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Dealing with Supercritical Flow in Culvert

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Abstract

This paper proposes structural hydraulic models to control supercritical flows in culverts. Baffle blocks are designed to be placed in the culvert with the purpose of transforming supercritical into subcritical flow. The supercritical flow needs to be controlled so that scour will not occur at the downstream section of the culvert which is normally made of loose particles of the existing channel. The uncontrolled scour would eventually lead to failure in the embankment. Three baffle block designs were proposed in the experiments with different shapes and arrangement. It was noticed that the occurrence of baffle blocks significantly dampen the supercritical flow, for which Froude number of the approaching flow becomes smaller and velocity becomes slower. This signifies that the supercritical flow has been entirely transformed to subcritical flow. Energy losses were also computed for all designs and the results were compared.

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Keywords: Culvert; baffle block; supercritical flow; energy loss.

1. Introduction

A *culvert* is a short covered structure (or conduit) designed to pass water (river flows, drainage flows etc.) through an embankment, as shown in Fig. 1. It consists of three main parts, namely the inlet, barrel and outlet (Fig. 1). It can be considered as a 'small bridge' because it also connects the opposite sides of the channel (river). Because of its size, it is normally more economical than a bridge. Flows in the culvert can be

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classified as full or partly full, resulting in pressurized flow or open channel flows, respectively. The culverts are normally made either in circular or box shape.

The culvert is designed based on the expected flows in it. It can be designed to cater either *subcritical* or *supercritical* flow. The former occurs when the *Froude number* (F) is smaller than 1 while larger than that value for the latter. Froude number is defined as the ratio of inertial forces to gravitational forces as given by Eq. 1, and is known as one important dimensionless parameter in open channel flows.

$$F = \frac{v}{\sqrt{gy}} \qquad (1)$$

where v is the velocity of the approaching flow (m/s), y is the depth of the approaching flow (m) and g is the acceleration due to gravity (m^2/s).

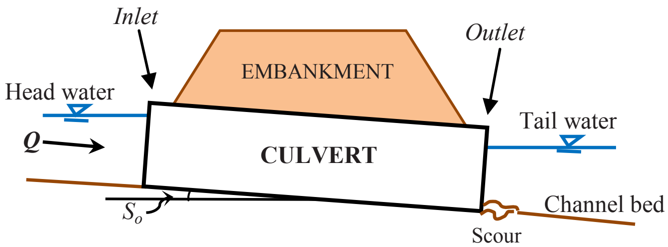


Fig. 1. Side view of a culvert placed under the embankment of a water passage

The supercritical flow has the characteristics of being fast with shallow water depth. The velocity will be so strong that it is capable to erode the bed of the channel if not controlled wisely. Thus, it is important to consider the protection at the bed when allowing supercritical flow in a channel. Without proper bed protection, the section downstream of the culvert which is normally made of loose particles of the existing river will be seriously eroded, as illustrates in Fig. 1. Eventually, this will lead to the collapse of the embankment.

Quite often energy dissipation structures are designed to control the occurrence of supercritical flow in a channel. Some typical examples of energy dissipation structures are drop structure, baffle and chute blocks and many more. These structures are normally built at the toe of a spillway of the dam ([1], [2], [3]) or recently in a re-regulating pond [4] targeting at controlling the velocity of the approaching flow. The application of energy dissipation structures on culverts, however, has never been proposed. Thus, it is interesting to study the response of these two combinations in the laboratory. Therefore, this paper intends to illustrate the characteristics of supercritical flows in a box culvert with and without the presence of energy dissipation structures. The response was described based on the amount of energy loss computed at the outlet of the culvert. The analysis was carried out experimentally. The goodness of the designs can be seen by the amount of energy losses occurring in the culvert. Note that the analysis carried out in the paper is based on the assumption that the designs are free from any possible sediment depositions, which may interrupt the flow.

2. Hydraulics of Flow in Culvert

In *open channel flow*, the energy (H) of flow in a channel can be determined using Eq. (2),

$$H = y + \frac{v^2}{2g} \qquad (2)$$

For flows within two sections along a channel, say Section 1 and 2, the energy losses, E_L between these two sections can be computed using

$$E_L = H_1 - H_2 \tag{3}$$

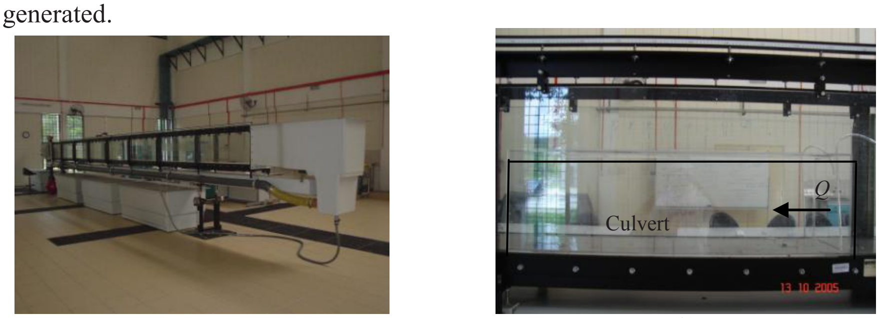
If a culvert is introduced in a channel, the energy losses are contributed by three components, namely, the (i) entrance loss, (ii) friction loss and (iii) exit loss of the culvert. These can be addressed by

$$\Sigma E_L = K_{ent}\left(\frac{v^2}{2g}\right) + \left(\frac{n^2 v^2 L}{R^{4/3}}\right) + K_{ex}\left(\frac{v^2}{2g}\right) \tag{4}$$

where, n is the Manning coefficient and R is the hydraulic radius (m) of open channel flow. K_{ent} and K_{ex} are the entrance and exit coefficients for a culvert, respectively.

3. Methodology

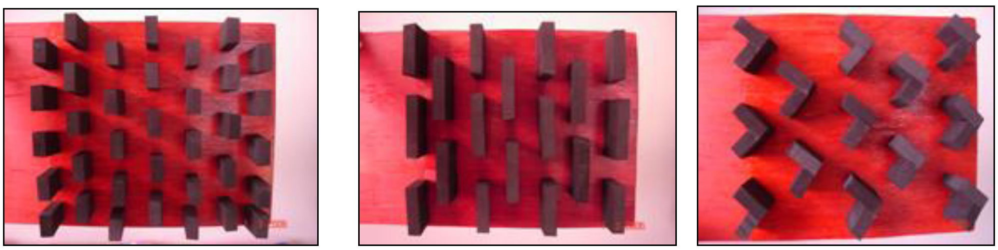
The experiments were carried out in a flume of 30 cm wide x 45 cm deep and 10 m long, as shown in Fig. 2(a). A culvert model with dimensions of 30 cm wide x 30 cm deep x 1 m long was placed inside the flume [Fig. 2(b)]. Both the walls of the flume and culvert were made of transparent glasses so that flows in the flume could be visualized clearly. The discharge was measured using a flow meter and water depths were measured using a point gauge. The slope of the flume was adjustable so that different Froude numbers ($0 \leq F \leq 2.0$) could be generated.



(a) (b)

Fig. 2. Side view of experimental set up (a) Side view of flume (b) Culvert model placed in flume

Baffle blocks were used in the study to control the high supercritical flow in the flume. They were placed close to the downstream area of the culvert [Fig. 2(b)] because scours in the channel bed are likely to occur immediately after the culvert. The baffle blocks were proposed in three different sizes and arrangement, as shown in Fig. 3. The heights of all models were made constant as 5 cm. Details on the properties of the models are given in Table 1.



(a) (b) (c)

Fig. 3. Plan view of baffle block models in the culvert (a) Model 1 (b) Model 2 (c) Model 3

Table 1. Properties of different baffle block models

Model	Shape	Dimension (cm) (width x length x height)	*Coverage of surface area (cm^2)
Model 1	Rectangular	1.5 x 3 x 5	158
Model 2	Rectangular	1.5 x 8 x 5	189
Model 3	Chevron	1.5 x (3 x 3)** x 5	117

* *Coverage surface area = Surface area of a unit block x Number of blocks*

** *Length at two sides of the model*

The experiments were carried out for ranges of Froude numbers (F) from 0 up to 2 by varying the discharge (Q) and slope (S_o) of the flume. For each test run, the water depth of the approaching flow (y_{ave}) was first measured at a point further upstream of the culvert. It represents a uniform flow condition in the flume without any obstacles in it. Note that the parameter F was calculated based on y_{ave}. Water depths immediately upstream and downstream of the culvert were also measured and labelled as y_{ups} and y_{down}, respectively. The energy difference along the culvert could then be computed using Eq. 3. The whole experimental procedure was again repeated with different baffle block models. Consequently, energy losses could be captured and compared for different baffle block designs.

4. Results and Discussion

Energy losses (E_L) were computed to measure the performance of flow in the culvert for conditions with and without the baffle block. The energy loss was described as the difference between the energy measured immediately downstream of the culvert and of the approaching channel (H_1). Fig. 4 provides an overview on the analysis carried out. The figure shows that flows without any baffle block designs (*control flow*) tend to produce supercritical flow (F >1) with less energy being dissipated. On the other hand, when the flow was kept similar to the control flow but with the presence of baffle blocks, the velocity of the flow significantly reduced, resulting in subcritical flows (F <1). This was supported by the fact that higher percentage of energy loss was also visible in the figure. Fig. 5 provides visual comparisons on the change in flow of the three models compared to the control flow. Also given in the figure are the corresponding F and y_{ave} of the flow.

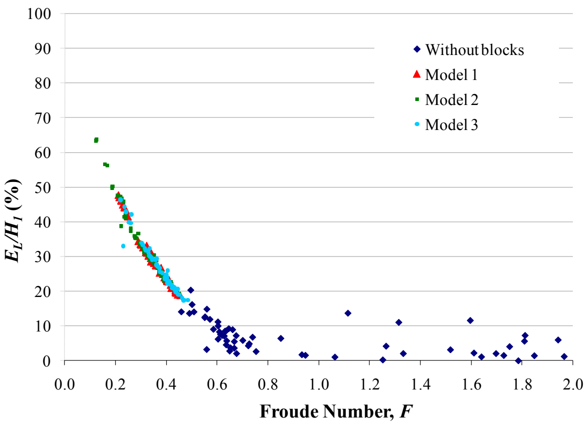
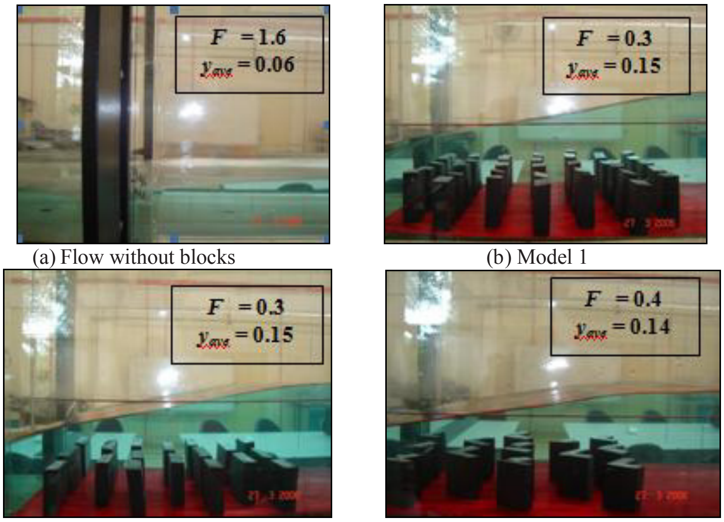


Fig. 4. Comparisons in energy losses (EL/H1) for all baffle block models.

Table 2. Comparisons in energy losses (E_L/H_1) for all baffle block models at Q = 0.0169 m^3/s and S_o =1/90

	Energy loss, E_L/H_1 (%)
Flow without blocks	2.2
Flow with Model 1	31.0
Flow with Model 2	**32.6**
Flow with Model 3	29.4



(a) Flow without blocks (b) Model 1

(c) Model 2 (d) Model 3

Fig.5. Flow visualizations observed in the flume at discharge, Q of 0.0169 m^3/s and slope, S_o of 1/90.

Table 2 provides a closer view on the performance of the three baffle block designs for Q of 0.0169 m^3/s and S_o of 1/90. Apparently, baffle block Model 2 provides the highest amount of energy dissipation. This is true as the model has more surface area coverage (Table 1) as compared to the other two models. This has become one advantage as the tendency of the flows being 'hit' by these structures will be very high, thus dampening it from carrying high energy downstream.

5. Conclusions

This paper proposes three baffle block models to be placed in a culvert with the purpose of transforming the supercritical to subcritical flow. Controlling the flow velocity immediately downstream of a culvert is important to avoid scour at the bed of the channel, which might eventually lead to failure of the embankment. Experiments showed that the presence of baffle block in a culvert significantly dampen the approaching flows which also results in the reduction of energy. Among the three models, the one that provides the most surface area coverage *i.e.* Model 2 was found to give better performance compared to the other two models for Froude number ranges up to 2.0. This paper has proven that the idea of applying energy dissipating structure in a culvert is reasonable. However, certain precaution should be given when the approaching flow carries significant amount of loose particles which taken might disturb the performance of the structure.

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