results and mathematical model output may be achieved. However, some discrepancies reaching to as high as 20% in terms of total energy losses may be observed , which may be attributed to the effect of the air entrainment.

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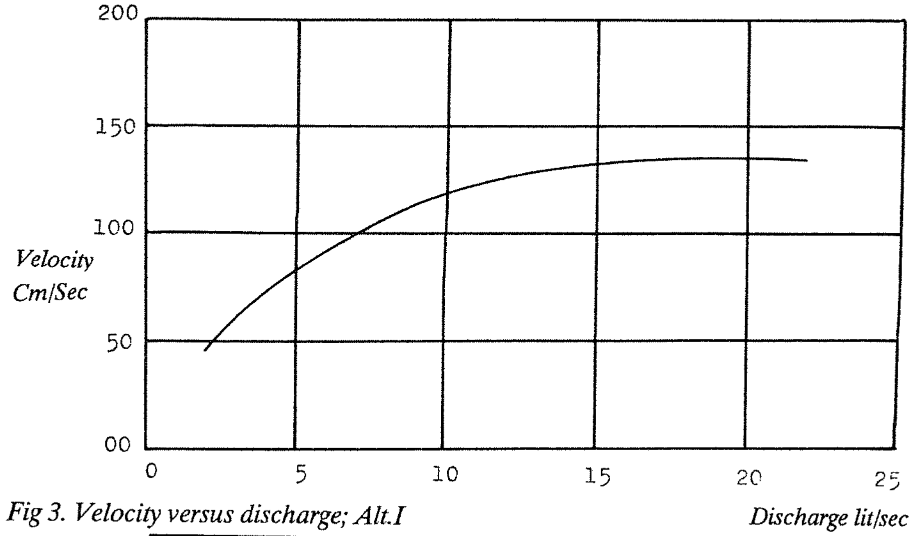


Fig 3. Velocity versus discharge; Alt.I

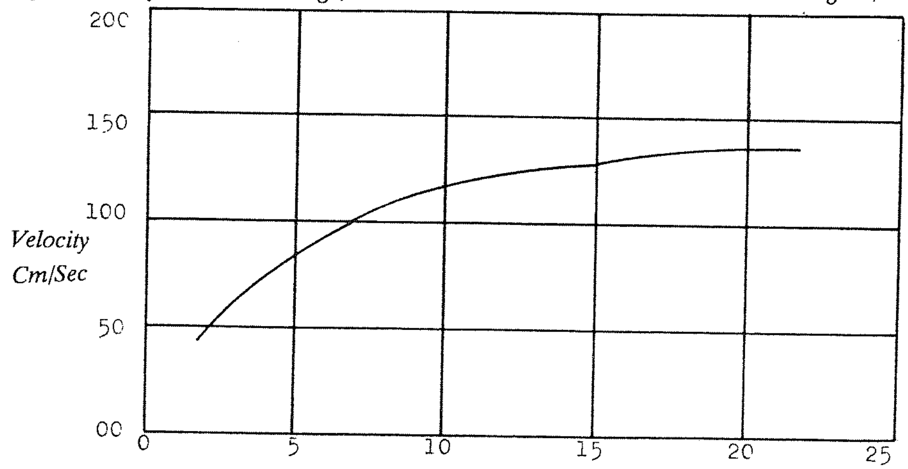


Fig 4. Velocity versus discharge; Alt.II

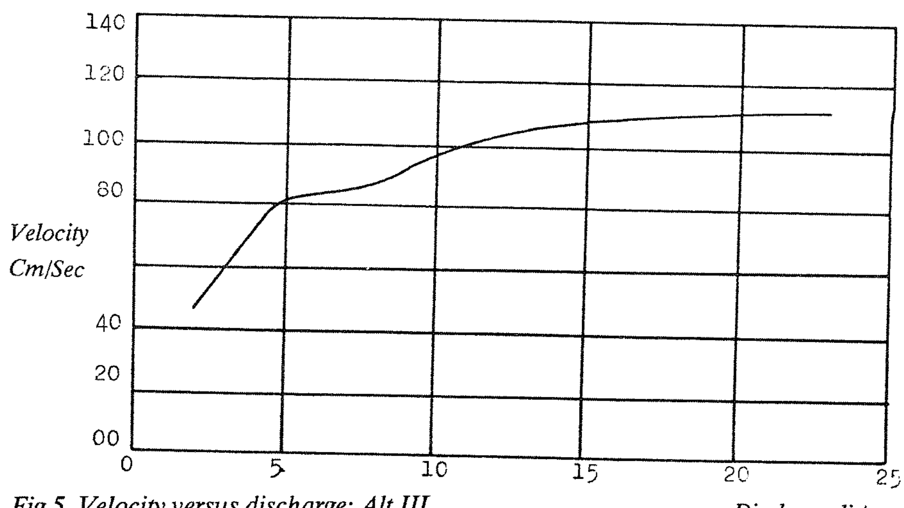


Fig 5. Velocity versus discharge; Alt.III

relationship between given parameters by means of best fit technics. The specific energy (E) - discharge (Q) relationship so obtained may be shown as follows:

$$E = a\,Q^X \qquad (12)$$

"a" and "X" were found to have the following values for different alternative models.

Alternative	*a*	*x*
I	*3.01*	*0.767*
II	*2.92*	*0.754*
III	*1.75*	*0.670*

In order to compare energy dissipation efficiency of different alternatives , specific energy - or head loss - of the flow at the toe should be determined for identical discharges. Table 3 presents the results of such calculations.

According to Table 3 , alternative III is more effective in energy dissipation compared to other variants , which means by decreasing steps height , more energy can be dissipated over spillway face for a given discharge. Also,it is clear that the lower the discharge intensity , the higher would be the energy loss on the spillway face.

To evaluate experimental records , a computer programme was developed on the basis of Bauer method described in section 3. The progromme starts with computation of average velocity and normal flow depth at a given step tip using boundary layer thickness , and proceeds in determining total energy losses at the same location by calculating form drag resistance and friction.

However, the effect of air entrainment in energy loss has not been taken into account due to the complexity of the mathematical model involved. This may be the cause of some discrepancies observed between test results and the computed values which may be as high as 20% in terms of total energy losses at the toe.

5.CONCLUSIONS

The combined mathematical-hydraulic model investigation of the stepped spillways revealed that:

a) Due to a considerable energy dissipation produced by the steps of the spillway face , the required stilling basin size at the toe is minimal.

b) The lower the discharge intensity, the higher would be the energy dissipation for a given step geometry.

c) Although the effect of each step as a resisting element on the energy dissipation is improved by increasing the hight of the step, the overall energy loss on a stepped spillway is increased by decreasing step height for a given discharge intensity.

d) A fairly good agreement between experimental

Table 3. Specific energy at the toe of different alternatives for identical discharges.

Discharge Litre/Sec.	*Specific energy at the toe, E, in Cm*		
	I	*II*	*III*
3	*3.5*	*3.7*	*3.6*
5	*5.2*	*5.4*	*5.0*
8	*7.4*	*7.7*	*6.9*
10	*8.8*	*9.1*	*8.0*
15	*11.9*	*12.3*	*10.5*
20	*14.9*	*15.3*	*12.7*

Table 2. Hydraulic characteristios of the flow at toe of spillway models.

Average velocity, Vo = Q/y.b

Specific energy, E = y + V2o/2g

Froude number, F = Vo/(g.y.cos 0)1/2

Head loss ration, RH = (head loss/total head)100

Steps height, hI = 24 mm

hII = 30 mm

hIII = 20 mm

Alternative I					Alternative II					Alternative III				
Run No	V Cm/s	E Cm	F	R_H %	Run No	V Cm/s	E Cm	F	R_H %	Run No	V Cm/s	E Cm	F	R_H %
I-1	42.0	2.4	1.095	97.0	II-1	42.0	2.5	1.268	97.0	III-1	46.0	2.6	1.199	97.0
I-2	59.0	3.47	1.445	96.0	II-2	63.0	3.6	1.590	96.0	III-2	57.0	3.3	1.439	96.0
I-3	60.0	3.83	1.355	96.0	II-3	70.1	4.2	1.714	95.0	III-3	66.0	4.2	1.571	95.0
I-4	81.3	5.44	1.785	94.0	II-4	81.0	5.3	1.829	94.0	III-4	83.0	5.5	1.874	94.0
I-5	85.0	5.98	1.789	93.7	II-5	88.0	6.1	1.894	93.5	III-5	83.0	5.9	1.693	94.0
I-6	99.6	7.76	1.935	91.9	II-6	112.0	8.8	2.308	91.0	III-6	85.0	6.8	1.541	93.0
I-7	109.0	9.06	2.009	90.7	II-7	116.0	9.6	2.213	90.0	III-7	96.0	8.1	1.662	92.0
I-8	116.0	10.40	1.952	89.4	II-8	126.0	11.4	2.215	88.0	III-8	106.0	9.6	1.703	90.0
I-9	126.0	12.00	2.024	87.9	II-9	130.0	12.4	2.129	87.0	III-9	106.0	10.4	1.569	89.0
I-10	131.0	13.10	1.994	86.9	II-10	134.0	13.4	2.063	86.0	III-10	108.0	11.3	1.491	88.0
I-11	134.0	14.20	1.913	86.1	II-11	139.0	13.6	2.026	85.6	III-11	112.3	12.3	1.472	88.0
I12	-	-	-	-	II-12	135.0	14.6	1.872	85.7	III-12	113.0	13.3	1.389	87.0

To measure actual inflow to the flume, a 90° vertex angle V - notch with a discharge coefficient of $C_o = 0.14\ (2g)^{1/2}$ - which was determined experimentally - together with a point gage that could measure the water surface elevation in the head tank were used. A second point gage was installed in the model bay to determine the water surface elevation upstream of the crest. The vertical flow depth at specified equally spaced locations including spillway toe were also measured by means of scale strips.

Due to the flow condition at the toe and unreliable velocity measurements by conventional velocity meters, no direct velocity evaluation was made. Sorensen (7) reports that a maximum error of 10 - 15% in the velocity values calculated from continuity equation may be involved. However, to avoid velocity changes and consequently head losses due to sudden enlargement at the toe of the model tailrace flume was constructed with the same width as the spillway flume itself. Tailrace flow depth measurements were made on the horizontal section of the flume downstream of the toe where air entrainment had significantly diminished.

Test conditions including discharge, actual head on the crest and normal flow depth at the toe for different spillway section models and for each test run are presented in Table 1.

4.ANALYSIS OF THE RESULTS

Table 2 shows hydraulic parameters of the flow at the toe of spillway model for different alternative. The plots of toe velocity versus discharge were prepared on the basis of the results and are presented in Figures 3, 4 & 5.

A computer programme known as STATGRAPH was employed to plot variation of mean flow velocity and specific energy against discharge. The programme could calculate a correlation coefficient and establish a general

Table 1. Test conditions for different sectional hydraulic models

H=Head on the crest *Q=Discharge* *y=Normal flow depth*

AlternativeI				*AlternativeII*				*AlternativeIII*			
Run No	*H mm*	*Q l/s*	*y mm*	*Run No*	*H mm*	*Q l/s*	*y mm*	*Run No*	*H mm*	*Q l/s*	*y mm*
I-1	70.0	1.89	15	II-1	71.3	1.98	14	III-1	72.4	2.06	15
I-2	84.5	3.03	17	II-2	84.4	3.02	16	III-2	80.9	2.71	16
I-3	90.7	3.62	20	II-3	90.3	3.58	17	III-3	90.3	3.58	18
I-4	104.0	5.09	21	II-4	102.3	4.89	20	III-4	103.0	4.97	20
I-5	110.3	5.90	23	II-5	109.7	5.82	22	III-5	112.0	6.13	25
I-6	126.0	8.07	27	II-6	125.1	8.08	24	III-6	124.0	7.94	31
I-7	135.0	9.78	30	II-7	135.0	9.75	28	III-7	135.0	9.78	34
I-8	149.2	12.55	36	II-3	149.0	12.51	33	III-8	149.0	12.51	40
I-9	160.0	14.95	40	II-9	159.3	14.79	38	III-9	159.5	14.83	47
I-10	169.5	17.27	44	II-10	169.8	17.34	43	III-10	169.5	17.27	54
I-11	180.0	20.07	50	II-11	180.0	20.07	48	III-11	179.0	16.79	59
I-12				II-12	185.0	21.49	53	III-12	189.5	22.82	67

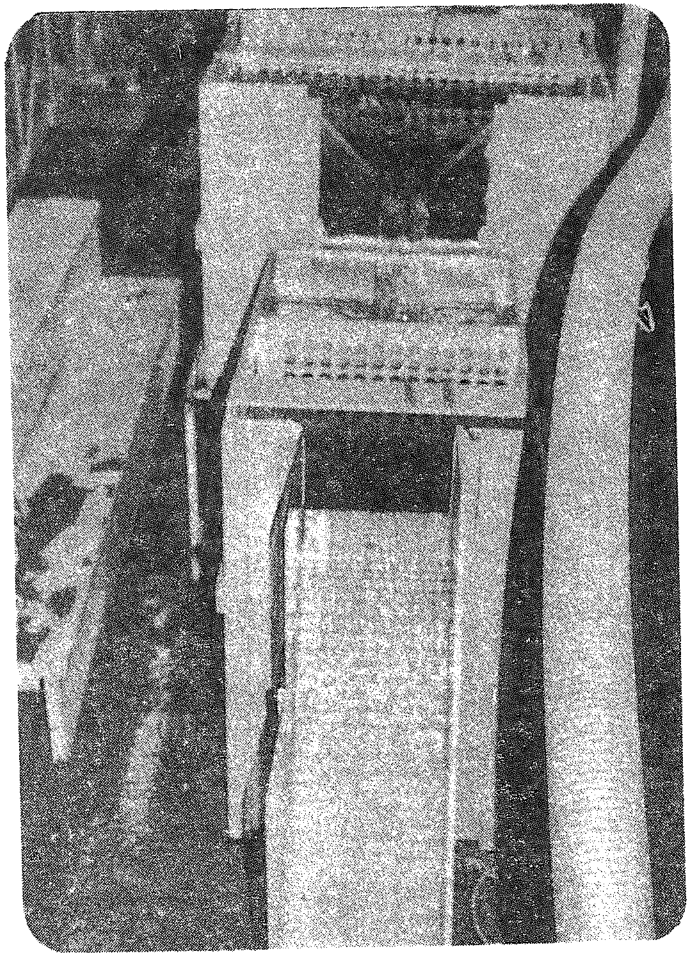


Plate 1. Experimental setup,general view.

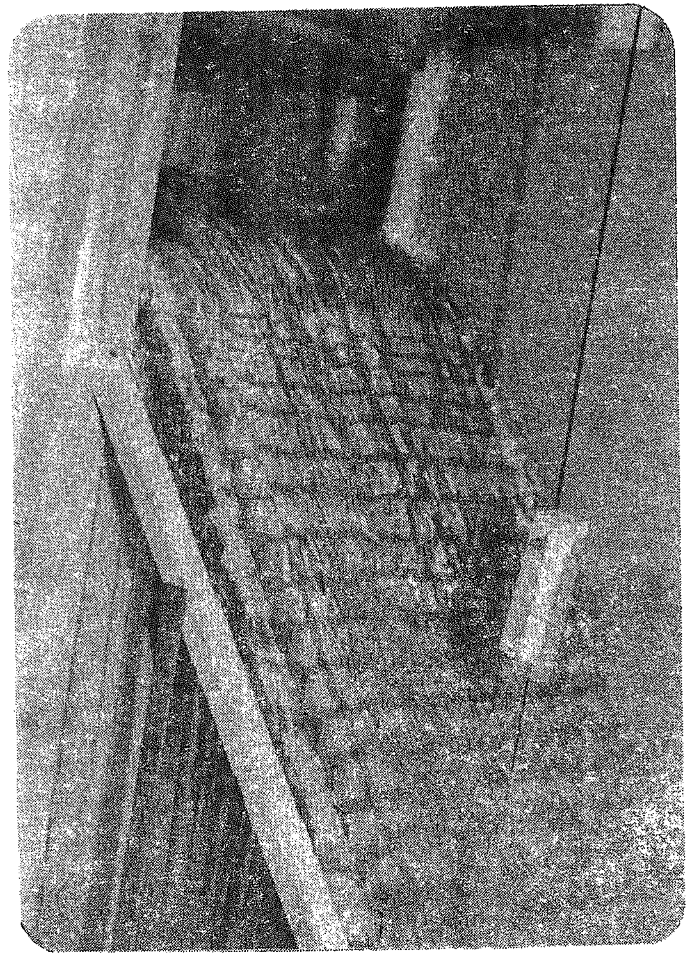
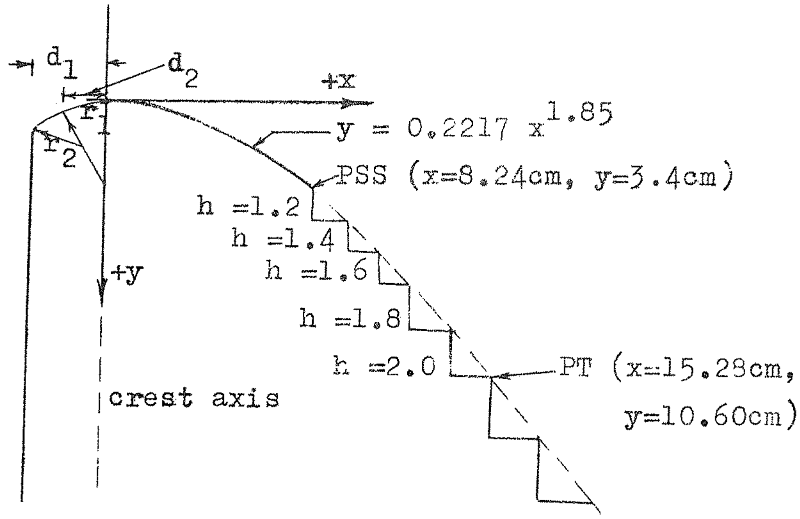
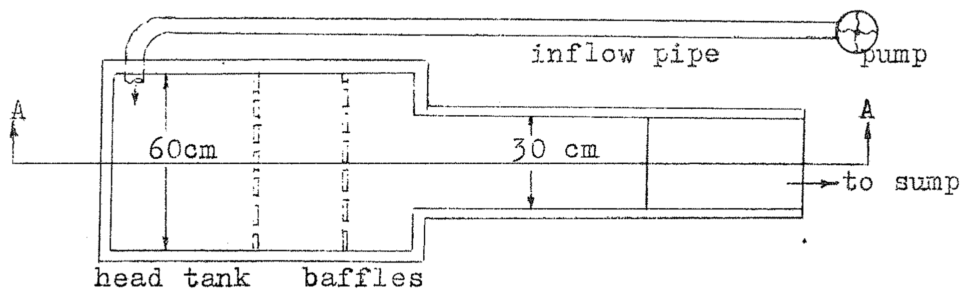


Plate 2. Flow over stepped spillway model;
Q=14.83 lit/sec.

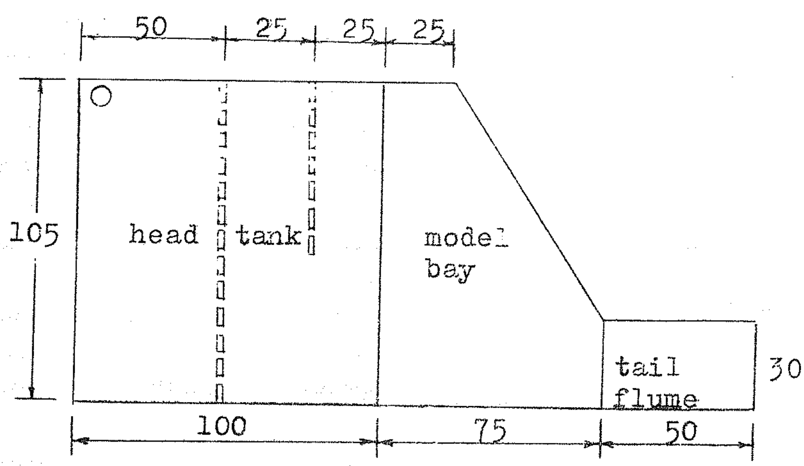
were 20 mm and 16 mm respectively. General layout of the investigation setup is shown in Figure 2 schematically and in Plates 1 & 2 actually.



Modified WES Standard Profile into a Stepped Profile; Upper portion



PLAN



SECTION AA

Fig 2. Crest profile,plan and sectional sketch of test flume. All dimensions are shown in cm.

To consider the effect of relative distance - defined as L/h or distance between two adjucent step tips/height of a step - on the resistance of the roughness elements of following equation may be used (3,4).

$$\frac{L}{h}=\frac{(1+cot^2\theta)^{1/2}H}{H\cos\theta}=\left[\frac{1+cot^2\theta}{cos^2\theta}\right]^{1/2} \quad (4)$$

in which θ is the slope angle of the channel bed, H is the vertical height of a step and other parameters have been defined above. Derivation of equations 3 & 4 is based on the assumption that the total shear resistance is approximately equal to the form drag shear resistance, hence it can be written as:

$$\gamma R \sin\theta = C_D h /L. [\rho \; \overline{V}^2/2] \quad (5)$$

With reference to Figure $1, L=L_1/cos\theta, h=Hcos\theta$, tan $\theta = H/L_1$ and R is the hydraulic radius with respect to the the bed, and γ is the weight of the flowing fluid; ie $\gamma \;\; = \rho\gamma$.

Based on the theory of boundary layer development on a steep rough open channel, the flow properties may be found by Bauer method(1). According to this method, for a given roughness height, K, and at a distance X from the origin of a conventional spillway, mean flow depth in terms of turbulent boundary layer thickness, δ, may be computed by:

$$(\delta/X) = a/(X/K)^Z \quad (6)$$

$$V_o = (2gX\sin\theta)^{1/2} \quad (7)$$

$$d = (0.10 + q/V_o)\cos\theta \quad (8)$$

Constant a and exponent Z have been reported to be in order of 0.024 and 0.13 respectively. Now, considering the head loss due to the resistance of each step on a stepped spillway which is given by:

$$h_L = C_D h \;\; \overline{V}^2/2g(d-h) \quad (9)$$

One may calculate total energy losses at the tip of each step using equation 8,9, and any convenient frictional equation such as Chezy's.

3.EXPERIMENTATION:

Three segmental models were constructed to conduct the proposed investigation. The scale of the models were chosen in accordance with USBR recommendations and typical procedures for hydraulic model studies of high spillways(2). The USBR recommendation calls for a scale of not less than 1:60 for high to medium size spillways, therefore a 1:25 scale model deemed to be satisfactory. To define prototype-model scale relationships, the Froude similarity criteria was adapted as the gravity forces dominate in such hydraulic structures. Moreover, the models could not be built to distorted scale due to significant horizontal and vertical components of velocity and acceleration involved in the flow over spillways. The following scale relationships were used:

$$V_m = (1/5)\,V_P \quad (10)$$

$$q_m = (1/125)\,q_P \quad (11)$$

in which V_m and V_P are mean velocity of the flow in the model and prototype respectively; q_m and q_P are discharge intensity-ie Q/L - in the model and prototype respectively.

A minimum flow depth of 150 mm over the crest of the spillway mode and a minimum model crest width of 150 mm are recommended by Bureau of Reclamation to minimize effects of viscosity and surface tension. In this investigation, the models were so designed and tested that the above recommendations could be satisfied. The crest of the spillway models had a length of 300 mm and the profile was determined in accordance with the WES procedure as shown in Figure 2. The unstepped portion of the crest and five transitional steps which were located at upstream of the point of tangency, were kept unchanged in different model alternatives and only the stepped portion of the spillway model had different geometries.

Model steps in the first alternative were of 24 mm height and 19 mm width corresponding to a prototype size of 600 mm and 480 mm respectively.

The second alternative employed steps of 30 mm height and 24 mm width corresponding to a prototype size of 750 mm and 585 mm respectively.

The height and width of the steps of third alternative

A stepped spillway is generally considered as an effective energy dissipator for gravity dams where hydraulic type stilling basins or buckets and plunge pools can not be utilized due to economic and/or construction limitations. Compared with conventional spillways, an average energy reduction of about 70% on the spillway face may be achieved by a stepped spillway and for dissipation of the remaining energy at the spillway toe, only a small structure may be needed.

A review study of the previous investigations (7,9,11) on this type of spillways indicates that usually a standard ogee profile is adapted as a basis for the design of steps so that the envelope of the step tips follows the standard profile down to the spillway toe. Upstream of the first step which is usually placed at the point of tangency on the spillway face, few transitional steps varying in size are provided to improve flow condition over unstepped portion of the crest.

However, no generalized criteria for determination of the steps geometery with respect to their hydraulic characteristics has been so far proposed. Although Sorensen(7) points out about similarities between flow conditions over stepped spillways and rough boundaries and recognizes the flow type to be of QUASI-SMOOTH, his experimental records were not analysed accordingly.

This investigation, hence, aims to evaluate certain design parameters such as steps geometery-discharge intensity interrelation and the slope angle of the channel bed affecting over a stepped spillway face.

2.THEORETICAL BASIS:

Flow over stepped spillways may be defined as a flow in rough steep open channel and the energy of the flow is to be dissipated by the resistance of the roughness elements on the bed so that the flowing water will not do any serious scour or erosion at the toe of the spillway. It has been found that the steps-ie roughness elements-could be treated as discrete, and standard values of drag coefficient may be used to predict the resistance offered by the roughness elements(5). It has been also observed that the form drag resistance contributes 92-98 precent of the total resistance at most of the roughness spacings (4).

The drag force on a step, F_B, may be calculated by the following equation:

$$F_B = C_D\, h\, B\, (\rho\ \overline{V}^2)/2 \qquad (1)$$

in which $\overline{V}$ is the mean velocity of flow in the channel, C_D is drag coefficient, B is the width of the channel, h is the step height prependicular to the main slope, and ρ is the mass density of the fluid. The variation of the drag coefficient with relative depth - ie D/h = flow depth/hieght of step _ may be defined by:

$$\frac{1}{(C_D)^{1/2}} = A_1\, Ln\,(D/h) + A_2 \qquad (2)$$

in which A_1 and A_2 are constants depending to the slope angle of the channel. The drag coefficient is expected to be a function of Froude number as well. Therefore, equation(2) should be modified to take into account the Froude number as follows:

$$C_D = m/(D/h)^x\,(F)^y \qquad (3)$$

in which m is a constant, x and y are exponents to be determined experimentally.

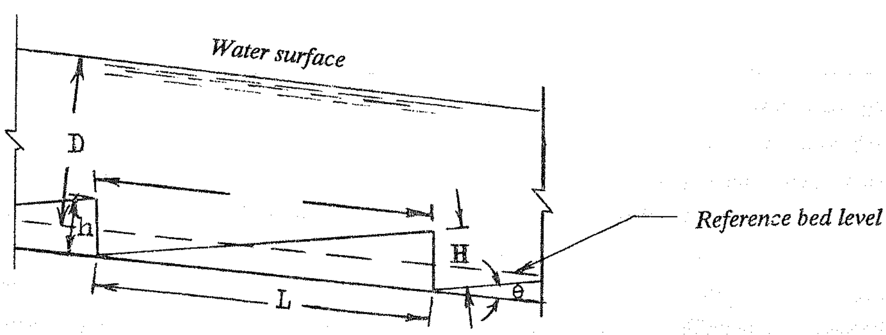


Fig 1. Definition sketch

AN INVESTIGATION INTO THE PERFORMANCE OF STEPPED SPILLWAYS

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ABSTRACT:

To evaluate design parameters affecting performance of stepped spillways as a substitute to conventional terminal structures a hydraulic model investigation was conducted. A mathematical model describing the energy dissipation mechanism on stepped spillways has been developed by treating the steps as resisting elements. Using drag resistance and boundary layer theories normal flow depth, mean velocity and specific energy could be computed at the tip of each step. Experiments have been conducted on three two-dimentional sectional models heving a standard ogee profile with continuous steps cut into the spillways face from just below the crest to the toe. A fairly good agreemant between experimental results and theoretical output indicates viability of the theory and suggests possibility of estimating energy dissipation by any given step geometry and for any given discharge.

1-INTRODUCTION:

Structural design of conventional spillway's terminal structure for high dams has been a matter of concern,as a number of such structures have been the sources of frequent,serious trouble. This implies that,except where the energy of the water is converted to electricity, the problem of energy dissipation is still not totally under control and remains as a serious concern for present and future generations(8). A possible way of avoiding the problem may be to integrate terminal structure into the spillway face, so that a fairly reliable design, as far as structual stability is concerned, can be obtained. Stepped spillways, being one of such designs, is not a new concept and had been used in a number of ancient dams of Iran.

As a part of a research progromme, a hydraulic model investigation has been conducted in the hydraulic lab. Civil Enging Dept. of Tehran Polytechnics, to study design parameters affecting performance of a stepped spillway.