Effect of High Flow on Local Scour on Energy Dissipation System

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Abstract—**The design of hydraulic structures deals with the flow of water and its effects on the built and natural environment. The construction of various water structures causes scour downstream due to the erosive action of water flowing over or through these hydraulic structures. Energy dissipating structures are the common engineering solutions applied to a water system to reduce environmental impact like local scour. The baffle blocks, for instance, are normally provided at the downstream section of high velocity flow (supercritical) simply to convert it to low velocity flow (subcritical). This paper illustrates the experimental investigation of local scour caused by high flow near an energy dissipation system. The system comprises several energy dissipation components such as the baffle block, chute block, steps and concrete apron. The hydraulic characteristics of flows surrounding the system were critically studied. The flow was studied under high flows (30 L/s). The effectiveness of the system was measured based on the percentage loss of energy captured by each energy dissipation component. The results show that the applied energy dissipation system sufficiently controls the local scour.**

Keywords-component; Energy dissipating structure; baffle block; local scour; high flow.

I. Introduction

The study of the erosion mechanism and scour morphology downstream of hydraulic structures has been of great interest for hydraulic engineers for many years. Infact, to avoid the structural collapse, the scour process is one of the primary factors that must be controlled. In a large stilling basin, the flow pattern that occurs is very complex and depends on several factors. The flow structure is also deeply affected by the presence of a mobile bed [1]. Scouring in excess can gradually undermine the foundation of hydraulic structures and cause failure. Because of its frequent occurrence, scour downstream of hydraulic structures constitutes an important field of research.

In this study experiments are conducted to collect the scour parameters (location and depth) and also the hydraulic characteristics (inflow, velocity, flow depth) of an energy dissipation system. This paper intent to cover the following objectives: (1) *calculate the energy loss caused by the baffle blocks*, (2) *study velocity profiles in the vicinity of the system* and (3) *investigate the location and depth of scour*. This study will be considered useful whenever the topologic layout of the stilling basin is expected to sufficiently reduce the local scour when the flow of water is high.

II. Literature Review

Hydraulic structure design deals with the water flow and its effects on the built and natural environment. However, it is not possible to be absolutely certain how a structure will perform due to the complexity of the physics of fluid flow. Sediments (soils and sands) are composed of aggregation of individual grains that have varying density, volume, shape and orientation. Therefore, an investigation is quite important on interactions between the fluid and sediment particles in open channel flows in hydraulics and river engineering [2]. Almost all phenomena that affect the design and analysis in hydrosystems engineering involve several correlated factors and local scour in stilling basins is one of the complex phenomena. A brief explanation of the hydraulic structures and scour phenomena is presented.

A. *Hydraulic Jump*

Flow from the outflow structure of a hydropower station carries an enormous energy which has the capability to erode surfaces placed at the downstream section, for instance a re-regulating pond. Usually the pond is provided as an intermediate structure to discharge the flow in a controlled manner to the downstream river. To alleviate the erosion problem, the energy from the supercritical flow must be reduced before it is released directly to the river. Therefore, the idea of forming a jump to dissipate energy of super critical flow from the spillway before it is discharged into the river is referred to as a *hydraulic jump* [3]. Fig. 1 shows a typical hydraulic jump formed on a spillway structure, where L is the length of hydraulic jump, H_* is the difference in the flow head before and after the jump, y_1 is the initial depth of water at the toe of the stilling basin and y_2 is the final depth of water after the hydraulic jump has occurred. The supercritical flow prevails immediately beyond the hydraulic jump even if dissipation occurs, without disturbance in the upstream flow. For this reason, a scour control downstream of any hydraulic structure is needed, where energy dissipation is completed [4].

Universiti Teknologi PETRONAS, Graduate Assistantship Scheme

Annual International Conference on Architecture and Civil Engineering (ACE 2013)

ISSN: 2301-394X
doi: 10.5176/2301-394X_ACE13.156

B. Stilling Basin

The most common form of energy dissipating structure is the hydraulic jump *stilling basin* that converts the super critical flow from the spillway into sub critical flow compatible with the downstream river regime [5]. These basins are constructed to dissipate excess kinetic energy downstream of chutes, gates and spillways. The dimensions of such structures depend on the length of jump (L) and the sequent jump depths (y_1,y_2) [6].

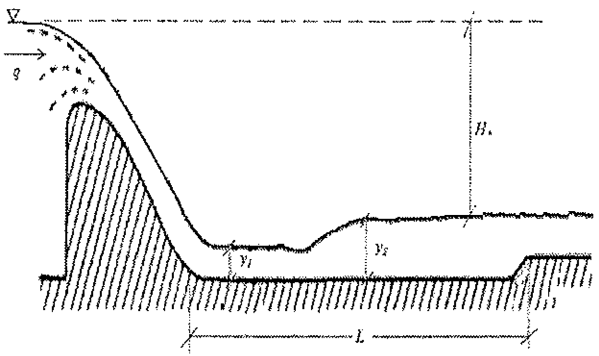


Figure 1. Hydraulic jump occurrence in a spillway (not to scale)

Although the stilling basins are purely based on an efficient hydraulic jump mechanism, in certain conditions other types of basins may have an increased reliability and may also prove to be cost effective. Standard basins as shown in Fig. 2 comprise baffle blocks, chute blocks and end sills developed by the US Bureau of Reclamation (USBR). In these standard stilling basins, baffle blocks are added for spreading out the incoming jet and directing it into the water body of the basin [6]. Theoretical as well as experimental considerations have shown that a baffle block line positioned transversal to an incident supercritical flow is an efficient energy dissipator [4].

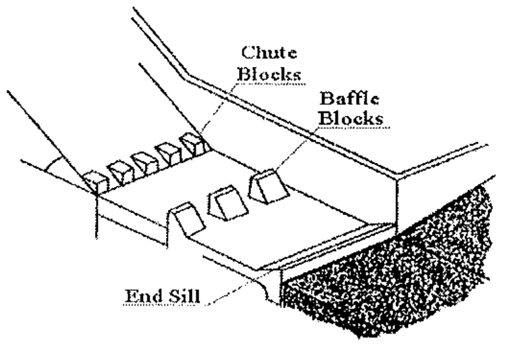


Figure 2. Stilling basin with chute blocks and baffle blocks [6]

The use of concrete prisms as a protection system to dissipate energy and to limit erosion and scour of the river bed at the outlet of a diversion tunnel was studied [4]. On the basis of test results, design criteria were developed for estimating the scour hole geometry, its location, and the required size of the prisms as well as the total area to be protected. Also, for instance, as reported in [1] a detailed investigation of the trend in design of baffled basins and of drag forces, pressure fluctuations, and optimum geometry was carried out.

The most serious problem with the hydraulic jump dissipator is more of structural strength rather than hydraulic efficiency. The stilling basins suffer serious damage arising from uplift, vibration, cavitation and hydrodynamic loading. As Froude number increases, the turbulent size arising downstream of the basin also increases. Complete energy dissipation does not occur only within stilling basin, but also beyond the basin exist. As a result, scour hole may occur downstream of the basin. Scour damage downstream of stilling basin may cause structural damage and in some cases may result in complete failure of the structure [3]. The influence of a stilling basin on local scour was studied, concluding that the scour depth could be reduced by a percentage of the actual scour depth that may occur if the there is no stilling basin present downstream of the hydraulic jump [7].

C. Local Scour

Naturally, scour occurs due to the erosive action of flowing water including the morphological changes in rivers and also because of the construction of various types of water way structures [8]. *Local scour* is the erosion of bed surface as a result of the impact effect of flowing water over or through hydraulic structures [9]. The sediment particle lying on the equilibrium scoured bed is acted upon by the drag force F_D, lift force F_L and the submerged weight of that sediment particle F_G, as shown in Fig. 3 [3].

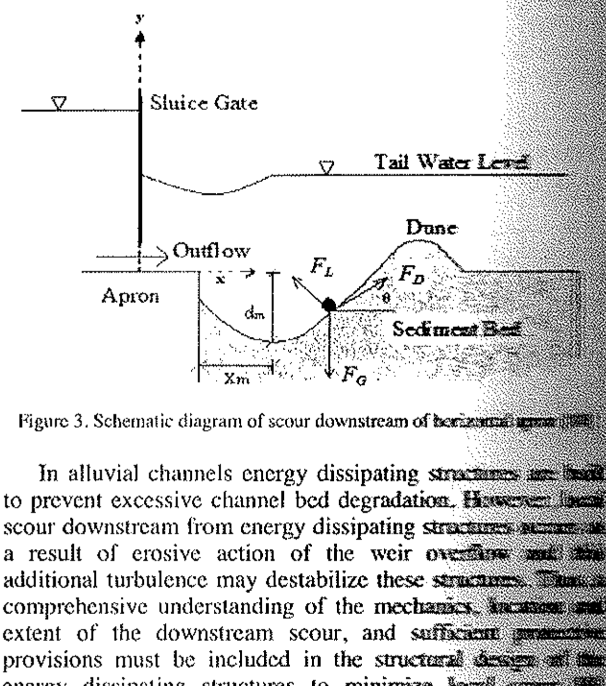


Figure 3. Schematic diagram of scour downstream of horizontal apron [10]

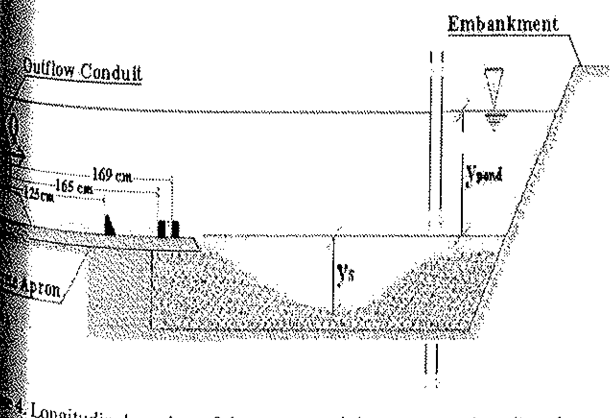
In alluvial channels energy dissipating structures are built to prevent excessive channel bed degradation. However, local scour downstream from energy dissipating structures occur as a result of erosive action of the weir overflow and the additional turbulence may destabilize these structures. Thus, a comprehensive understanding of the mechanics, location and extent of the downstream scour, and sufficient protective provisions must be included in the structural design of the energy dissipating structures to minimize local scour [9]. Although these structures are built to inhibit excessive bed degradation in alluvial channels, they also cause scouring due to the erosive action of water flowing over the structure. The of local scour downstream from energy dissipating ...s takes into account the scour parameters depth d_m and ...of maximum scour x_m as shown in Fig. 3. The scour ...downstream of hydraulic structures is experimentally ...d by many researchers e.g., [11], [12], [13]. The location ...th of maximum scour over erodible bed was ...ated by [11]. Based on the experiments conducted by ...ur characteristics like the locations of maximum scour ...peak of dune and the variation of maximum scour ...were correlated with time through the development of ...al expressions. The rate of scour downstream of a rigid ...was also studied by [12]. A semi empirical theory based ...acteristic mean velocity in the scour hole was proposed ...to predict the time rate of scour. The evaluation of ...hole through distinguished phases and the functional ...of bed protection downstream of large hydraulic ...es was studied [13]. The similarity in the development ...ur profiles, controlling of scour mechanism and ...ion of scour geometry was studied by [14]. The work ...ed that the main parameters that control the scour are ...operating head, sediment size and roughness of the ...dissipating arrangement provided downstream.

III. Methodology

...e methodology adopted to achieve the objectives of this ...described in this section.

...erimental Setup

...hysical model of a water retaining structure (pond) was ...ted within a study area of 27 m x 12 m at the ...iti Teknologi PETRONAS (UTP) Hydraulics ...ory. Fig. 4 illustrates longitudinal section view of the ...etaining structure with the inclusion of its energy ...tion systems (baffle blocks, concrete apron). The inflow ...ximately 30 L/s is released into the pond from the ...conduit. The discharge flows on the concrete apron ...s into the three rows of baffle blocks that are arranged ...tance of 125, 165 and 169 cm, respectively from the ...conduit. The experimental area of about 5 m x 4.25 m ...de of loose-bed (sand). The water level y_{pond} was ...ined to a specific range of values for each set of ...ent.



...4. Longitudinal section of the water retaining structure (pond) and energy dissipation system (not to scale)

As water is released from the outflow conduit, it travels towards the baffle block line positioned transverse to the incident supercritical flow to reduce its kinetic energy. First, it flows over the concrete apron, which dissipates the energy to some extent. Next, the first row of baffle blocks (placed 125 cm from outflow conduit) dissipate the energy of the incoming flows. The second (placed 165 cm from outflow conduit) and third (placed 169 cm from outflow conduit) row of baffle blocks further dampens the kinetic energy. The velocities and water depths are critically recorded between the aligned arrangements of baffle blocks. Theoretically, it is assumed that from this point (third row of baffle blocks) onwards, the supercritical flow has been converted to subcritical flow, along with the velocity reduced to a sufficient extent.

If scour will occur at the downstream section of the energy dissipation system, it will be visually observed on the sand area at the vicinity of the concrete apron. These experiments also take into account the values of scour depths (y_s), as depicted in Fig. 4.

B. *Experimentation*

Experimental data were collected for high flow condition. A set of measurements for each experiment involved the discharge of the incoming flow (Q), velocity (V), water depth (y), water level in the pond (y_{pond}) and local scour depth (y_s).

The discharge was maintained at 30 L/s. The water level in the pond was taken under the dry (y_{pond}= 0 cm) and partly submerged (y_{pond}= 9 to 14 cm) conditions. For each measurement taken, time was synchronized accordingly. This is important as time was also recorded when measurements were conducted. Experiments were carried out for a period of approximately 1 hr.

The velocity and water depth measurements were conducted at several points of interest, which were numbered chronologically. Water depth measurement was conducted by using a point gauge. The point gauge is a portable device that provides reading on a millimeter (mm) scale. Current meters were used for measuring the velocity. The current meters were built with propellers that were able to produce velocity readings up to 2.5 m/s for low water level. The propellers attached to the current meters provided inputs to the data logger, thus velocity in the unit of cm/s was reported through its automatic conversion. The inflows through the outflow conduit were recorded using the ultrasonic pipe flow meter. It is a portable device to measure pipe flow that could provide readings up to 6 m^3/s.

After each run of experiment, the whole pond was allowed to drain and dry. Once dried, the next stage of measurements involved observing any scour pattern on the sand bed. For instance, the bed topography could be observed as shown in Fig. 5 at a specific Q and y_{pond}. Strings were used to locate the scour and deposition of the sand bed, which were measured using the point gauge as well.

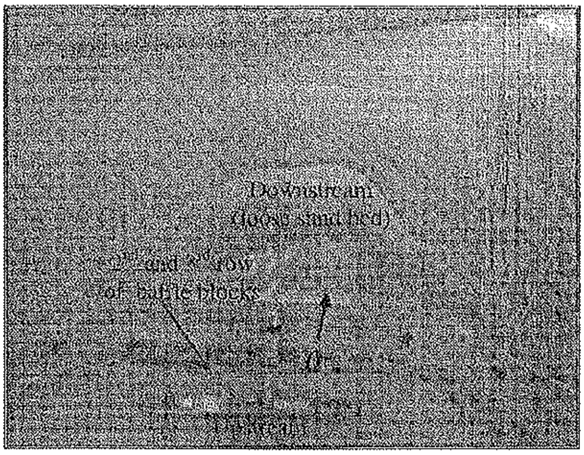


Figure 5. Front view of expected bed topography due to scours for a given Q and y_{pond} conditions

The final output of these experiments is presented in the next section.

IV. Results and Discussion

This section presents results reported for high flow (Q~30 L/s) under dry pond condition (y_{pond} = 0 cm) and partially submerged pond condition with (y_{pond} = 9 cm and 14 cm). Discussion is provided on the effectiveness of energy being dissipated under the above-stated pond conditions.

The points A, B, C and D were taken chronologically along the centre line of outflow conduit. The distances of these points from the outflow conduit were 65, 110, 150, and 180 cm, respectively. The location of observation points and the dimensions of baffle blocks are as shown in Fig. 6. At all these points, measurement of velocity and flow depth was taken so that the changes in hydraulic parameters mentioned above were also observed.

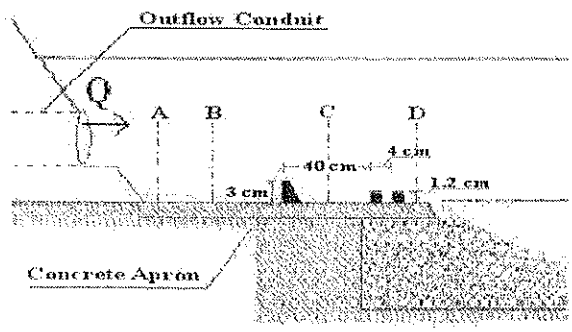


Figure 6. Location of the observation points and baffle block dimensions

After each line of obstruction, the specific energy (E) is computed using Eq. 1,

$$E = y + V^2/2g$$

where, y and V are the flow depth and velocity measured at each point, respectively. Table 1 shows the measurements taken for velocity and flow depth along the points specified earlier.

TABLE 1

Points	Dry Pond Condition		Submerged Pond Condition			
	y_{pond} = 0 cm		y_{pond} = 9 cm		y_{pond} = 14 cm	
	V	y	V	y	V	y
	cm/s	cm	cm/s	cm	cm/s	cm
A	113	13.2	96	15.9	78	19.7
B	86	15.5	73	16.5	65	19.9
C	62	17	62	17	46	20.3
D	39	18	41	18	33	20.5

A comparison of the changes in velocity and flow depth at every measurement point for different flow conditions is given in Figs. 7 and 8.

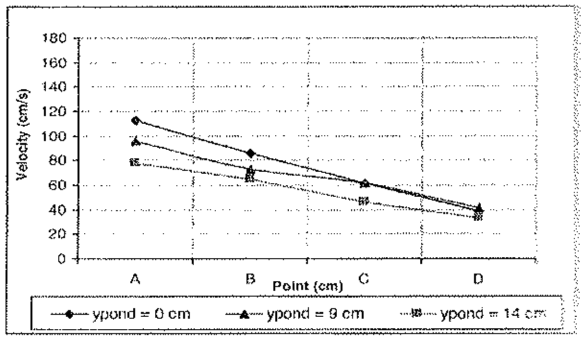


Figure 7. Comparison between the velocity changes at each point for the specified flow conditions

As shown in Fig. 7, for all the flow conditions the velocity profile followed a declining trend. For dry pond condition, the velocity significantly reduced from point A to D, following a constant decline, whereas for submerged pond conditions the velocities reduced mildly.

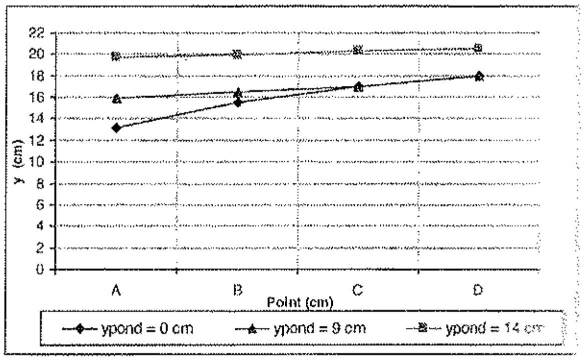


Figure 8. Comparison between the flow depth changes at each point for the specified flow conditions

The flow depth increased along the specified points for each of the pond condition as shown in Fig. 8. For dry pond condition, the flow depth is substantially increased from point A to point B and C, subsequently following a mild increase at point D. The flow depth increased slightly for submerged pond condition as y_{pond} was tried to maintain at specific depth.

The energy loss caused by the baffle blocks placed transverse to the flow is the main criterion to judge the effectiveness of the whole energy dissipation system. The energy at first point A was initially assumed as 100% and was expected to be dissipated by the baffle blocks provided downstream of the flow. Eq. 2 gives the value of energy loss, E_L (%) at each point with respect to energy at point A, E_A.

$$E_L = \frac{E_{B,C,D} - E_A}{E_A} \times 100 \qquad (2)$$

Fig. 9 shows a comparison of the percent of energy loss at every observation point for the different flow conditions.

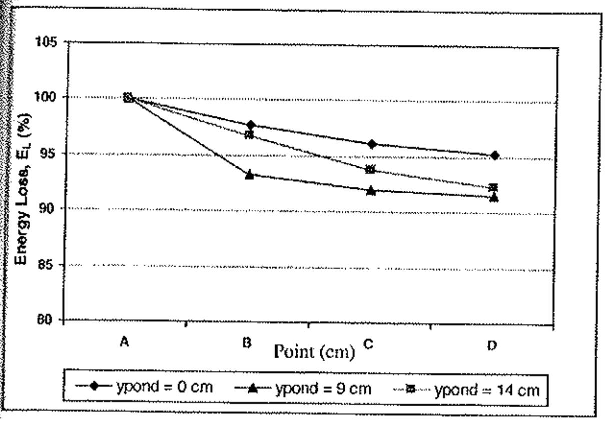


Figure 9. Comparison between energy losses at each observation point for the specified flow conditions

As shown in Fig. 9, at point A the energy is assumed to be maximum since it is a point nearest to the outflow conduit. Later, the energy is subsequently reduced due to the baffle blocks provided on the apron. For submerged pond condition of 9 cm, the energy is substantially reduced from point A to B thereafter reducing mildly. As for the unsubmerged pond condition and submerged condition of 14 cm, the energy is fairly reduced by the baffle blocks.

The scour depth along the center line of the outflow conduit for the specified flow conditions are graphically presented in Fig. 10.

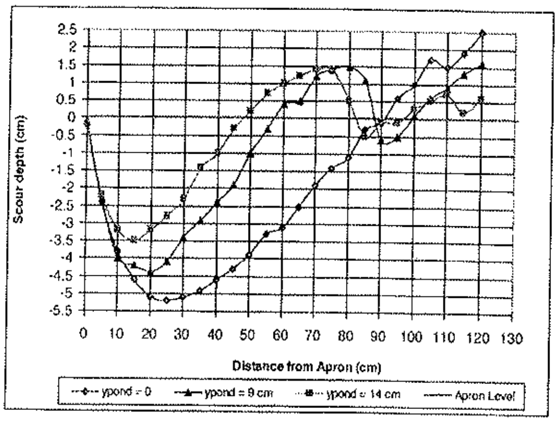


Figure 10. Scour depth for different flow conditions

The location and depth of scour that occurred downstream of the energy dissipation system was observed when the pond was dried after each experimental run. Fig. 10 depicts the maximum scour that occurred for dry pond condition, proving it as the most vulnerable state of scouring in the pond. The submerged conditions offer relatively lesser scour depth, with minimum scour depth resulting at pond water level of 14 cm.

V. CONCLUSIONS

This paper discusses the application of a series of energy dissipation system placed downstream of a water retaining structure. The hydraulic characteristics of the flow were critically studied and any scours observed at the downstream section of the structure was reported.

For high discharge, the energy loss impact of energy dissipation system applied is comparatively high in submerged pond condition of 9 cm. However, if there is a dry or partially submerged condition of 14 cm, the energy loss is not as significant as in the submerged pond condition of 9 cm.

The experimental results show that the hydraulic characteristics (velocity and flow depth profiles) conformed well to the theories of flow as mentioned in the literature review of this paper, proving that the applied energy dissipation system could control the local scour. However, it was also observed, that local scour still occurred downstream of the structure, proving the design of baffle blocks of the energy dissipation system needs improvisation based on experimental results.

The scour depth for each of the conditions studied, highlights partially submerged condition of 14 cm as being the most effective one to control excessive scouring. It is observed that maximum scour depths occurred for the dry pond condition.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the Universiti Teknologi PETRONAS (UTP) for the support provided for this research.

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