Studying the Effect of Froude Number and Densimetric Froude Number on Local Scours around Circular Bridge Piers

Md Abdullah Al Faruque

Abstract**—**A very large percentage of bridge failures are attributed to scouring around bridge piers and this directly influences public safety. Experiments are carried out in a 12-m long rectangular open channel flume made of transparent tempered glass. A 300 mm thick bed made up of sand particles is leveled horizontally to create the test bed and a 50 mm hollow plastic cylinder is used as a model bridge pier. Tests are carried out with varying flow depths and velocities. Data points of various scour parameters such as scour depth, width, and length are collected based on different flow conditions and visual observations of changes in the stream bed downstream the bridge pier are also made as the scour progresses. Result shows that all three major flow characteristics (flow depth, Froude number and densimetric Froude number) have one way or other affect the scour profile.

Keywords**—**Bridge pier scour, densimetric Froude number, flow depth, Froude Number, sand.

I. Introduction

SCOUR is the removal of granular bed material by the action of hydrodynamic forces in the vicinity of hydraulic structures. Local scour around bridge pier is of considerable interest in civil engineering. Structures built in rivers and estuaries are prone to scour around their foundations. If the depth of scour becomes significant, the stability of the foundation may be endangered, with a consequent risk of damage and failure. Scouring processes are influenced by significant number of variables. Complexity of flow patterns makes analysis more difficult. Most of the laboratory tests on bridge pier scour study were done in a test condition where flow past a surface mounted object. Fig. 1 shows a condition of flow past a circular cylinder and one can note the formation of horseshoe vortex at the junction of the cylinder and the channel bed, which will make additional contribution to the scour around the cylinder base. Reference [1] pointed out that a very large percentage of bridge failures can be attributed to pier and abutment scour. Reference [2] mentioned that the hydraulic factors such as stream instability, long-term streambed aggradations or degradation, general scour, local scour and lateral migration are blamed for 60% of all US highway bridge failures. The structural integrity of the bridge is affected due to the reduction of the lateral support caused by the removal of granular bed materials from the immediate vicinity of the foundation of bridge piers. Excessive scour in the bridge pier can be a cause of the bridge failure and influence public safety directly.

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Reference [4] blamed 266 numbers of bridge failure (52.88%) to the hydraulic failure when comparing a total of 503 bridge failure. Reference [4] blamed the pier scour to be the second largest cause of failure among bridges. Due to the overwhelming bridge failure due to excessive scour of the bridge pier, it is in urgent need to look over the present design parameters used to estimate the depth of the bridge pier scour. Various researchers proposed different equations to evaluate the different scour parameters and the differences in those equations are quite extensive. The cost of bridge pier foundation is very high and excessive pier scour estimation would result excessive project cost. As rightly mentioned by [5], the scour is not only a safety concern, but an economical issue as well. It is also a catastrophic failure with little time to respond or save. Due to overwhelming bridge failure due to excessive scour of the bridge pier, it is in urgent need to look over the present design parameters used to estimate the depth of the bridge pier scour. Critical and essential highway bridges need to remain operational after a disaster to allow for continued evacuation and an effective emergency response, therefore a bridge's response to extreme loading conditions is critical. Bridge damage caused by scour has received more and more attention [6]-[11]. During the Colorado flooding in September 2013, 30 bridges have been reported to be destroyed and another 20 bridges seriously are damaged in flood-ravaged areas [14]. Most of these bridge damages are caused by foundation soil washed away. Scouring around piers, abutments and pile foundations can be aftermath of the flooding and the bridges spanning the waterway are under substantially higher risk category. Question of performing a full-scale physical experiments on bridges are near to none possibility and logistically will be very expensive. Continuous improvement of the capacity of computing hardware and software opens up the new horizon for the researchers using finite element modelling to simulate highway structure in increasing level of detail and complexity [12]. Researchers find the finite element method very versatile and they can model various complicated problems similar to its actual physical characteristics. Meshes are formed to create the finite element model and it is done by mixing elements of different shapes, types and material properties. This will result a model closely resembling the structure proper.

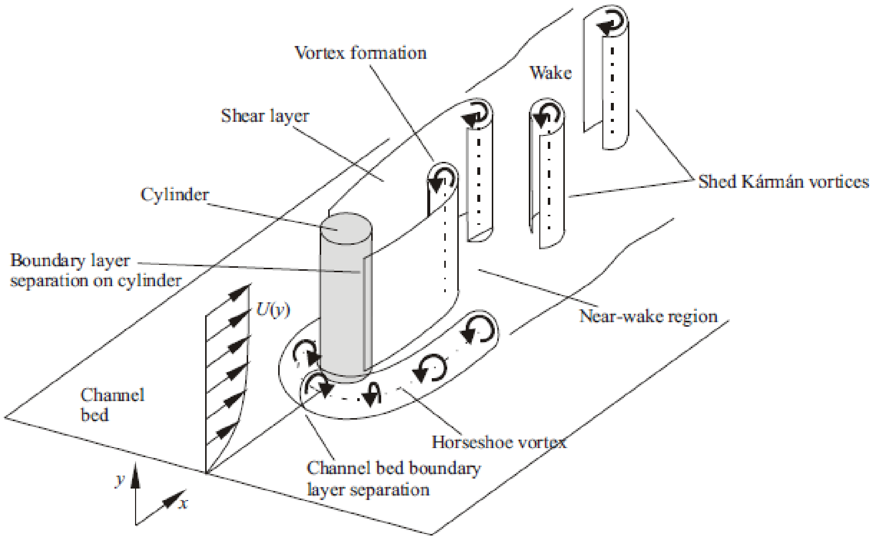

Fig. 1 Circular cylinder mounted normal to a channel bed – Adopted from [3]

II. Experimental Setup

Experiments will be carried out in a 12-m long rectangular open channel flume (cross-section 1200 mm x 1050 mm) at the Rochester Institute of Technology (RIT). A schematic of the open channel flume and the experimental setup is shown in Fig. 2. The water is re-circulated by two 25-horsepower centrifugal pumps. The sidewalls of the flume are constructed of transparent tempered glass to facilitate velocity measurements. The flume is a permanent facility. A sufficiently thick bed made up of uniform sand particles will be leveled to create the test bed. The flow conditions will be maintained to permit local scour to occur (i.e. no general scour) and there will be no net transport of sand beyond the edge of the bed. Downstream of the bed, a sand trap was provided to prevent any accidental transport of sand particles into the pump/piping assembly. Series of tests were planned to examine the effect of flow depth, velocity, sediment size, pier size, pier shape and contraction ratio on the local scour around bridge piers. Depths of flow were varied from 100 mm to 200 mm. The highest limit of flow depth will result in a width-to-depth ratio of 6. Reference [13] noted the formation of secondary current caused by the side wall for the flow in an open channel with a width-to-depth ratio < 5 and the flow conditions in this current series of tests are considered to be two-dimensional free of secondary current. The effect of common non-dimensional flow parameters like densimetric Froude number ($F_o = U_o/\{g(\Delta\rho/\rho)d_{50}\}^{1/2}$) and flow Froude number ($F_r = U_o/(gH)^{1/2}$) was studied because these parameters represent the combination of many individual parameters. The critical velocity for each test conditions will be verified experimentally to avoid general scour and will limit the actual test to 90% of the critical velocity. To condition the flow, flow-straighteners were used at the beginning and the end of flume. Careful attention was given in maintaining the flow conditions to ensure that sand movement cannot be initiated. A sand trap at the downstream of the bed was made as a precautionary measure to avoid any accidental damage of the pump/piping assembly with the transport of sand particles into it.

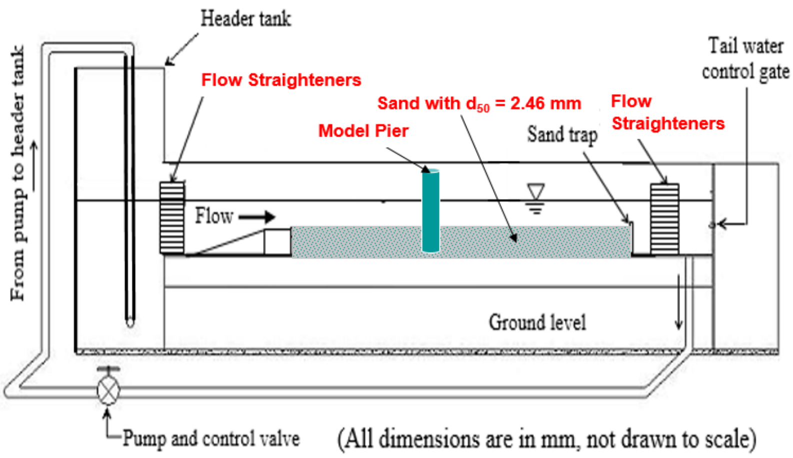

Fig. 2 Schematic of the open channel flume and experimental setup

The schematic diagram of the flow field is shown in Fig. 3 with the scour parameters of interest are: maximum scour depth, location of maximum scour depth, maximum scour width, location of maximum scour width, maximum length of the scour hole, location of maximum scour depth, maximum ridge height, location of maximum ridge height, maximum ridge width, location of maximum ridge width and the distance of the end of the ridge from the bridge pier.

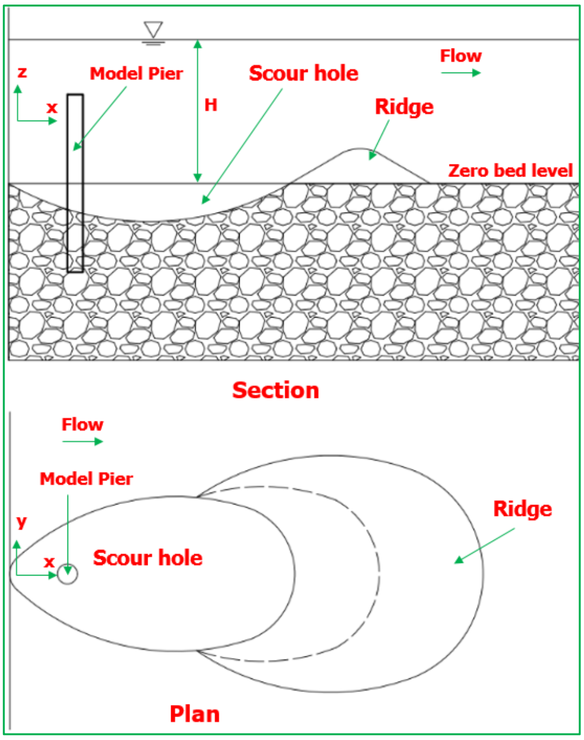

Fig. 3 Schematic diagram of the flow field

The above mentioned scour parameters are related to various flow conditions like depth of flow, velocity of flow, bed materials, contraction ratio, shape and size of the bridge pier. The researchers find it paramount to understand the effect of various flow conditions on different scour parameters. In addition to retrieve the scour parameters data, the video of the tests to explain the visual observation of the development/progression of the scour hole and ridge was recorded. Still pictures of the scour hole was taken after draining out the water at the completion of the test and were explored the possibility of variables individually affects the magnitude of scour parameters or several variables collectively act to influence the scour.

A summary of the test conditions is presented in Table I. Five different flow depths (H) corresponding to same Froude number (F_r = 0.35) and five different flow depths (H) corresponding to same densimetric Froude number (F_o = 2.24) were chosen for the study. Some of the tests were repeated to ensure repeatability. With progress in time, the dimensions of the scour hole do not change significantly and a quasi-equilibrium stage is reached. Tests were conducted until asymptotic conditions were attained.

TABLE I
SUMMARY OF THE TEST CONDITIONS

Test #	Pier Size (d - mm)	Flow depth (H - mm)	Velocity (U_o – m/s)	F_r	F_o	Test duration
M1	50	100	0.347	0.35	1.72	24 hrs.
M2	50	120	0.379	0.35	1.88	24 hrs.
M3	50	140	0.41	0.35	2.04	24 hrs.
M5	50	180	0.465	0.35	2.31	24 hrs.
M6	50	200	0.491	0.35	2.44	24 hrs.
C	50	100	0.45	0.454	2.24	24 hrs.
D	50	120	0.45	0.415	2.24	24 hrs.
F	50	130	0.45	0.398	2.24	24 hrs.
H	50	150	0.45	0.371	2.24	24 hrs.

III. RESULTS

Fig. 4 Schematic of the scour hole and the ridge

As the pump reaches operating speed, the water hits the upstream face of the pier, causing zero-velocity at the back and eventually increased velocity at the sides of the pier. This causes quick progression of the scour hole in the longitudinal direction. The increased velocity in the lateral direction causes scour progresses in the lateral direction. Nevertheless, the progression of scour in the lateral direction is much slower in comparison to the scour in the longitudinal direction. The scoured materials are deposited in the downstream and the ridge formed together with the scour hole. One can see the suspension of bed materials at the very early stages of the scour process where the suspended materials convected with the fast moving main flow and added to the downstream ridge. Fig. 4 provides a schematic of the scour hole and the ridge that is formed downstream of the scour hole. With progress in time, the depth of scour increases while retaining the same general shape of the hole, which is more-or-less elliptical in shape. As scour progresses, the scour hole attains an equilibrium stage, while the ridge portion is still developing. Turbulent bursts also contribute to the formation of scour hole by transportation of the sand particles downstream the pier. The turbulent bursts initiated scour is very much different compared to the scouring process reported earlier, both in the process and in magnitude. Scour process by turbulent bursts are mainly from the rolling motion of the sand particles from turbulent burst but not possess the strength to cause large-scale scour. Turbulent bursts occur more frequently at the beginning of the tests and one can see less and less turbulent burst with the progression of time. The turbulent bursts can be seen throughout the test period but with loosing strength and intensity as the test progresses.

Fig. 5 shows the plan view of the scour hole for five different flow depths with the same Froude number. As one can see from the plan view, all the profiles are different although the tests are done with the same Froude number. Plan size of the scour hole increases with the increase of flow depth but width and length of the scour hole is much closer with higher flow depth. Fig. 6 shows the plan view of the scour hole for four different flow depths with the same densimetric Froude number. As one can see from the plan view that all the profiles are different although the tests are done with the same densimetric Froude number but the difference of scour hole size is smaller than the difference of scour hole size for tests with same Froude number.

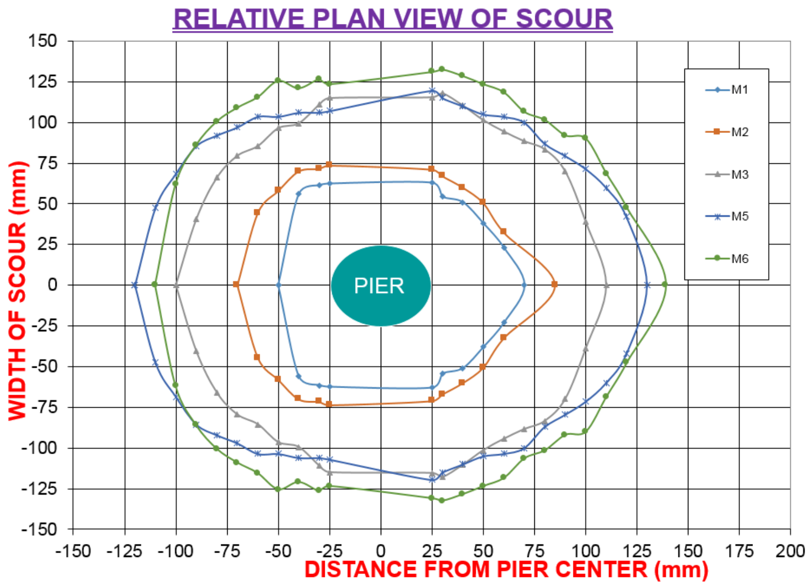

Fig. 5 Plan view of the scour hole for same Froude number.

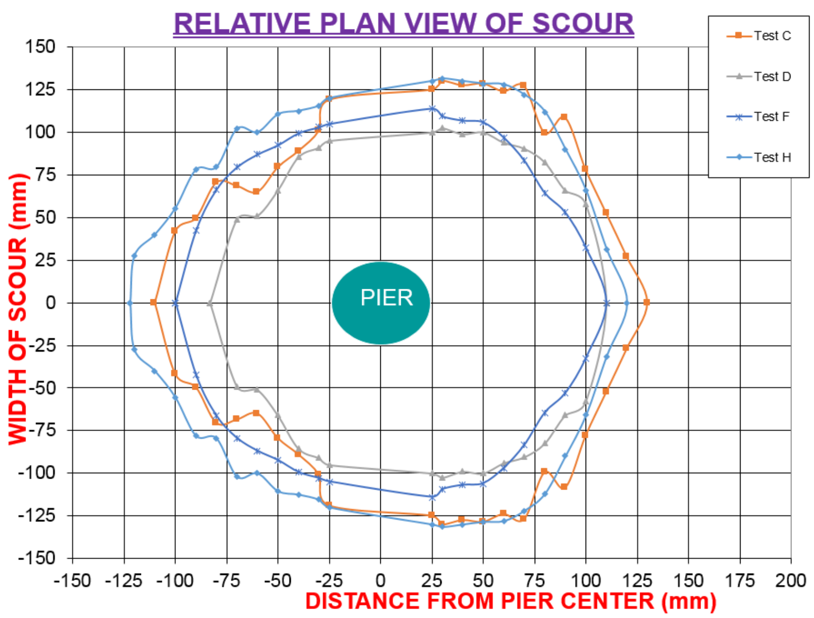

Fig. 6 Plan view of the scour hole for same densimetric Froude number

Fig. 7 shows the sectional view of the scour hole along the centerline of the pier (side view) for five different flow depths with the same Froude number. As one can see from the sectional view that all the profiles are different although the tests are done with the same Froude number. Sectional view also shows that the maximum depth of the scour hole increases with the increase of flow depth with location of the maximum depth of scour is always at the back of the pier and not dependent on the flow depth. Fig. 8 shows the sectional view of the scour hole along the centerline of the pier (side view) for four different flow depths with the same densimetric Froude number. As one can see from the sectional view that all the profiles are different although the tests are done with the same densimetric Froude number but the difference between the profiles is smaller than the difference of profiles for tests with same Froude number.

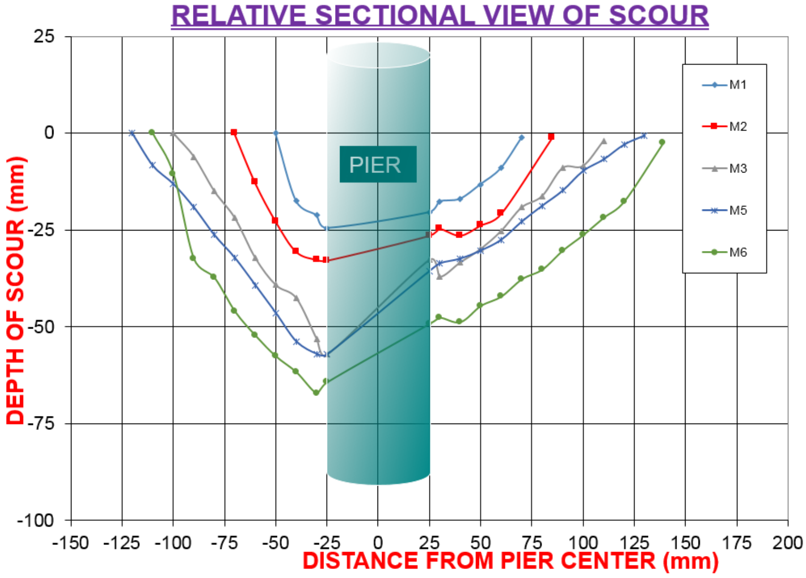

Fig. 7 Center line profile of the scour hole for same Froude number

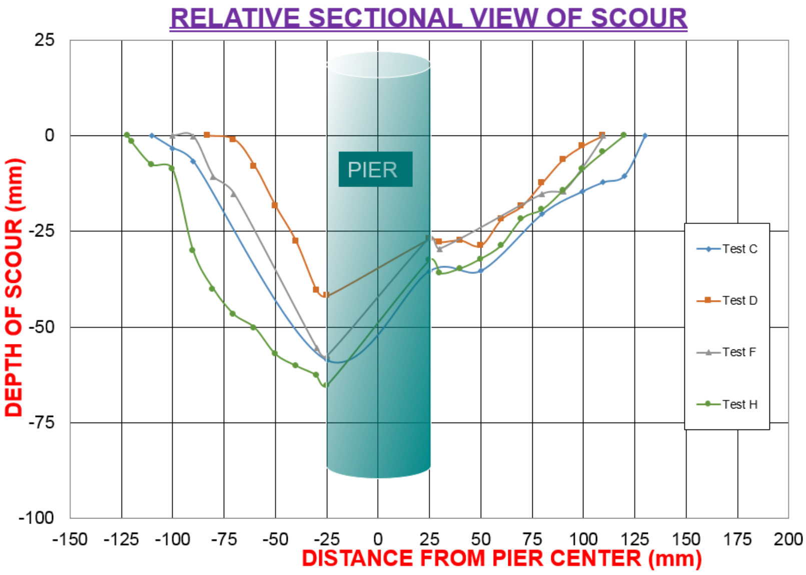

Fig. 8 Center line profile of the scour hole for same densimetric Froude number

IV. Conclusion

An experimental study with different flow depths was carried out to understand the effect of Froude number and densimetric Froude number on different scour parameters. The variables of interest include the profile of the scour hole, formation of the ridge, progression of scour hole and ridge with respect to time. The main findings are summarized as follows:

1. The length, width and maximum depth of the scour hole is different even for the series of tests with the same Froude number.
2. The length, width and maximum depth of the scour hole is different even for the series of tests with the same densimetric Froude number.
3. The location of maximum depth of the scour hole is located at the back of the pier base.
4. The ridge formation downstream of the scour hole has significant effect on the river/channel alignment.
5. Time required to reach the asymptotic condition of the scour development is dependent on flow depth, flow Froude number and densimetric Froude number.
6. Scour progresses very fast at the beginning of the tests but slowed down significantly after two/three hours.

7. Length of the ridge keep on expanding for a very long time compared to the scour hole expansion.
8. Present research also indicates that tests with lower flow depth cause the ridge in front of scour hole to be flat and elongated.
9. Elongated ridge formation causes general scour downstream of the river/channel for tests with higher flow velocity.

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