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An Approach to Optimal Design of Trapezoidal Labyrinth Weirs

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Abstract: Trapezoidal labyrinth weirs offer significant flow magnification for the available width of approach channel and that of the downstream chute. These types of weirs may find great utility and hence will have to be designed and provided for river linking projects. There are many factors such as head to crest height ratio, angle of side walls, vertical aspect ratio, apex width and approach and conveyance channel conditions that influence the capacity of weir and hence the hydraulic design of labyrinth weir. In this paper, a mathematical model for optimum C_d for labyrinth is proposed and a methodology has been suggested for the optimal hydraulic design of trapezoidal labyrinth weir.

Key words: Weirs · Channels · Flow magnification · Hydraulic design

INTRODUCTION

Weir is an artificial barrier in a watercourse. Provision of weir increases water surface level upstream, for some flow conditions. Typically all the weirs are characterized by a drop in water level in the water course from elevated upstream level to natural downstream level. This drop may tend to disappear during high flood conditions. In engineering terms a weir must be able to satisfy the fundamental requirements viz. Hydraulic performance, Structural stability and Environmental impact & safety aspects. Weirs are normally provided for any one or more of the following fundamental functions:

- Water Level Management
- Flow Measurement
- Environmental Enhancement
- Channel Stabilization

Generally a spillway consists of some type of control structure which is normally placed perpendicular to the flow direction. The capacity of spillway or a weir refers to the discharge for a given head of flow over its crest. If the capacity of weir is to be increased for a given width of approach, the labyrinth spillway or weir offers a feasible alternative. Labyrinths are the weirs folded in plan view. Labyrinths are also used to control water quality by aerating the flow. Labyrinths can also serve as drop structures on canal systems. If used on a canal system, a set of labyrinth weirs will serve as energy dissipators and at the same time maintain a more constant flow depth in canal than could be achieved with a conventional drop structure.

LITERATURE REVIEW

Taylor [1] conducted experiments on triangular labyrinth weirs and presented his results in terms of flow magnification, i. e. ratio of the labyrinth flow to the flow for a sharp crested linear weir having the same channel width. As a follow up to Taylor's work, Hay and Taylor [2] proposed a design procedure for triangular and trapezoidal labyrinth weirs. However the expression for discharge coefficient used in the procedure was not dimensionally homogeneous. Similarly Darvas [3] used the experimental results of the model studies of Woronora and Avon weirs in Australia and developed a family of curves for designing labyrinth weirs. Lux [4] assessed the hydraulic performance of labyrinth weirs using data obtained from flume studies and the specific models. He introduced another discharge coefficient based on the total upstream head.

Tullis *et al*. [5] conducted a series of experiments with different labyrinth angles in the range of 6° to 18° and proposed the expressions for coefficient of discharge for labyrinth weir. These values of coefficients of discharge can be used in the linear weir equation and resulting labyrinth weir discharge can be obtained. Table 1 shows a list of some of the labyrinth weirs constructed worldwide.

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Table 1: List of labyrinth weirs/spillways

Name and Country	Year	Q, cumec	H, m	P, m	w, m	l, m	N
Alfaiates, Portugal	1999	99	1.60	2.50	13.2	37.5	1
Avon, Australia	1970	1420	2.16	3.00	13.5	26.5	10
Arcosso, Portugal	2001	85	1.25	2.5	13.3	16.68	1
Bartlett's Ferry, USA	1983	5920	2.19	3.43	18.3	70.3	20.5
Boardman, USA	1978	387	1.77	2.76	18.3	53.5	2
Cimia, Italy	1982	1100	1.50	15.50	30.0	87.5	4
Dungo, Angola	1985	576	2.40	4.30			
Flamingo, USA	1990	1591	2.23	7.32	95.1	67.4	4
Navet, Trinidad	1974	481	1.68	3.05	5.49	12.8	10
Ute, USA	1983	15570	5.79	9.14	18.3	73.7	14
Woronora, Australia	1941	1020	1.36	2.13	13.41	31.23	11

LAYOUT AND GENERAL DETAILS

Figure 1 shows a general layout of a trapezoidal labyrinth weir.

Notations used are:

A = Inside apex width
B = Length of labyrinth apron
H = Total upstream head
L = Effective length of weir
N = Number of cycles
P = Weir height
l = Length of one cycle
t = Wall thickness
W = Total width of labyrinth
w = Width of one cycle of labyrinth
α = Angle of side legs or labyrinth angle

CHARACTERISTICS OF FLOW

When the weir is placed at an acute angle to the flow, the flow becomes three dimensional. For straight weirs, all the streamlines are perpendicular to the crest and are two-dimensional. But for inclined weir, like a labyrinth weir, the streamlines under the nappe are almost perpendicular to the crest, whereas at the free water surface the streamlines are pointing towards the downstream direction. The labyrinth weir flow becomes further complicated due to interference of jets near the upstream apex of the labyrinth. At high discharges, the jets from adjacent crests strike each other and in the process create a nappe that is not aerated. This results in decrease of discharge coefficient of the weir. Obviously, the magnitude of impact increases as the labyrinth angle decreases and the head over the crest increases. Hence it is observed that the underside of the nappe is aerated for low heads only and the advantage of labyrinth diminishes as the head over the crest increases.

FACTORS AFFECTING THE PERFORMANCE

From the model studies it has been found that with increase in H/P ratio, the flow magnification decreases for a labyrinth weir i.e. as the head increases crest coefficient continues to decrease and the spillway capacity ultimately equals to that of a linear weir having crest length equal to apron width. Inside apex width, A, also affects spillway capacity. Provision of this apex width differentiates a trapezoidal labyrinth from a triangular labyrinth. It reduces the net length of the labyrinth weir and decreases the spillway capacity. Hence, apex width should be as small as possible. The apex width is provided to avoid the effects of nappe interference in the labyrinth. Upstream and downstream conditions also influence the hydraulic functioning of labyrinth. The flow downstream from the labyrinth should be supercritical to avoid submergence effects.

For a head, the nappes from two weirs placed at an angle with each other would have an impact over a specific length of the weir crest. This is referred as nappe interference. The effect of nappe interference is to decrease the discharge over the labyrinth. Another crucial parameter is labyrinth angle, α. This affects the capacity as well as the layout of labyrinth. The smaller labyrinth angles produce a higher capacity with lower reservoir elevations. This happens because smaller angles offer larger effective lengths. A larger angle is normally chosen in case of a spillway replacement where there is an existing apron width available and hence its full width can be used to minimize changes to the upstream and downstream channels. Vertical aspect ratio, w/P ratio also influences

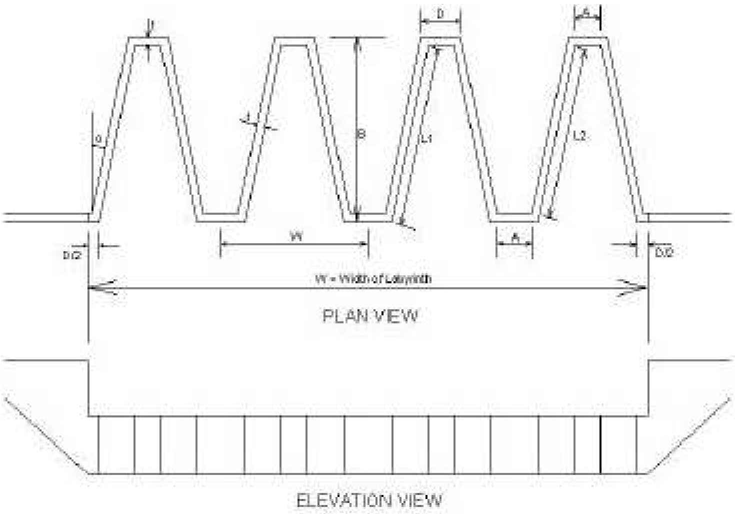

Fig. 1: Layout of trapezoidal labyrinth weir

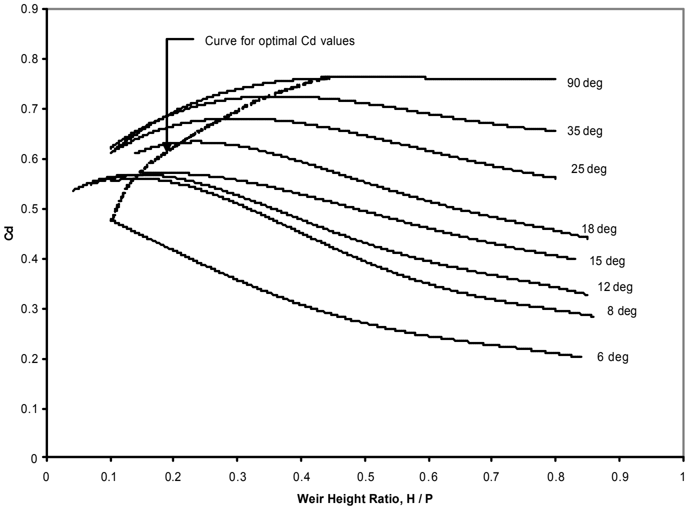

Fig. 2: Design curves [5]

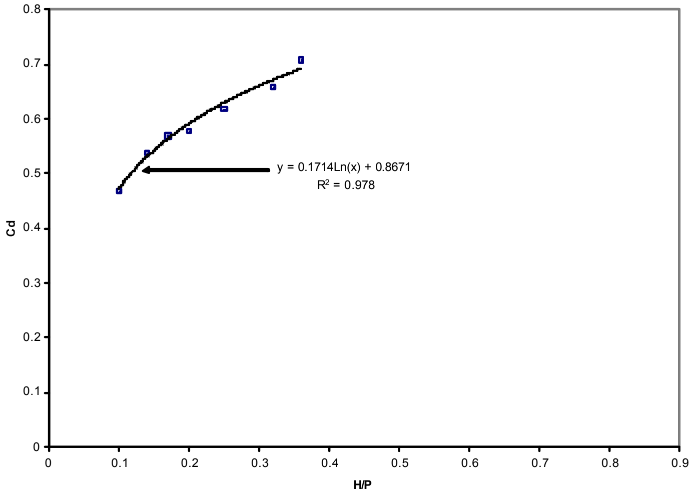

Fig. 3: Curve of optimum Cd

Table 2: Table of coefficients

α	6°	8°	12°	15°	18°	25°	35°	90°
A	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
B	-0.24	1.08	1.06	1.00	1.32	1.51	1.69	1.46
C	-1.20	-5.27	-4.43	-3.57	-4.13	-3.83	-4.05	-2.56
D	2.17	6.79	5.18	3.82	4.24	3.40	3.62	1.44
E	-1.03	-2.83	-1.97	-1.38	-1.50	-1.05	-1.10	0

the hydraulic efficiency of labyrinth and the recommended range for this ratio is from 2 to 4.

DESIGN CONSIDERATIONS

Tullis *et al*. [5], based on their experiments for different labyrinth angles, presented the design curves for labyrinth weirs with quarter round crest shape. The linear weir equation with modified C_d values is proposed to be used. Hence the capacity of labyrinth weir is given by

$$Q = (2/3)\, C_d\, L\, (2\, g)^{0.5}\, H^{1.5} \tag{1}$$

Figure 2 shows the design curves proposed by Tullis *et al*. [5].

These data were expressed in a regression model in the form

$$C_d = A + B(H/P) + C(H/P)^2 + D(H/P)^3 + E\,(H/P)^4 \tag{2}$$

The coefficients in equation (2) for different labyrinth angles are given in Table 2.

Observing the curves for discharge coefficients for labyrinth weirs (Fig. 2), it is found that there is a peak for each of the curve at the initial stage, followed by a long recession limb. It is suggested that while designing the layout of the labyrinth, the C_d should lie close to the peak values of the curve. Another regression analysis is carried out and a curve of optimum values of C_d is obtained. It is shown in Fig. 3.

The optimum C_d is given by:

$$C_d = 0.1714 \ln (H/P) + 0.8671 \tag{3}$$

It is hereby proposed to use Eq. (1) in conjunction with Eq. (3) so as to decide upon labyrinth angle, α and the length of labyrinth weir, L, suitable to site specific conditions.

PROPOSED METHODOLOGY

Based on the analysis carried out in this paper following methodology is suggested in designing a trapezoidal labyrinth. The procedure shall be applicable to quarter round crest shape of weir.

- From the available control levels, the total head 'H' is to be worked out which includes the estimated inlet losses.
- Also crest height 'P' can be worked out by subtracting approach channel elevation from crest elevation of the weir.
- Thickness of crest wall is deduced from structural stability considerations and inside apex width shall be assumed in the range of t to 2 t for trapezoidal labyrinth.
- For the weir height ratio, optimal value of 'C_d' can be determined from Eq. (3) and the required effective length of control structure 'L' can be worked out using the Eq. (1).
- As far as possible vertical aspect ratio, w/P shall be in the range of 2 to 4.
- Different possible layouts with the labyrinth angle corresponding to the optimal C_d value, by varying length of labyrinth apron 'B' can be considered and the layout feasible for the approach and conveyance channel conditions can be finalized.
- If no layout is possible for optimal C_d value, then Tullis *et al.* [5] design curves shall be referred to obtain layout of labyrinth such that the adopted C_d value lies closer to the optimal C_d value.

CONCLUSIONS

Owing to the inherent advantages of labyrinth weirs regarding flow magnification and structural strength, the labyrinth weirs shall find more and more applications especially when the river linking projects in India are likely to be taken up in the near future. Analysis of the data from Tullis *et al*. [5] has been carried out and a new mathematical model, Eq. (3) to work out the optimal coefficient of discharge for labyrinth weir is obtained. Outline of the methodology for the design of labyrinth weir is suggested, to determine the layout of the most economical labyrinth weir which would also exhibit better hydraulic functioning.

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