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TECHNICAL NOTE

Experimental Study for Protection of Piers Against Local Scour Using Slots

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ABSTRACT

The most important causes of bridge failure are local scour. In this study, laboratory experiments were conducted to investigate the effectiveness of slot as a protection device in reduction of depth of scour at cylindrical piers under clear water flow conditions. The development time of scour depth at the circular pier with and without a slot as a protection device was conducted. The experiments focused on the effect of using different lengths of slot, calculating efficiency and deriving a suitable equation. It was observed that the scour depth decreases as the size of slot length increases; and also the maximum reduction in scour depth equals to 49%. The technique of dimensional analysis was used, and based on laboratory results an empirical formula was derived by using IBM SPSS statistics v24 software. The coefficient of determination (R^2) was determined to be (0.961), There was a good agreement between the predicated and observed data.

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NOMENCLATURE

BR	V	v	Mean velocity of approach flow
D_p	Pier diameter	v/v_c	Flow intensity
d_{16}	Sediment size for which 16% of the particles are finer	v_c	Critical flow velocity for sediment entrainment
d_{50}	Median particle size	v_{*c}	Mean approach velocity at the threshold condition
d_{84}	Sediment Size for which 84% of the Particles are Finer	w_s	Slot width
d_s	Maximum scour depth below the bed level	y	Flow depth
F_p	Pier Froude number	z_s	Sinking depth of slot
t	Scouring time	σ_g	Geometric standard deviation of sediment size distribution
		μ	Dynamic viscosity of fluid

1. INTRODUCTION

Bridges across rivers are very important form for a country to achieve the physical communication. The major causes of a bridge failure are due to foundation, structural and hydraulic failures but majority of bridge failures as yet had been due to hydraulic conditions. Pier scour is the major possible causes of hydraulic failures of a bridge particularly in alluvial channels where the riverbed scours. Scour is defined as “a natural phenomenon caused by the erosive action of flowing stream on erodible beds” according to Wang [1]. On the other hand, Chiew [2] defined local scour as “a decrease in bed elevation in the vicinity of an obstruction as a consequence of the flow influence of the obstruction”. Exorbitant scour can cause bridge breakdown, the interruption of traffic activity and possibly deaths. The potential losses from bridge failures and the need to safeguard against the same have encouraged for better understanding of the scour process and for better scour protection methods and equations. The capability to secure bridge pier against scour is a vital issue in bridge safety. For control of scouring around bridge piers the used methods can be classified into two types: (1) Direct methods, through increasing the resistance of streambed. This is usually done by using riprap, gabions, cable-tied blocks and etc. around the piers [3-4]. (2) Indirect methods. In these methods, the flow pattern around the piers is modified to reduce shear stresses on the riverbed, and consequently reduce the depth of the scour hole.

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Flow altering devices used to protect piers against local scour include internal openings through the pier, one of these method is slot [5-7]. Grimaldi et al. [8] indicated that the values of scour depth are always smaller in the experiments with slots than without. The slot affects the local scouring from the beginning of the process, irrespective of the value of Z_s/h. This countermeasure seems to control short-term as well as long-term scouring at bridge piers. Tafarojnoruz et al. [9] studied the effectiveness of slots with three sinking depth Z_s (Z_s= h/2, h/3, h/6, where h = undisturbed approach flow depth); and the maximum efficiency was (33.2%) for (Z_s= h/2). Since the development of scour process is governed by many factors, the exact protection against it is difficult in practice. Therefore, this research is concerned with an experimental study of the use of a slot for protection against pier scour. The study objectives are to investigate the local scour around circular pier with a rectangular slot of different lengths with round edges, and derive a formula to predict the maximum scour depth around the pier with slot by using the experimental data and with help of dimensional analysis techniques.

2. SCOURING AROUND PIER WITH PROTECTION USING SLOT

The mechanisms of scouring and flow pattern around a bridge pier are very complex and have been described by various investigators [10-14]. The vortex is made by a mix of main flow at the upper stream segment of the pier and potential flow at the downstream way along the front surface of the pier. Dargahi[11] and Tanaka [15] explained that the local scour size is related to size and strength of the vortex flow. Local scour around a pier occurs because of the down flow at the upstream face and the horseshoe vortex at the base [16-17]. Separation of flow stream at the sides of the pier also creates the wake vortices [10]. Figure 1 shows the flow and scour pattern around a cylindrical pier [18].

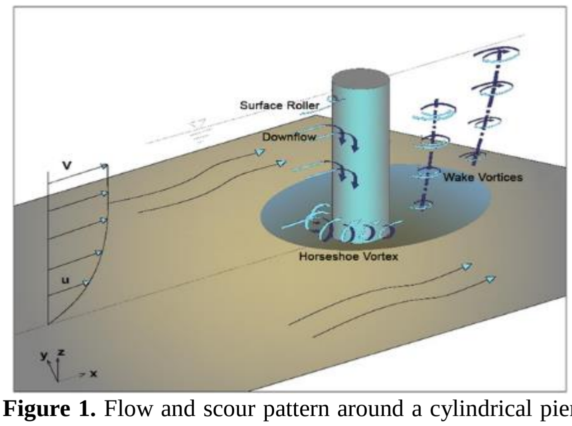


Figure 1. Flow and scour pattern around a cylindrical pier [18]

Reduction of scouring can be achieved by using a slot through the pier, which helps to pass most of the flow through it, as it leads to the reduction of the strength of the vortex flow (down-flow and horseshoe vortex) and this causes reduced scour depth.

3. DIMENSIONAL ANALYSIS FOR PIER PROTECTED BY SLOT

The dimensional analysis technique is very important before experiments to find out the most important variables that affect the depth of scour which is the subject of this study. Therefore, the dimensional analysis was performed first and then the experiments were carried out accordingly.

The geometry of scour around a circular pier protected by slot depends on flow conditions (approach depth and velocity), fluid parameters (density and viscosity), sediment properties (grain size, sediment density and geometric standard deviation), pier characteristics (pier diameter), channel geometry (channel width), time, and slot characteristics (slot length, slot width and location in the bed). Therefore, for using a slot as a protection device, the scour depth would be as function of the following parameter:

$$(d_s)=f(y, v, v_c, g, \rho, \mu, d_{50}, \rho_s, \sigma_g, D_p, S, B, t, l_s, w_s, z_s) \quad (1)$$

in which y=flow depth, v= mean approach flow velocity, v_c=critical velocity, g= gravitational acceleration, ρ= density of the fluid, μ= dynamic viscosity of fluid, d_{50}=median particle grain size, ρ_s= density of the sediment $\sigma_g=\left({d_{84}}/{d_{16}}\right)^{0.5}$ =geometric standard deviation of sediment size distribution, d_{16}= sediment size for which 16% of the sediment is finer, d_{84}=sediment size for which 84% of the sediment is finer, D_p=pier diameter, S= slope of the channel, B=channel width, t=scouring time, w_s= slot width, l_s= slot length and z_s=sinking depth of the slot.

From the above equation, it can be shown that σg is a dimensionless term. Using dimensional analysis, Equation (1) can be written from Buckingham π-theorem:

$$F(d_s/D_p, \quad y/D_p, \quad v_c/v, \quad D_p\, g/v^2, \quad v\, D_p\, \rho/\mu, \quad d_{50}/D_p, v\, D_p\, \rho_s/\mu, \sigma_g, S/D_p, B/D_p\, .\, {}^{t}/_{t_e}) \quad (2)$$

After simplification and eliminating the parameters with constant values and applying the following considerations to Equation (2): (1) σg < 1.5 for uniform sediment with $Dp/d50$>25, this ratio can be excluded from the scour formula [19], (2) Horizontal channel floor without any inclination, (3) for B/Dp ≥ 10, side-wall (or blockage) effects due to pier presence are negligible [20], (4) constant slot width and sinking depth, (5) and it is independent of dimensionless time at equilibrium conditions. So Equation (2) can be written as:

$$d_s/D_p = f(y/D_p.\ v_c/v.\ D_p\, g/v^2.\ l_s/D_p) \quad (3)$$

From the above equation, the scour depth ratio (d_s/D_p) for pier protected by slot varies with flow depth ratio (y/D_p), flow intensity (v_c/v), pier Froude number $(D_p\ g/v^2)$, and slot length ratio (l_s/D_p) the schematic diagram of slot is shown in Figure 2.

4. EXPERIMENTAL WORK

Experiments were done at the Hydraulic Laboratory of Civil Engineering Department, University of Basrah. The main channel consisted of 5.72 m long and 0.61 m width. The discharge measurement was done by a sharp crested full width weir fixed at the upstream section of the flume. Both bed profile and depth of flow were measured by a point gauge having an accuracy of ±1 mm. Some coarse gravel was spread on specific length of the upstream side in order to distribute the inflow uniformly. A tail gate was situated at the end of the channel to control the flow depth at desired levels.

The sediment used in all tests was uniform sand with a mean size diameter d_50=0.34 mm and its grain size distribution curve is shown in Figure 3. The geometric standard deviation of the grain size distribution was1.296 less than 2, that were selected to maintain clear water condition without formation of ripple according to Hoffmans [21]. Length of working section equals to 1.8 m and its thickness equals to 8 cm.

To avoid wall effect on scouring process, "the pier diameter should not be more than 10% of the flume width" [22]. Therefore, in this study a circular pier of diameter 40 mm made of wood with smooth surface was used.

Experiment of equilibrium time was done at two different flow intensity $({}^{v}/_{v_c})$, The critical velocity was evaluated from Melvill's equations [23] as follows:

$$ {}^{v_c}/_{v_{*c}} = 5.75 log(5.53y/d_{50}) \quad (4)$$

$$v_c = 0.0115 + 0.0125 d_{50}^{1.4} \quad (5)$$

$0.1mm < d_{50} < 1mm$

The results are shown in Figure 4; it can be seen that approximately 95% of scouring [24] occurs during the first 2 hours. Therefore, in all experimental runs, duration of 3 hours was selected for each run at which equilibrium time conditions occurs.

5. PIER SLOT MODELS

In each pier used in the experiments, the slot was obtained by drilling a vertical rectangular opening with round edges opening through the center of the pier. The slots have a constant width equal to (1/4 $pier\ diameter$) to achieve the optimum condition according to Grimaldi [8]. The sinking depth of each slot is equal to (1/2 $slot\ length$). Experiments were conducted to five different lengths of slot (3, 3.5, 4, 4.5 and 5 cm) to establish the aims of this work, as shown in Figure 5.

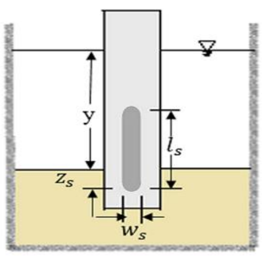


Figure 2. Schematic diagram of slot

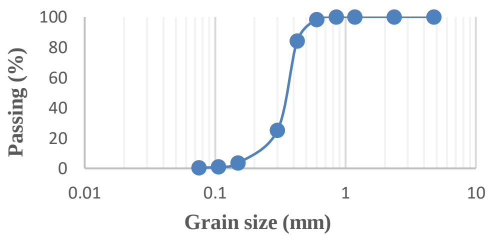


Figure 3. The grain size distribution curve for sediment that used in test

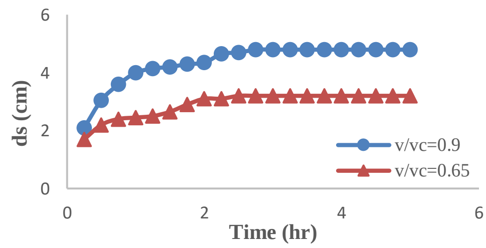


Figure 4. Scour depth variation with different duration

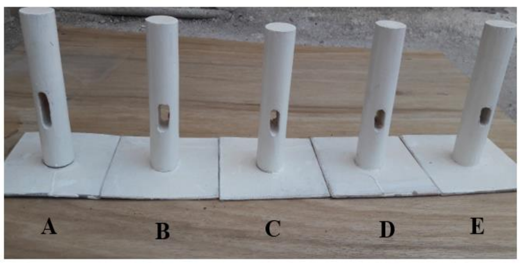


Figure 5. Models of pier with slot, with different lengths of slot (l_s), A=5 cm, B= 4.5 cm, C=4 cm, D= 3.5 cm and E= 3 cm

6. RESULTS AND DISCUSSION

At the conclusion of each run, the scour depth was estimated utilizing point gauge. The impact of various factors on scour depth and relating exchanges is discussed as follows:

6. 1. Variation of Scour Depth with Flow Depth, Flow Velocity and Pier Froude Number

Variation of scour depth with variation of flow depth, flow velocity and pier Froude number around bridge pier with and without slot protection was analyzed by plotting scour depth against each variable and keeping other factors constant. Figure 6 shows the scour depth variation with flow depth, it indicates that the increase of flow depth causes an increase in scour depth in front of the pier even with slot protection. The reason behind that is decreasing effect of bow wave that appears in the free surface and rotating in the opposite direction of the horseshoe vortex.

Figure 7 shows scour depth variation with flow velocity, it indicates that the increase in scour depth in front of the pier because of the increase of flow velocity even with slot protection. Increased flow velocities in front and sides of the pier lead to increase the capacity of flow to produce the scour hole by entraining sediment particles. While results indicated that scour depth increases with increasing pier Froude number.

6. 2. Scour Depth Variation with Length of Pier Slot

The slot was located at the center of the pier with constant slot width ($w_s = D_p/4$), as shown in Figure 8. Five slot lengths were used in order to deduce the effect of slot length on the scour depth. Actually, the slot diverts portion of the down-flow through its opening, resulting in a reduction of the scour depth. In pier slot tests, the scouring process was just like that of an unprotected pier. It began from the pier upstream sides and then extended all around it. Figure 9 indicates the decrease of scour depth in front of the circular pier because of increase in slot length for five different slot lengths.

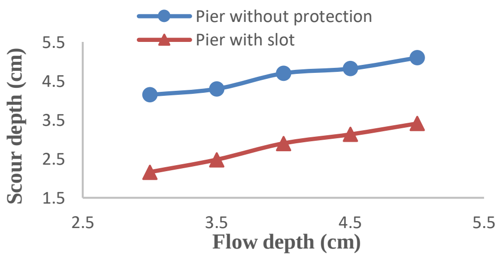


Figure 6. Scour depth variation with flow depth

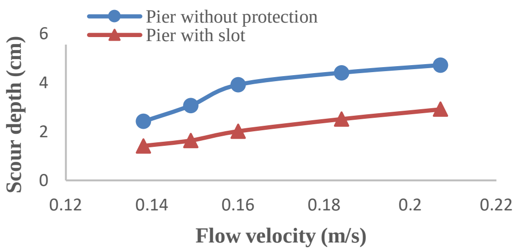


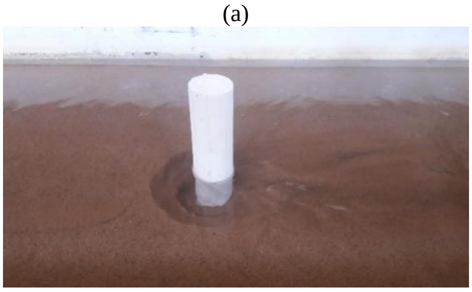
Figure 7. Scour depth variation with flow velocity

7. DEVELOPMENT OF NEW FORMULA

The computer package IBM SPSS Statistics (Statistical Package for the Social Sciences) was used to make analysis for the slot equation derived from dimensional analysis through a non-linear regression analysis. In order to generalize the experimental results to form a relationship that includes the effects of slot lengths, about 80% of the experimental data used to conduct the analysis and reached the following; model:

$$d_s/D_p = c_0 * \{(y/D_p)^{c_1} * (v/v_c)^{c_2} * (F_p)^{c_3} * (l_s/D_p)^{c_4}\} \quad (6)$$

(a)



(b)

Figure 8. Pier protection by slot with length: (a) during run, (b) after run

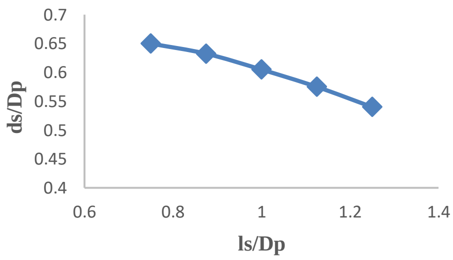


Figure 9. Variation of scour depth with slot length

The SPSS Nonlinear Regression Analysis, gives the following values for the constants
$c_0 = 0.415 \quad c_1 = 0.989 \quad c_2 = 2.06 \quad c_3 = -0.749$
$c_4 = -0.358$
So, the equation becomes:

$$d_s/D_p = 0.415 * \{(y/D_p)^{0.989} * (v/v_c)^{2.06} * (F_p)^{-0.749} * (l_s/D_p)^{-0.358}\} \quad (7)$$

The determination coefficient (R^2) for this formula is (0.961).

The remaining 20% of experimental data is used to test the above equation. To show the agreement between the predicted and the observed records, a statistical comparison is used, as shown in Figure 10.

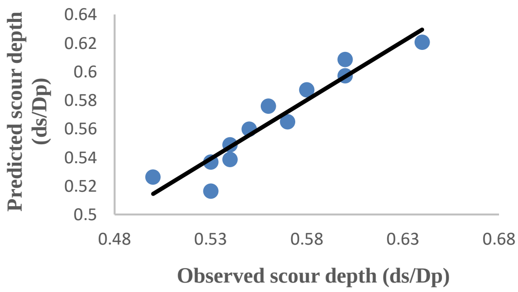


Figure 10. Comparison of Equation (7) between SPSS and experimental data

8. CONCLUSION

This study deals with the protection of bridge piers against local scour by using a device called slot. Slot is an opening in the pier as it was studied, where several slot lengths were considered. Experiments were conducted in a laboratory channel under clear water conditions. The important results have been reached are that; the depth of scour has a direct relationship with both of flow depth and flow velocity, and as a result each of them effect on the capacity of the flow to cause scour. When a slot is used as a scour countermeasure, the slot diverts portion of the down-flow through its opening, resulting in a reduction in scour depth. The experimental runs have shown that the efficiency of slot in scour reduction increases with the length of slot. The efficiency of scour reduction increased from 31 to 49% with increased length of the slot and keeping all other parameters constant.

Dimensional analysis technique was used to identify the important variables to be studied in laboratory experiments and an empirical formula also reached to estimate the scour around bridge piers when using a slot. The formula gave a good determination coefficient, and the results of the calculated data were in good agreement with the measured data.

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چکیده

مهمترین علل شکست پل، تخلیه محلی است. در این مطالعه، آزمایشهای آزمایشگاهی به منظور بررسی اثربخشی اسلات به عنوان یک دستگاه حفاظتی در کاهش عمق آبشستگی در خیابانهای استوانه ای تحت شرایط جریان آب آشامیدنی انجام شد. زمان توسعه عمق شستشو در اسکله دایره ای با و بدون اسلات به عنوان یک وسیله حفاظتی انجام شد. این آزمایش ها بر اثر استفاده از طول های مختلف شکاف، محاسبه بازده و برآورد معادله مناسب متمرکز شده است. بر حسب مشاهدات که عمق آبشستگی به دلیل افزایش طول اسلات افزایش می یابد؛ و همچنین حداکثر کاهش عمق آبشستگی برابر با ٤٩٪ است. روش تجزیه و تحلیل ابعاد مورد استفاده قرار گرفت و بر اساس نتایج آزمایشگاهی، یک فرمول تجربی با استفاده از نرم افزار آماری SPSS v24، به دست آمد. ضریب تعیین (R2) تعیین شد (٠,٩٦١)، توافق خوبی بین داده های پیش بینی شده و مشاهده شده وجود داشت.

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