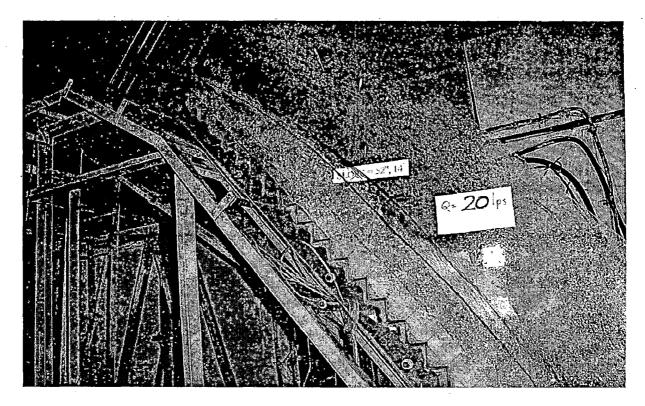


Fig. 31 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 20 lps per 20cm wide spillways.

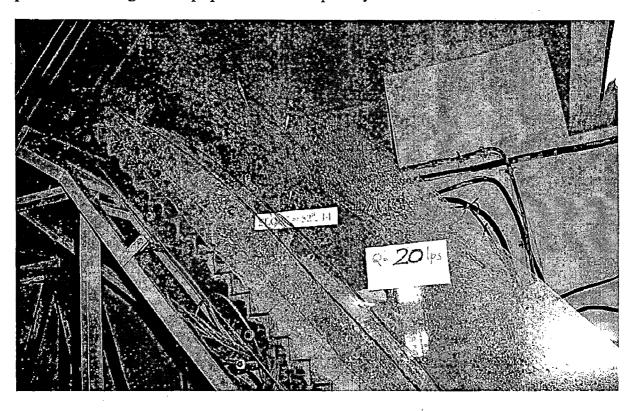


Fig. 32 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 20 lps per 20cm wide spillways.

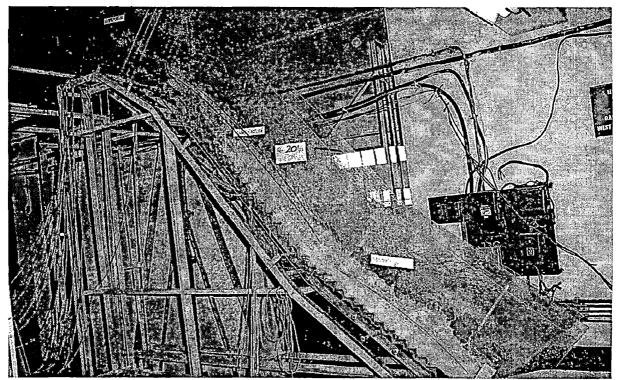


Fig. 33 Flow pattern in multislope stepped spillways in convex and concave region without suppressor plate at a discharge of 20 lps per 20cm wide spillways.

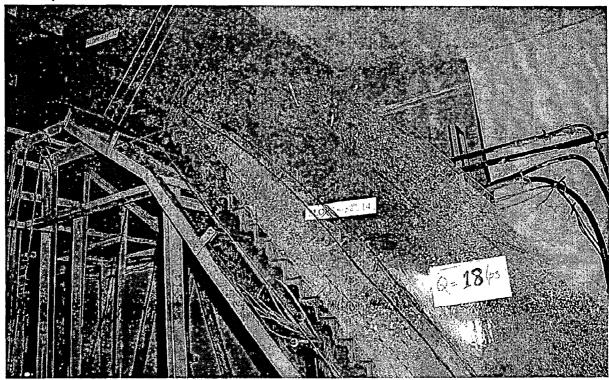


Fig. 34 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 18 lps per 20cm wide spillways.

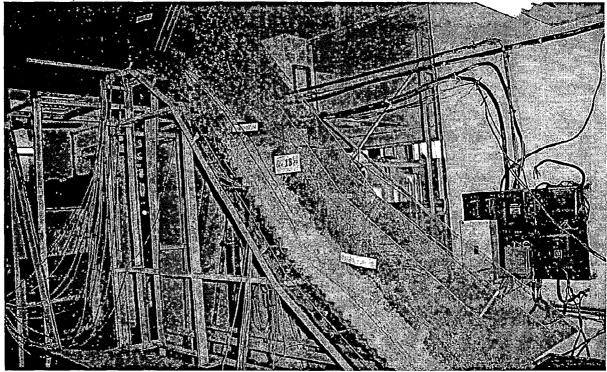


Fig. 35 Flow pattern in multislope stepped spillways in convex and concave region without suppressor plate at a discharge of 18 lps per 20cm wide spillways.

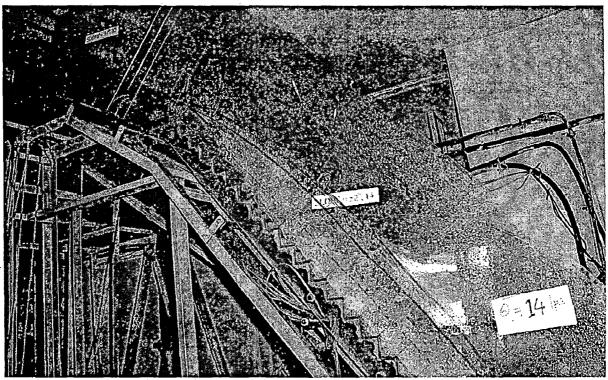


Fig. 36 Flow pattern in multislope stepped spillways in convex region without suppressor plate at a discharge of 14 lps per 20cm wide spillways.

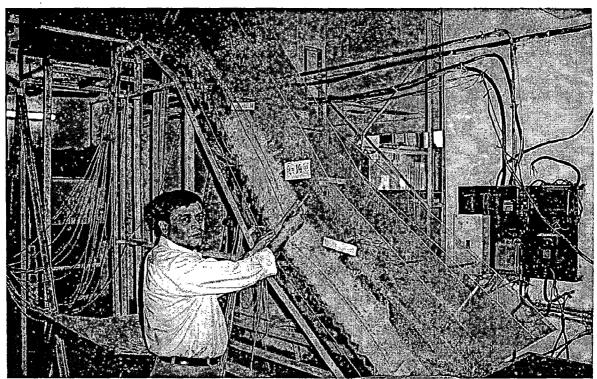


Fig. 37 Flow pattern in multislope stepped spillways in concave region without suppressor plate at a discharge of 14 lps per 20cm wide spillways.



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.

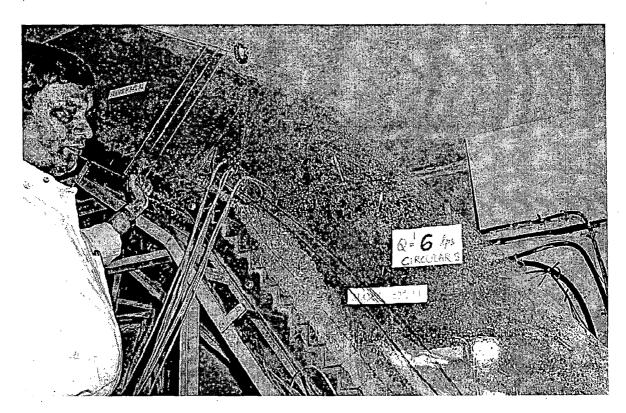


Fig. 42 Flow pattern in multislope stepped spillways in convex region with circular suppressor plate at a discharge of 6 lps per 20cm wide spillways.

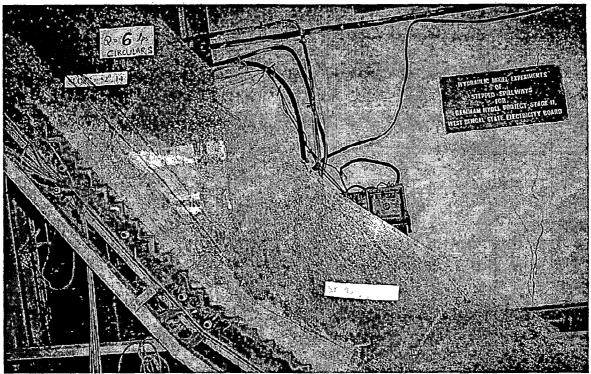


Fig. 43 Flow pattern in multislope stepped spillways in concave region with circular suppressor plate at a discharge of 6 lps per 20cm wide spillways.



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.

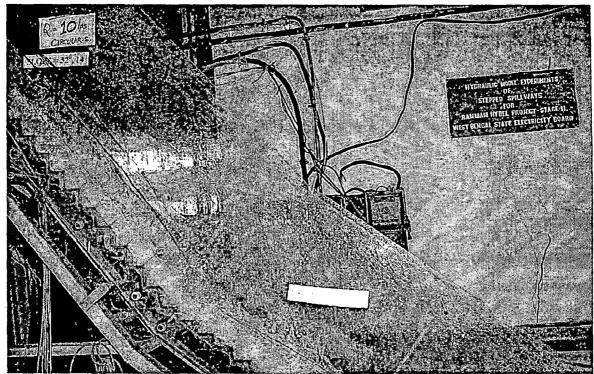


Fig. 45 Flow pattern in multislope stepped spillways in concave region with circular suppressor plate at a discharge of 10 lps per 20cm wide spillways.

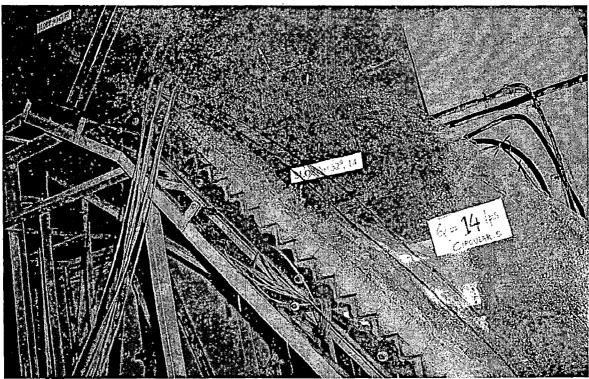


Fig. 46 Flow pattern in multislope stepped spillways in convex region with circular suppressor plate at a discharge of 14 lps per 20cm wide spillways.

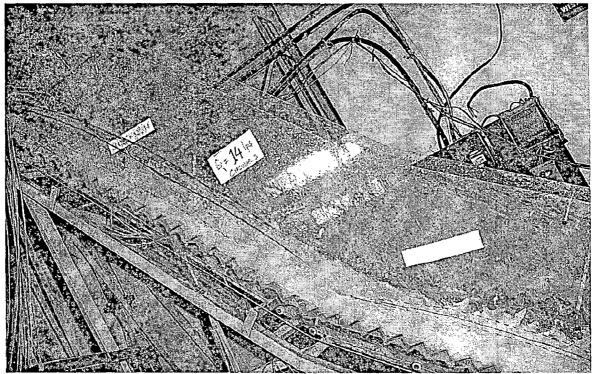


Fig. 47 Flow pattern in multislope stepped spillways in concave region with circular suppressor plate at a discharge of 14 lps per 20cm wide spillways.

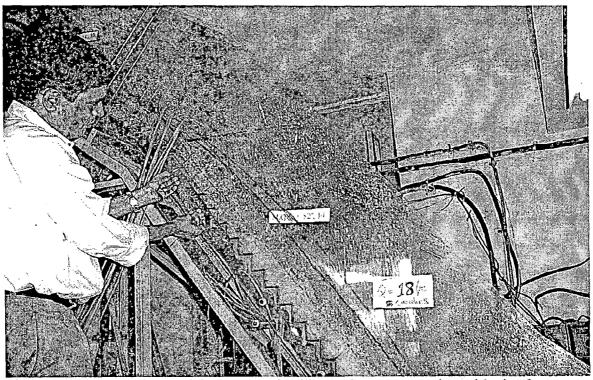


Fig. 48 Flow pattern in multislope stepped spillways in convex region with circular suppressor plate at a discharge of 18 lps per 20cm wide spillways.

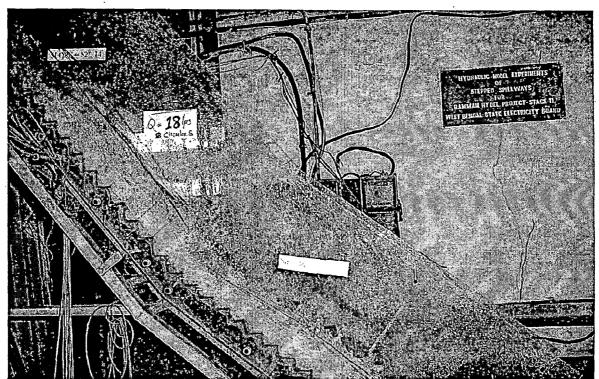


Fig. 49 Flow pattern in multislope stepped spillways in concave region with circular suppressor plate at a discharge of 18 lps per 20cm wide spillways.

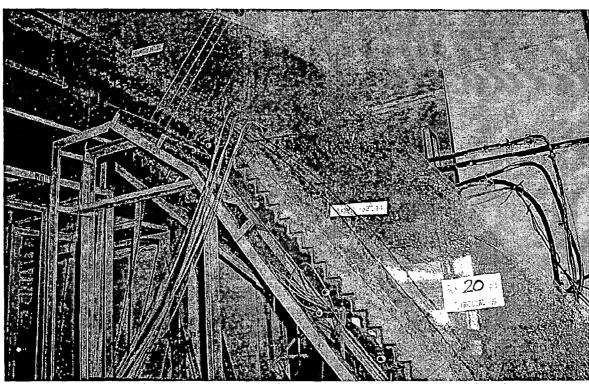


Fig. 50 Flow pattern in multislope stepped spillways in convex region with circular suppressor plate at a discharge of 20 lps per 20cm wide spillways.

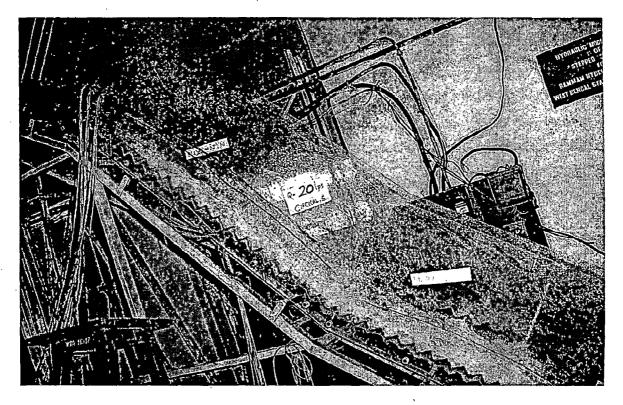


Fig. 51 Flow pattern in multislope stepped spillways in convex and concave region with circular suppressor plate at a discharge of 20 lps per 20cm wide spillways.