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An experimental study of scouring threshold time of different geometrically shaped bridge piers

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ABSTRACT
Local scouring around bridges' piers have always caused many great challenges, especially when flood is imminent in locations around rivers. This phenomenon has caused the development of a great hole in the vicinity of bridge pier. In case that the bridge design would not be properly implemented, this hole will further deepen and by approaching to the bridge foundation, it will endanger the bridge structure. Any destruction at the time of floods would incur both direct and indirect social and economic costs for inhabitants. The long-held solution I this filed was to position bridge pier's foundation in a depth higher than scouring depth, such that the bridge foundation would not be affected at the time of flood. Local scouring at the time of flood is a time-dependent phenomenon and since flood flow is displayed in the form of hydrograph, it can be declared that whatever happens in reality is local scouring as a result of non-permanent flows.Numerous studies have been undertaken regarding the impacts of scouring as a result of non-permanent flood waters. Hydraulic numerical models have been used extensively in recent years. Three-dimensional models are much more frequent among them because they're more compatible with physical reality of the phenomenon. The present study which has been undertaken as a laboratory experiment in Ahwaz' Water and Electricity Laboratory to investigate the impact of scouring around bridge pier with different geometrical shapes in various depths (i.e. 0.29 0.32, and 0.39), was aimed to find out the best model for bridge pier in terms of the best strong geometrical shape against scouring time threshold in the vicinity of bridge pier.
Keywords: local scouring, scouring depth, non-permanent water flows, hydraulic numerical modelling

Introduction
Bridges are considered as one of the most functional structural elements for a river which have been used for long by people. The long history of bridge construction has illustrated that not only structural and technical issues matters in designing bridges, but also hydraulic factors must be considered in the design process.

Generally, many of damage incurred on concrete bridges include expansion seams within bridge's deck, neoprene failure, concrete failure in central piers, concrete failure in abutments, and scouring of riverbed and bridge's piers.

In Iran, many people die every year as a result of this phenomenon and numerous fatalities and financial damages. According to the statistics provided with regard to country's bridges in different eras, it can be argued that the occurrence of scouring around bridge's piers is one of the main reasons enumerated for bridge's instability. This phenomenon is considered as a serious threat for the stability of the structures located in the water's flow path, such as piers. As a result of scouring, a deep hole will be developed around bridge's pier and will weaken its stability, such that it may be destructed as a result of a great flood. These destructions and incurred damages will lead to loss of connecting roads, fatalities, financial losses, and disruptions in transportation system. In case bridge's piers will be protected against scouring and proper ways ell be recommended to predict scouring, we can prevent the occurrence of such damages. One of the main factors involved in scouring phenomenon is flow's depth and velocity, the size of particles existing in riverbed, the status of deposits in the flow path, and physical shape of piers.

Besides incurring destructive damages on flow path, scouring can also impact other flow-related parameters indirectly and incur negative consequences. Therefore, it's necessary for hydraulic engineers to extensively get familiar with mechanisms involved in this process, such that they could get prepared for that. However, it has been observed that fighting against erosion in some parts of the river may incur destructive damages in upper or lower pats of the river due to effecting the path's morphology and thus, more extensive damages will be incurred (Guide to Methods for Calculating Scouring).

Literature shows that horseshoe whirlpools as well as risings do play a significant role in scouring development within bridge piers (Breusers & Raudkivi, 1991). The excavation of scouring hole by horseshoe whirlpool continues onward to the extent that the water level within the scouring hole will be expanded and the whirlpool's energy will decrease. In this condition, the scouring depth will reach balance.

Scouring id categorized in different ways. One of the categories is local scouring. Local scouring is developed as a result of obstacles such as bridge piers, lateral bearings, and water breakers included within water flow. These obstacles may accelerate the local flow and its turbulence and depending on the structural shape, they can create whirlpools, and consequently incurring additional erosional forces on the bed around the structure. Therefore, the rate of deposition movement and local erosion will be increased in locations around such structures and will lead to local lowering down of the riverbed compared with the general level of water flow (Chiew, 1992).

In recent years, various methods have been applied extensively to control scouring phenomenon. They are divided into two main categories including riverbed consolidation (such as the use of China and Gabion stones) and lowering down the intensity of whirlpools (such as waterfront, split, and collar). The choice of each of these protective approaches depend upon the hydrological and geotechnical conditions of the riverbeds.

Water fronting is one of the many various methods which affect the scouring depth upon prevention of whirlpool development. Chiu and Lim (2003) have recommended the use of victimized water-fronting in upper part of the pier as a protective solution to reduce local scouring. Since the location of water fronting in upper part may incur structural damages, Grimaldi et al (2009) have provided a novel use of water fronting. They attempted to investigate the water fronting scouring mechanism in lower hand of the pier. They found that two holes will be developed in the lower hand and the lowest distance between pier and water front had the highest impact on the result, such that it would reduce the scouring depth in front of the pier to %26/ they declared that however no previous experiment has been undertaken to precisely determine the exact location of maximum scouring depth (lower or upper hand of the water front), but it seems that for proportions of channel's width to pier's diameter lower than 16.7, the location of maximum scouring depth will be transferred to lower hand of the water front.

Razi et al. (2010) investigated the impact of water front location on reducing the depth of scoring. They illustrated that whenever the water front is located in upper hand of the per or exactly in its middle, the scouring danger in lower hand of the pier will be more perceived and therefore it's not recommended to locate the water front in upper part of the pier. In addition, upon locating the water front in lower hand of the pier and in its exact vicinity, the scouring dept. in the fronting part of the pier would be reduced to %30. Pagolyar et al (2010) conducted a laboratory experiment on the simultaneous use of water front and Gabion in the presence of piles of tree branches and leaves. Their results showed that the presence of water front will first reduce the scouring; however, as soon as the ware front is inserted, the scouring will quickly develop and will reach the value of scouring depth in no-water front and no-Gabion mode. Tafarroj Nowrouz et al. (2012) have investigated various protective solutions to control scouring in one-piers. Their results for water front showed that whenever the water front is located exactly in the vicinity of the pie, the depth of scouring in frontal part of the pier will be reduce for %17.2.

The literature shows that one of the main factors contributing to bridge destruction is bridge pier's geometrical shape's behavior toward the scouring incurred as a result of flow morphology and whirlpools developed as a result of flow pattern-dependent variations. Furthermore, it seems that the use of water front is a simple, cheap and functional solution to decrease local scouring around bridge piers.

Considering the fact that relationships determining the scouring phenomenon are somehow complex and scholars have provided multiple solutions for that but none of them are functional enough, thus it's necessary to undertake experiments of physical model in the laboratory to achieve exact results. Accordingly, the present study seeks to answer the following questions:

1. The impact of threshold on temporal development of scouring around bridge piers
2. The impact of flow landing value on the scouring developed around bridge piers and its correlation with different geometrical shapes of bridge piers.

Materials and Methods

Dimensional analysis of scouring threshold around bridge pier in the presence of water front

Generally, the following required parameters can be written down as follows:

$$f= (ys, L, yo, d50, q, \rho, \mu, g) \tag{1}$$

Where ys is the souring hole's depth, yo is downstream depth, Q is the water flow in width unit, L is the distance between water fronts, Ls is the scouring length, d50 is the diameter of riverbed's deposition, g is ground acceleration, μ is viscosity, ρ is the specific mass, fr is the landing value, and yc is critical depth.

In case ys is considered as one of the most significant profile dimensions of scouring length, and define the maximum scouring depth in relative balance time, it can be argued that parameters influential in determining scouring are as follows:

$$f= (ys, L, yo, d50, q, \rho, \mu, g) \tag{2}$$

Considering the general application of equation (2), Buckingham π method for dimensional analysis, this method is used to define dimensionless parameters and the following equation is obtained upon the choice of repetitive variables of (q, ρ, yo) in any of dimensionless proportions and just after finalizing the analysis.

$$\frac{ys}{yo}=f(\frac{yc}{yo},\frac{1}{yo},fr) \tag{3}$$

Considering the present limitation, it's impossible to investigate all variables.

Units and dimensions

In hydraulic field, three main dimensions including mass (M), length (L), and Time (T) exists. According to Newton's second relation, the following equation can be used:

$$F = ma \tag{4}$$

Where F is the force, M is the mass and a is acceleration. Then considering the following equations:

$$a = \frac{\partial V}{\partial t} \tag{5}$$

$$V = \frac{\partial L}{\partial t} = \frac{L}{T} = LT^{-1} V = LT^{-1} \tag{6}$$

$$\frac{\partial V}{\partial T} = a = \frac{LT^{-1}}{T} = LT^{-2} a = LT^{-2} \tag{7}$$

We'd have:

$$F = MLT^{2} \tag{8}$$

Accordingly, the order of all variables used in hydraulic from a dimensional viewpoint can be illustrated as a combination of one, two, or three main dimensions of L, T, and M 9Pousti, 2005).

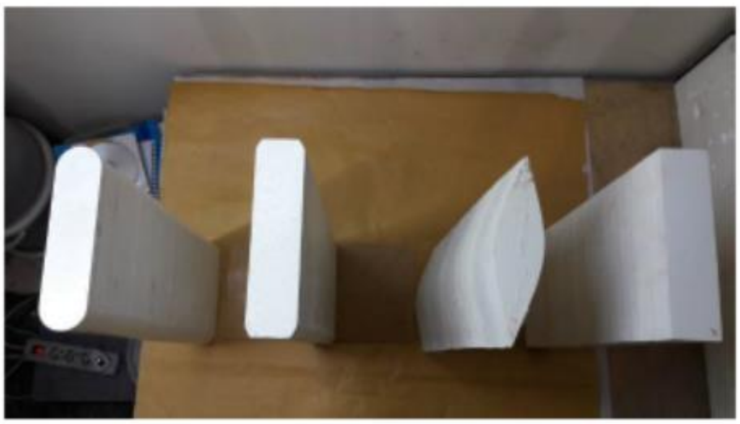

Figure 1: the geometrical shaped of piers used in experiments

Figure 2: the flume used in this study

Flume dimensions

The characteristics of the applied laboratory flume are as follows:

Length: 7.5 m

Width: 30 cm

Depth, 45 cm with variable tangent

Glass body (in order to observe the developed hydraulic conditions)

The constituent parts of the laboratory flume

1. Flume's output tank: the point where water is accumulated after passing the flume's length;
2. The output channel at the end of the flume: the path leading water to the terminal tank;
3. Pump's on/off switch: in order to activate/deactivate the pump installed on the flume;
4. Pump;
5. Water flow measurement device: in order to achieve the suitable water flow in order to conduct the experiment under the intended flow;
6. Open-head rectangular glass channel: it's the intended path for the experiment and is used in order to measure water depth, the time of scouring occurrence with a glass body in order to be able to observe the hydraulic conditions formed;
7. Water flow regulation valve: in order to regulate and control the water flow;
8. The relaxation pond located at the beginning of the flume: it works as such: it will reduce the water flow to the flume from the beginning to prevent the quick washing out of the sand located at the bed of the flume.
9. Water tanks for transmission of water to laboratory flume: supplying water from the open-head ground tanks made up of fiber glass, with a lead of steel, with the capacity of each tank being equal to 1100 L.
10. The terminal valve: in order to regulate the required water height in a channel, a falling rectangular overflow has been used in exit part.
11. Water centrifuge pump: in order to transfer water to the flume a LOWERA centrifuge pump (FHS4 100-200/55/P ELP model, made in Italy) with maximum flow of 176 square meters per hour and flow height of 14.6 m and 5.5 KW power has been used.

Experimental setup

At first, the pier to be experimented has been installed and then the deposits in the flume's bed have been flattened using a constant tangent levelling gear. Next, eh rectangular valve located at the fume's terminal is closed and the required water flow is regulated using a pump in order to make the deposits wet. Then, the rolling valve and the rectangular valve located at the end of the flume are used to achieve the intended 15 cm depth.

After 1.5 hour, the pump is restarted and the water flow existing in the channel has been slowly drained in order to prevent any impact on the topography of the water existing in the channel's bed. After full drainage of the water existing in the flume, the constant topographic flow of the bed around the pier, in both lower-hand and upper hand parts have been measured using a laser meter with a precision of 0.1 mm. The recoding distance for both width and length has been sent constant as 1 cm I order to investigate the changes.

Granulation of deposits

The required deposits in this experiment must be homogenous in terms of granulation or particle size. To this end, the sands have been sieved. The required deposits in this experiment have been considered as one square meter. This value has been determined based on the flume dimensions and the dimensions of scouring hole. The sieved deposits have been delivered to soil mechanic laboratory in order to determine the granulation of the sand articles. As recommended by Raudkivi and Ettema (1983), the mean diameter of the particles must be larger than 0.7 in order to prevent repel formation. In addition, another issue to be considered was to prevent the formation of scouring in the entrance part under larger water flows. Therefore, the deposits with an average diameter of d_{50}=1/5mm have been predicted and sieved (Table 1).

Table 1: the classification of different deposited particles and deposition characteristics

Sieve diameter in mm	2	1.18	850µ	600 µ	425µ	300µ	250µ	150µ	160µ	75µ
Sieve number	10	16	20	30	40	50	60	100	140	200

Table 2: Deposit characteristics

D10	D16	D50	D84	D95	σg
0.75	0.85	0.9	1.1	2	1.1

Points recording

In order to pick and record the points, a laser meter instrument has been used. A graded and netted sheet has been inserted in upper part of the flume and the laser meter has been included on it in order to facilitate the picking and recording process. This process has been done in a way such that the recording and picking intervals will be set as one centimeter. After recording the characteristics of hole and deposited pile resulting from the scouring in this study and comparing them with the initial mode of the bed, the erosion and deposition values in different points have been determined.

Balance time

One of the main parameters in the formation of scouring phenomenon is balance time. In present study, a balance experiment has been undertaken in the most critical conditions of 1.8 L/s (the pier without any split and collar) for six hours.

Procedure

At the beginning of each experiment, the intended pier as well as the water front have been installed and then, the deposits located at the channel's bed have been levelled using a constant tangent moving gear (Figure 3)

Figure 3: levelling the deposits located around the pier

Before initiating the pump, the terminal valve has been closed and then clear water has been guided slowly through the channel. After the water has been levelled up and making sure about wetting of the deposits after some hours, the pump has been initiated under a low water flow and it has been regulated to reach the intended flow through the main rolling valve on the input tube through the relaxation pond. Upon the precise and simultaneous regulation of rolling valve and lower-hand valve, the flow depth of 15 cm and the intended water flow have been realized.

After 1.5 hours, the pump has been turned off and the water existing in the channel has been drained slowly in order not ti impact the bed's topography. After some time and full drainage of water from the channel. The laser meter device has been used to measure the depth, with a precision of less than 0.1 mm. then, the topography of the bed around the pier in both lower and upper hand of the pier have been recorded (Figure 4).

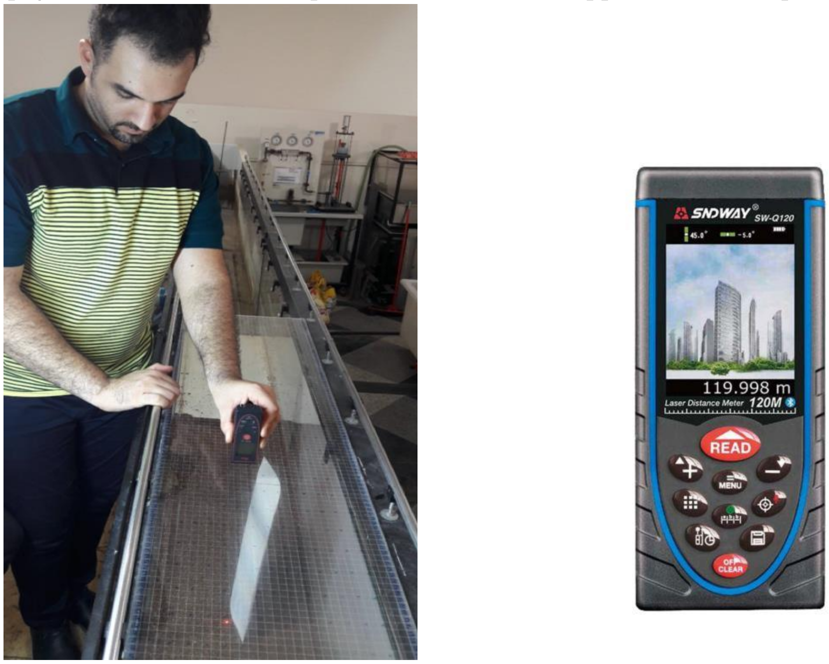

Figure 4

In order to conduct a precise measurement of the changes in water bed, the distance interval between length and width points has been considered at 2 cm. The total picked points for n experiments and throughout all experiments for the formation of water bed's topographic network and its details was n points.

Figure 5: a) scouring around the pier with different geometrical shape of the pier in the presence of water front; b) scouring around the pier with different geometrical shape and without presence of water front

Flow depth in the flume

Eliuter and Hager (2002), recommended a water depth of more than 15 mm in order to prevent the impacts of depth coarseness. Therefore, the water depth has been set constant in all experiments (i.e. 15 cm). Besides, scouring has been analyzed in clear water.

Flow intensity within flume

In order to control erosion and transmission of deposits included in upper-hand of the piers, the average flow velocity must be lower than critical velocity (i.e. $u<u_c$)). In all the experiments conducted in this study, the proportion of shear velocity to critical shear velocity was 0.93. The critical shear velocity has been obtained from Shield's critical parameter. The water flow for all the experiments has been selected as 15 L/s an all the experiments have been undertaken in sub-critical conditions and for landing value of 0.32.

In previous sections, all the instruments, equipment and all other required actions to conduct experiments based on experimental scenarios have been explicated. In his study, according to scenarios included in table 2, 1 experiments have been conducted on piers with different geometrical shaped with a width of 4 cm and diameter of 1.6 cm in water flows of 29, 32 and 35 respectively.

Table 3: experimental scenarios

Pier name	Nmber of experiments (n)	Water height (cm)	Water flow (lit/s)	Flow's landing number (Fr)	Pier's width (cm)	Time interval
P1	3	15	29 32 35	0.26 0.29 0.32	4	180
P2	3	15	29 32 35	0.26 0.29 0.32	4	180
P3	3	15	29 32 35	0.26 0.29 0.32	4	180
Control	3	15	29 32 35	0.26 0.29 0.32	4	180

Results

The experimental STUDY of the impact of threshold on temporal development of local scouring around the bridge pier with different geometrical shapes

Experimental investigation of bridge pier's scouring threshold

Figure 5 present the comparison between the scouring depth in a time interval of 180 minutes in the presence of bridge piers with different geometrical shapes and different landing numbers. In addition, the developed scouring depth has been investigated in different landing numbers of 0.29, 0.32, and 0.35. According to the diagrams, it can be concluded that the higher time and flow's landing number, the higher will be scouring depth. The lower scouring depth can be justified in the light of the fact that different geometrical shapes of bridge pier will reduce a huge part of the descending flows resulting I excavation of the hole. It will also weaken the whirlpools invading bridge piers with proper functioning and will prevent further excavation of the scouring hole. The installment of threshold in front of the bridge pier helps protecting the bridge pier against factors contributing to the formation of scouring hole such as horseshoe

whirlpools. The threshold has been installed in a location near the bridge pier, in frontal position, considering the previous literature.
In figure 6, the comparison between the scouring in control pier (simple rectangular shape) in the presence of threshold and in 180 minutes and with landing numbers of 0.29, 0.32 and 0.35 is presented. As the figure suggests, the scouring depth will increase upon any increase in timing and landing of the flow of horseshoe whirlpools. The reason behind the development of scouring holes around bridge piers is the change in flow pattern by the bridge itself. In the sections to follow, this pier is used as a control one in order to make comparisons with other piers in different geometrical shapes.

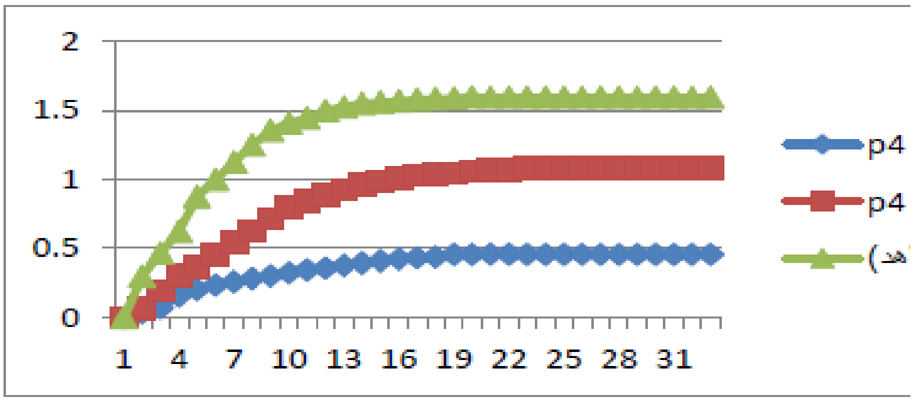

Figure 6: the comparison for the control pier in the presence of threshold under landing numbers of 0.29, 0.32, and 0.35.

Figure 7 provides the comparison between different bridge piers with the control one in the presence of threshold and under constant landing number of 0.29. As it's evident, upon any increase in timing, the depth of scouring will increase as well. In the comparison made between different kinds of piers, the best performance goes to P1 pier among others. Upon any increase in the time, the destruction intensity will be higher.

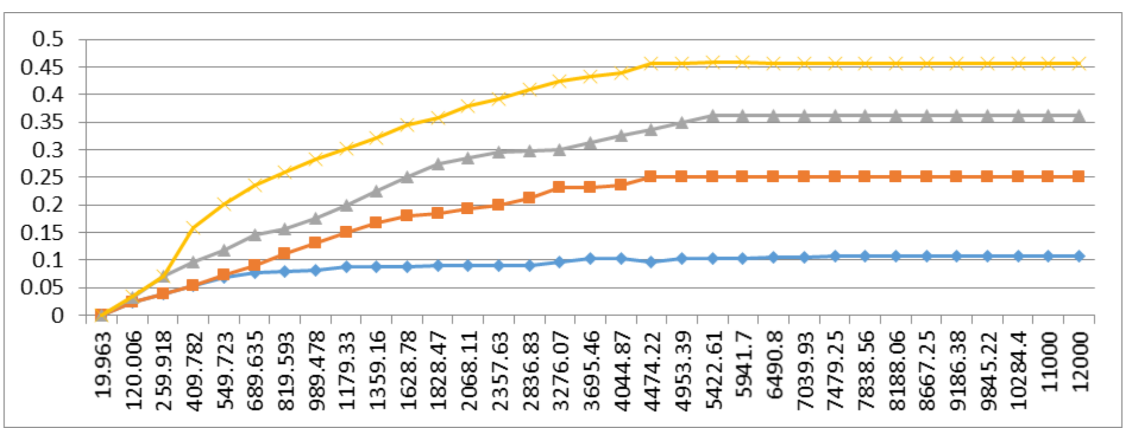

Figure 7: the comparison between the scouring of bridge piers in the presence of threshold and in landing number of 0.29

Figure 8 presents the comparison between different ridge piers with the control one in the presence of threshold and under constant landing number of 0.32. As it's evident, upon any increase in time, the scouring depth will increase as well. In the comparison made between different piers with different geometrical shapes, the best performance goes to P1. Any increase in time, will intensify the destructive power of scouring.

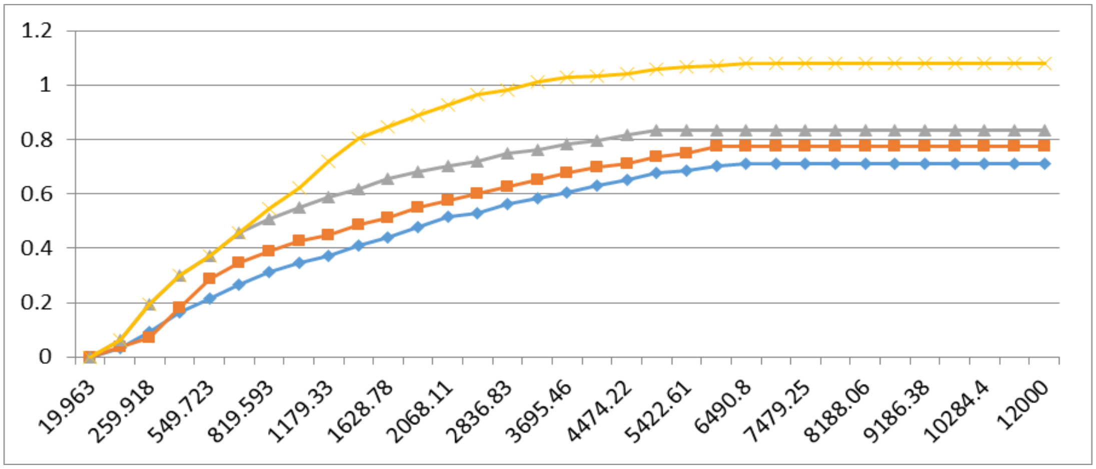

Figure 8: the comparison between scouring resulting from different geometrically shaped piers in the presence of threshold and under landing number of 0.32.

Figure 9 is a comparison between the amount of scouring in bridge pier and the control pier in presence of threshold and under constant landing number of 0.35. As it's evident, upon any increase in time, the depth of scouring will be increased. In the comparison made between different piers, the best performance goes to P1. Any increase in time, will intensify the destructive impact of scouring.

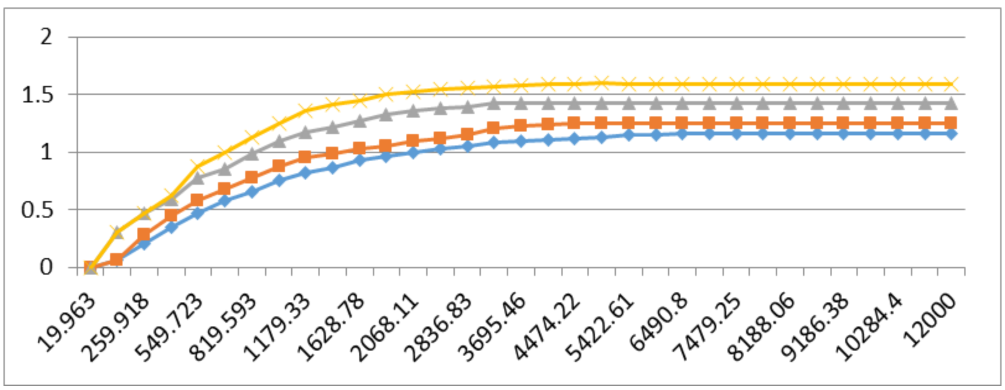

Figure 9: the comparison made between bridge piers in the presence of threshold and under landing number of 0.35

Comparison and analysis of scouring among different bridge piers (P1, P2, P3, and P4) under landing numbers of 0.29, 0.32, and 0.35

Figure 10 presents the comparison made between different bridge piers (i.e. P1, P2, P3, and P4) under various landing numbers of 0.29, 0.32, and 0.35. According to this figure, the longer the testing duration, various flow landing numbers will increase the depth of scouring hole. Two factors including flow time and landing contribute to this phenomenon.

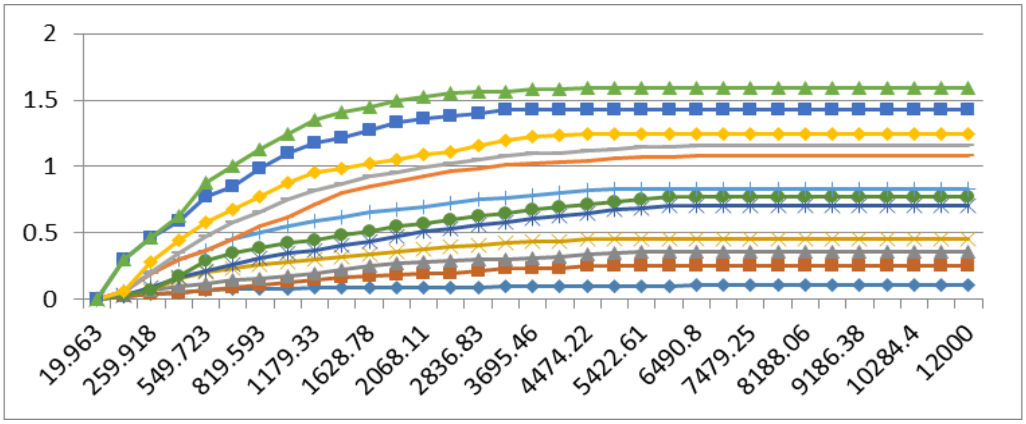

Figure 10: the comparison between scouring caused by bridge piers in the presence of threshold and its comparison with control pier under landing numbers of 0.29, 0.32, and 0.35

Conclusion

Scouring is regarded as one of the most destructive phenomenon for marine structures' piers. Bridges are considered as the most vital and sensitive of the marine structures. In case that souring wouldn't be considered in their design phase, it will contribute to extensive fatalities as well as financial damages.

Bridges as structures constructed on the bed river, change the flow pattern upon making any change in flow form and they will finally contribute to the formation of whirlpools by creating new patterns. These whirlpools will contribute to development of local scouring around bridge piers. Scouring happens when the water flow hits the bridge pier, then the flow velocity from river's bed toward the surface of the water will be increased and more pressure will be developed in higher water levels consequently. Therefore, a top-down compressive gradient will be formed on the pier, which will itself create a downward flow in front of the pier. This downward flow acts like a vertical jet and will scatter the deposited particles to the surrounding environment upon hitting the river's bed (Nouhani et al., 2013). Part of the downward flow which returns above, will be forced into moving in the direction of water flow as a result of hitting the general flow water of the river and will hit the pier once again. This flow circulation and its return within the excavated hole will form a whirlpool which is gradually extended in lateral sides of the pier and it will take the shape of a horseshoe. The formation of horseshoe whirlpool within the scouring hole will accelerate its excavation and the particles detached from the river's bed will be carried to lower-hand through the main water flow of the river (Breusers et al., 1997).

Considering the complexity governing this situation, the researchers couldn't still find a good solution for calculating the depth of scouring. Various factors contribute to this difficulty. To mention some are the form of waterway, flow characteristics, pier and support shape, their angle toward the flow and deposits' characteristics. Therefore, the construction of physical models is necessitated in order to achieve near-reality results.

In present study, his phenomenon has been investigated through the use of a physical model in order to get more precise results. Two variables including different geometrical shape of bridge pier and time interval have been considered in this study in order to investigate the maximum scouring depth.

Accordingly, four piers, and three flows for each (i.e. 0.29, 0.32, and 0.35) at a time interval of 180 minutes for each bridge pier, have been investigated against local scouring within laboratory flume. All the experiments have been undertaken according to a pre-specified scenario.

In order to compare the scouring in different piers with different geometrical shapes and variations of scouring depth in the specified time interval, a control experiment has been undertaken using the control pier (i.e. rectangular shaped pier). Then, various scenarios included in table 3-1 have been tested.

The following conclusions were drawn:

1. The higher the experimentation time, various flow landing numbers will lead to higher depth of scouring hole. Two factors including flow's timing and landing number contribute to this phenomenon.

2. The results of experiments show that threshold play a significant role in lowering down the scouring depth. Besides, it has been illustrated that the geometrical shape of bride piers will disturb the downward flows and decrease horseshoe whirlpools.
3. The best performance goes to P1 pier among others under the landing number of 0.29. Further, in the comparison made between different piers, it had been illustrated that control pier's performance equals 0.35.
4. The scouring depth for bridge pier decreases considering the geometrical shape of bridge. As a result, the geometrical shape of the piers plays a significant role in decreasing scouring phenomenon.

The results showed that all experiments conducted in different landing numbers in the presence of the threshold and in the same time interval has a lower scouring depth as compared with control experiment.

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