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Surface Characteristics of Scouring at Bridge Elements

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Abstract

Infrastructural elements of bridges mounted in alluvial stream beds are susceptible to scouring. Decision-making for the type and placement practice of relevant countermeasures to be implemented against scouring action is based on investigation of the characteristics of scour holes formed around piers and abutments. This would also lead to the estimation of the safe depth of burial of footings of bridge infrastructural elements. Sets of experiments have been performed to investigate time-dependent characteristics of scour holes around cylindrical and square piers and vertical-wall abutments under clear water conditions with uniform bed materials. In the course of the experiments, temporal variations in scour depth and scour contours were measured. Using this information, a number of empirical relations were developed for temporal variation in dimensionless scour surface area and scour hole volume. The findings of this study may provide useful information for the preliminary design of armoring countermeasures around such infrastructural elements.

Key words: Bridge, Abutment, Pier, Scour, Clear water, Countermeasure.

Introduction

The topic of bridge failure induced by excessive scouring at infrastructural elements has attracted the attention of many researchers since the middle of the 20^{th} century. In spite of the achievement of significant advances in the scouring phenomenon at bridge elements, there are still several aspects that need to be clarified. The majority of the previous studies are devoted to the determination of the maximum depth of scour around bridge elements. On the other hand, studies dealing with clear water conditions are mostly based on estimation of equilibrium depth of scour at bridge piers and abutments. In fact, the degree of implementation of scour countermeasures is not only dictated by the depth of scour but also by the characteristics of surface area and volume of the scour hole around such elements. This study is specifically focused on the investigation of geometric characteristics of scour holes.

Some of the earlier studies are based on estimation of temporal variation in scour depth at bridge piers and abutments. This section presents brief information on these studies. Chabert and Engeldinger (1956) were probably the first researchers introducing the effects of time and velocity on clear water and live bed local scouring at bridge piers. Shen et al. (1965) studied time-dependent variation in clear water scouring around bridge piers. In these studies, uniform bed materials were tested. Raudkivi and Ettema (1983) developed a chart giving temporal variation in scour depth around cylindrical piers using non-uniform sediments. Yanmaz and Altınbilek (1991) introduced a semi-empirical model giving time-dependent variation in clear water scour depth around cylindrical and square piers in uniform bed material. This model was based on application of the sediment continuity equation to the scour holes around such piers. Kothyari et al. (1992) investigated the pattern of scour evolution around cylindrical piers in uniform sediment under live bed conditions. Melville and Chiew (1999) developed an empirical equation giving the temporal variation in clear water scour at cylindrical bridge piers in uniform sediments as a function of equilibrium scouring parameters. They also introduced expressions giving a time scale for equilibrium conditions. The empirical scour-prediction equation proposed by Oliveto and Hager (2002) gave temporal variation in clear water scour depth around cylindrical piers in nonuniform sediments. It was based on extensive laboratory measurements. The models proposed by Ali and Karim (2002) and Mia and Nago (2003) were semi-empirical in nature, and based on simulation of the velocity and vortex fields as well as bed load transport rates in close vicinity to cylindrical piers in uniform sediment under clear water conditions. Chang et al. (2004) carried out experiments under steady and unsteady clear water conditions with uniform and nonuniform sediments to predict the evolution of scour depth at cylindrical piers. Yanmaz (2006) modified the previous model developed in Yanmaz and Altınbilek (1991) using a recent sediment pickup function for cylindrical piers. Among the aforementioned methods, the equation proposed by Oliveto and Hager (2002) is of practical importance; it is calibrated using extensive laboratory data including nonuniform bed materials. With the inclusion of additional data to the previous study reported in 2002, Oliveto and Hager (2005) proposed the following equation for cylindrical piers:

$$\frac{d_s}{L_R} = 0.068\sigma_g^{-0.5} F_d^{1.5} \log T_d \qquad (1)$$

where d_s = maximum depth of scour around a cylindrical pier, $L_R = b^{2/3}y^{1/3}$, b = pier width, y = approach flow depth, F_d= densimetric particle Froude number, which is defined as $u/(\Delta g D_{50})^{0.5}$ with u = mean approach flow velocity, Δ = relative density, g = gravitational acceleration, D_{50} = median sediment size, $T_d = t/t_R$, t = duration of flow, and $t_R = L_R/(\Delta g D_{50})^{0.5}$.

Studies of similar context have also been carried out for abutments. The following section provides brief information on these studies. Wong (1982) performed experiments to predict time variation in scour around short vertical-wall abutments. Similar studies were carried out by Tey (1984) for long abutments to investigate the effect of length of abutment on the scouring mechanism. Hoffmans and Verheij (1997) identified various phases during the evolution of scouring at bridge abutments. Cardoso and Bettess (1999) tested the effect of abutment length on temporal variation of scour depth around vertical-wall abutments. Ballio and Orsi (2001) proposed an exponential expression for abutment scour depth as a function of time. The method proposed by Kothyari and Ranga Raju (2001) was semi-empirical in nature and based on the use of previous data. Santos and Cardoso (2001) proposed an empirical equation for temporal variation in scour depth at vertical-wall abutments with reference to the effects of flow intensity, abutment length, and sediment size. Oliveto and Hager (2005) carried out experiments under similar conditions that were generated for cylindrical piers to end up with a similar expression presented in Eq. (1). The only difference in the scour-prediction equation for vertical-wall abutments is that the coefficient 0.068 in Eq. (1) is replaced by 0.085 and the abutment length is used instead of the pier width. Coleman et al. (2003) proposed an empirical equation for time-dependent variation in scour depth around vertical-wall abutments in uniform sediment. Dey and Barbhuiya (2005) developed a semi-empirical model to compute the time variation in scour depth at short abutments of vertical wall, wing wall, and semi-circular types in uniform and nonuniform sediments. The approaches of Cardoso and Bettess (1999), Ballio and Orsi (2001), and Coleman et al. (2003) are based on the estimation of equilibrium scouring parameters, which can be attained in relatively long flow durations, e.g., of the order of several days in laboratory medium. Another limitation is due to different definitions of the equilibrium scouring situations. The random nature of sediment-laden flow may restrict the achievement of ideal equilibrium conditions with exactly no sediment motion in close vicinity to the bridge element. Therefore, the accuracy of these equations is based on the precision of the expressions giving equilibrium scour depth and its time of occurrence. On the other hand, the semi-empirical models require repeated solution of differential equations for successive time increments. Further information on this topic can be found in Yanmaz (2006). As a final remark, Eq. (1) proposed by Oliveto and Hager (2005) is easy to apply, independent of equilibrium scouring parameters, and includes sufficient governing scouring variables. Therefore, it is of practical importance and will be used for verification.

In spite of the availability of a number of scour-prediction equations in the literature outlined above, there is still limited information on the geometric characteristics of scour holes at bridge elements. Therefore, engineering solutions, concerning especially selection of scour countermeasures and their placement details, would be subject to uncertainty. To offset this problem, additional experimental studies need to be conducted. The objective of this study is to investigate the temporal variation in geometric characteristics of scour holes around piers and vertical-wall abutments under clear water conditions using the scour contours, which were determined through a set of laboratory experiments.

The design of bridge foundations on the basis of equilibrium clear water scour depths may yield considerably greater values than may occur if the flow is of short duration. For a known time-to-peak value of design flood hydrograph, smaller scour depths may be obtained, which reduce the total cost of construction (Yanmaz and Altınbilek, 1991). Therefore, investigation of temporal variation of characteristics of clear water scouring at bridge elements is of importance for the estimation of the possible extension of the scour hole under design conditions. This would provide useful information for the selection of scour countermeasures to be implemented. The degree of severity of the problem is dictated by the sizes of the surface area of scouring and scour hole volume around infrastructural elements of bridges.

Experimental Studies

Experiments were conducted in 2 different flumes for piers and abutments, respectively. The pier models were tested in a 0.67-m wide rectangular flume using sediment with median grain size 1.07 mm. The scour hole development was investigated around a circular pier with 6.7 cm diameter and a square pier having side lengths of 6.7 cm. The axis of the square pier model was mounted with zero angle of inclination as the approach flow. The experiments for the vertical-wall abutments were carried out in a rectangular flume 1.25-m wide using uniform sediment having median size of 1.8 mm. Both flumes have a bed slope of 0.001. In the experiments, abutment models with lengths (perpendicular to the flow direction) of 12.5 cm and 10 cm having a constant width of 20 cm were tested.

During the experiments, the maximum scour depths around the pier and abutment models were measured against time relative to the initial bed level using a vertical scale attached to the interior of a hollow Plexiglas model with a stick having a small inclined mirror at its end. It is known that a very long duration is required to reach the equilibrium state under clear water conditions (Yanmaz, 2006). However, from a practical standpoint it is very difficult to perform a wide range of experiments with such a long duration. Therefore, the test duration of an experiment was limited by 6 h, during which the final equilibrium scour depths were not achieved although the rate of scour did decelerate to smaller values for all experiments.

The goals of the experiments are to observe time-dependent variation in the shapes of scour holes including the location and magnitudes of the maximum scour depths around the models. For the investigation of scour contours, experimental runs were performed with densimetric particle Froude numbers, F_d, of 2.52 and 2.38 for the pier and abutment models tested, respectively. Other values of F_d were not tested because of the fundamental similarity of all local scouring situations (Yanmaz, 2006). The experiments were stopped at the end of different test durations, namely 5, 20, 60, 100, and 150 min, to determine the contours of the scour hole around the pier and abutment models using point gages. At the end of an experiment, water was removed gently from the channel not to disturb the bed topography, and intensive measurements were carried out in a grid system around the model composed of joints separated by 2-cm intervals along and across the channel. After each run, the bed was flattened to run the experiment with the next duration. Time-dependent scour contours were then obtained for the pier and abutments tested. For the sake of brevity of this paper, only one of the contours for each element is shown in Figures 1 through 3, which are obtained at the end of the specified test durations. During the course of the experiments, it was observed that the maximum scour depths occurred around the centerline of the upstream face of the piers and around the upstream corner of the vertical-wall abutments, whereas the maximum accretions took place around the rear face of these elements.

Analysis of Experimental Results

The geometric characteristics of the scour holes around piers and abutments can be investigated using experimental results. When the time-dependent contours of the scour holes are investigated, it is observed that the scour contours are almost uniformly spaced and the shape of the scour hole around bridge piers can be approximated by an inverted cone having circular and square bases for the cylindrical and square piers, respectively. Side inclinations of the scour holes are approximately equal to the angle of repose of the sediment. Since the pier models are set at the mid-section of the channel, the scour contours are almost symmetrical with respect to the pier axis. Similarly, time-dependent scour contours around the vertical-wall abutments are also investigated. However, the contours around the vertical-wall abutment models are not as symmetrical as the ones developed around the piers since the abutments are mounted at the side of the channel. Since square corners yield greater separation at the upstream face of the piers, the scour hole around the square piers is greater than that of the cylindrical pier under the same flow conditions. This clearly indicates the effect of the shape of the pier on the scouring.

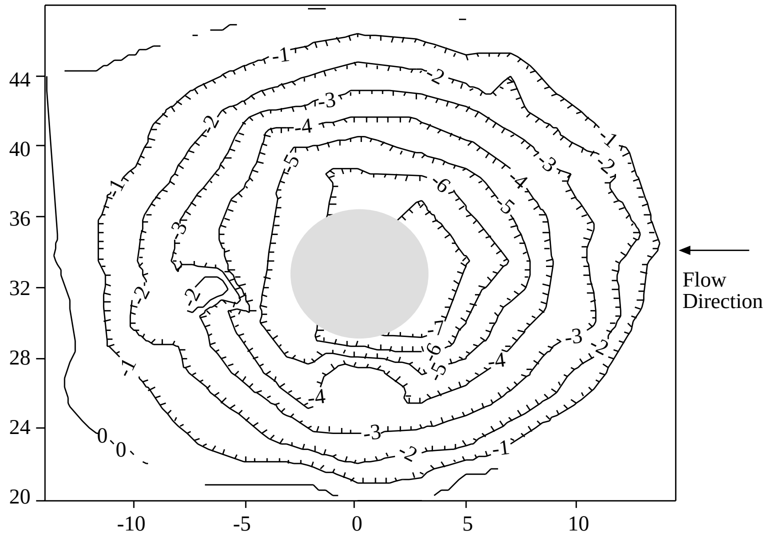

Figure 1. Scour contours (in cm) around the cylindrical pier measured at t = 60 min.

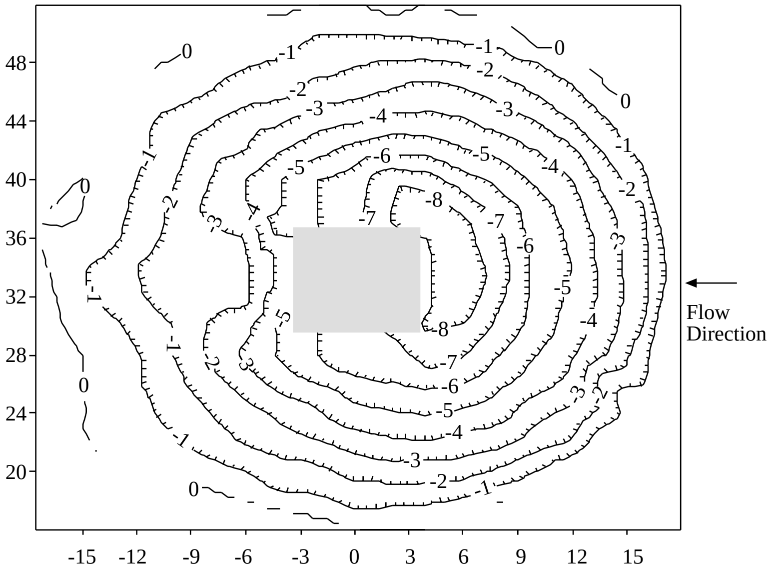

Figure 2. Scour contours (in cm) around the square pier measured at t = 60 min.

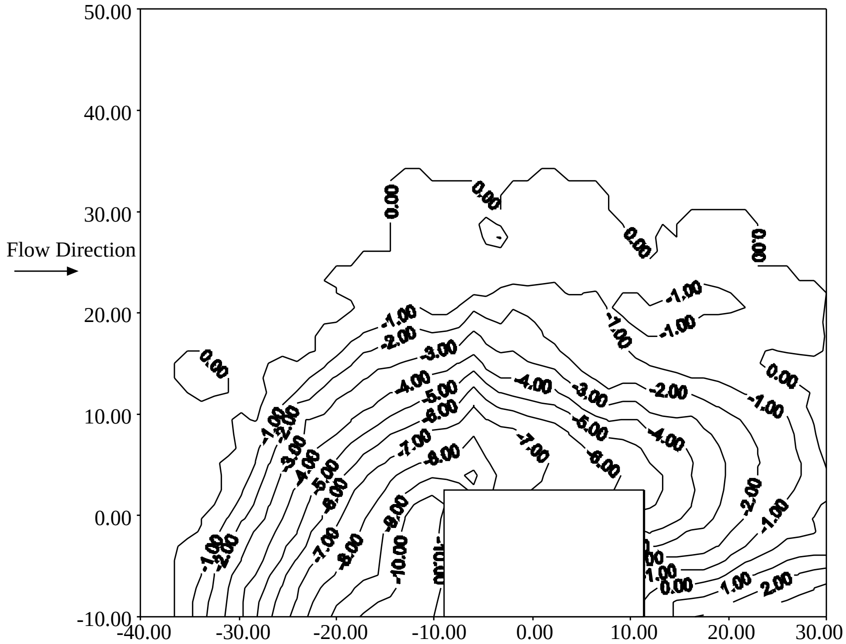

Figure 3. Scour contours (in cm) around the vertical-wall abutment measured at t = 100 min.

The surface area and volume of the scour hole around the bridge elements are computed at the aforementioned test durations using software based on the triangularization technique. This program is capable of evaluating the area and volume elements bounded by irregular contours. For the sake of practical applications, dimensionless surface area, A*, and dimensionless scour hole volume, V*, expressions are defined, in which A* is the ratio of the scour surface area to the base area of the element, whereas V* is the ratio of the volume of the scour hole to the base area of the element times the scour depth. The regression equations for these parameters with relatively high correlation coefficients, R^2, are as follows:

$$A^*_{cp} = 2.904T_s^{0.399} \quad (R^2 = 0.934) \tag{2}$$

$$A^*_{sp} = 3.570T_s^{0.398} \quad (R^2 = 0.991) \tag{3}$$

$$A^*_{va} = 3.722T_s^{0.182} \quad (R^2 = 0.962) \tag{4}$$

$$V^*_{cp} = 1.738T_s^{0.299} \quad (R^2 = 0.970) \tag{5}$$

$$V^*_{sp} = 1.279T_s^{0.400} \quad (R^2 = 0.990) \tag{6}$$

$$V^*_{va} = 0.681T_s^{0.265} \quad (R^2 = 0.940) \tag{7}$$

where the subscripts cp, sp, and va stand for the cylindrical pier, square pier, and vertical-wall abutment, respectively, and T_s is the dimensionless time parameter, which is taken as $tD_{50}(\Delta gD_{50})^{0.5}/b^2$ as also previously used by Yanmaz and Altınbilek (1991) and Yanmaz (2006), t is the time and b is the length of bridge element perpendicular to the flow direction.

As the literature lacks equations of similar context of those presented by Eqs. (2) through (7), the accuracy of these equations cannot be verified directly at this stage. However, the measured volumes of the scour hole can be compared by Eqs. (5) and (7) for cylindrical piers and vertical-wall abutments, respectively, by using the scour depth values obtained from the Oliveto and Hager (2005) approach, in these equations. In this analysis, only the scour hole volumes are taken into consideration since the expressions for the surface area of the scour hole are independent of scour depth values. The results of the comparative analysis are shown in Figures 4 and 5 for the cylindrical piers and vertical-wall abutments, respectively, in which V_e is the experimentally computed volume of the scour hole and V_m and V_{OH} are the predicted scour hole volumes computed from Eqs. (5) and (7) for cylindrical pier and vertical-wall abutment, respectively, using the experimental scour depths of this study and the scour depths obtained from Eq. (1). It was observed in the analysis that the scour hole volumes, V_{OH}, were slightly greater than V_e values. The correlation coefficients, R^2, between the V_e and V_m and V_{OH} values are also presented in Figures 4 and 5, which are relatively high, i.e. greater than 0.99. Moreover, the correlation coefficients between the 2 approaches are very close to each other. Therefore, one can conclude that scour depths measured in the experiments agree well with the findings of the Oliveto and Hager (2005) equation. Therefore, one can use the results of the Oliveto-Hager (2005) equation to compute the scour hole volumes around such bridge elements using Eqs. (5) and (7). Since the proposed equations for the volume of scour hole were verified satisfactorily for cylindrical piers and vertical-wall abutments using the Oliveto and Hager (2005) equation for the scour depths, the proposed equations can further be interpreted as follows. Variations in dimensionless area and volume against dimensionless time are shown in Figures 6 and 7, respectively. These figures imply that the rates of change of A* and V* decrease with respect to T_s. However, this decrease is more pronounced for the vertical wall abutments (see Figures 6 and 7). This may be due to the development of symmetrical flow conditions around piers, which may prolong the scouring action for longer durations.

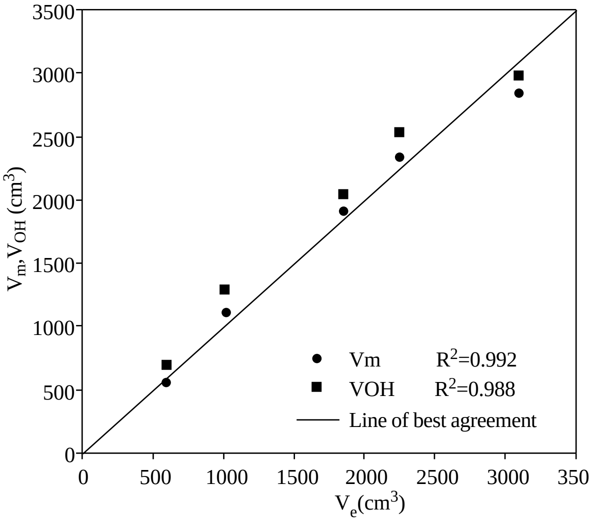

Figure 4. Comparison of scour hole volumes for cylindrical piers.

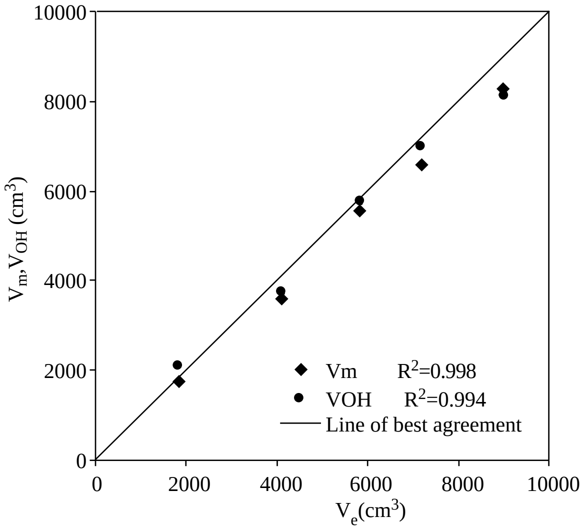

Figure 5. Comparison of scour hole volumes for vertical-wall abutments.

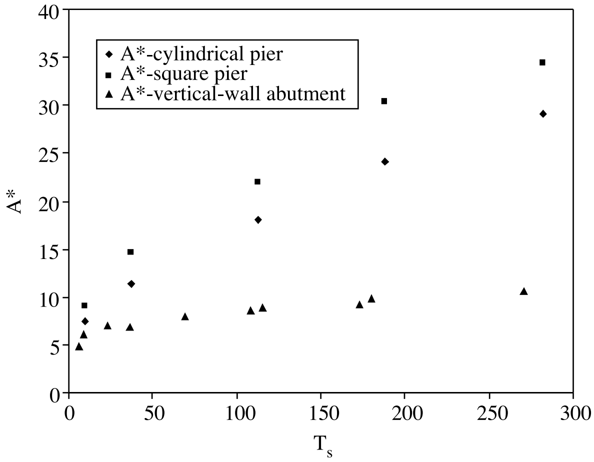

Figure 6. Variation in A* with respect to T_s.

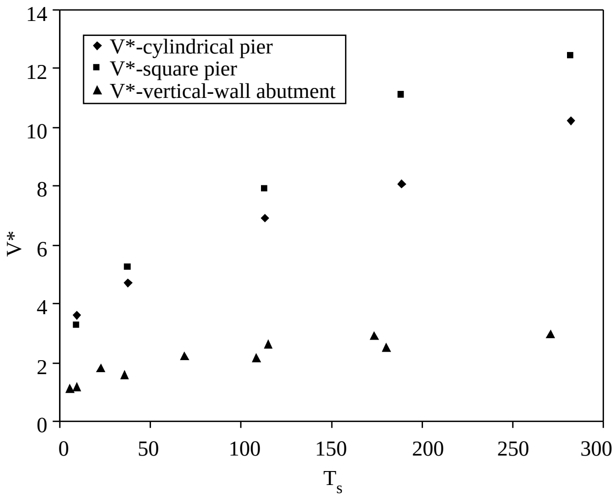

Figure 7. Variation in V* with respect to T_s.

Since the aforementioned equations dealing with the surface area and volume of scour hole are dimensionless, they can also be used for the practical prototype applications. These equations require selection of appropriate design parameters to be used in the dimensionless time term. The most crucial term in this parameter is the duration of the design flood. For a conservative design, sufficiently long flow durations, compatible to the local hydrologic conditions of the bridge site concerned, can be taken. The corresponding scour surface area and volume can then be obtained using respective equations. Since the volume of the scour hole gives the amount of bed material eroded from the surrounding of the element, it can give some clues about the depth of the protection area around the element, i.e. the number of armoring layers in the protection area. On the other hand, the size of the surface area of the scour hole dictates the extension of the armoring countermeasure around the bridge element. As a concluding remark, it should be emphasized, however, that additional experiments need to be conducted using different bed materials and flow conditions to generalize the design details of this armoring countermeasure, i.e. the extension of the area of protection as well as the size, layer thickness, and surface elevation of the riprap.

Conclusions

Experimental studies were carried out to observe the time-dependent geometric characteristics of the scour holes around cylindrical and square piers and vertical-wall abutments under clear water conditions with uniform bed materials. This information is needed for determining the safe depth of burial of bridge footings as well as for deciding the degree of protection to be implemented against excessive scouring. During the course of the experiments, it was observed that the maximum scour depths occurred around the centerline of the upstream face of the piers and around the upstream corner of the vertical-wall abutments, whereas the maximum accretions took place around the rear face of these elements. Using the experimental information, dimensionless empirical relations were obtained for time-dependent surface area and volume of the scour holes around these elements. These equations were then verified for the scour hole volume using the Oliveto-Hager equation for the scour depths. Very close results were obtained for the scour hole volumes using the experimentally determined values of scour depth and the findings of the Oliveto and Hager equation in the volume expression for the scour holes around cylindrical piers and vertical-wall abutments. Therefore, it can be recommended that one can use Eq. (1) to compute the depth of scour around a cylindrical pier or a vertical-wall abutment and further apply the proposed equations presented in this study, i.e. Eqs. (5) and (7) to compute the scour hole volume around such bridge elements. Equations giving the surface area of the scour hole around the bridge elements can also be used for preliminary purposes. Similar comparative analysis could not be carried out for the surface area of the scour hole around bridge elements at this stage since the respective proposed equations in this study are independent of scour depth values. As a final remark, the equations proposed in this study, Eqs. (2) through (7), are assumed to provide preliminary design guidelines for deciding the extension of placement of armoring countermeasures around infrastructural bridge elements. Additional experimental research is recommended to further verify these equations and to obtain detailed guidelines concerning placement details of armoring countermeasures, such as riprap.

Acknowledgments

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Nomenclature

A^*	dimensionless surface area of scour hole;
b	characteristic dimension of a bridge infrastructural element;
D_{50}	median sediment size;
F_d	densimetric particle Froude number;
g	gravitational acceleration;
L	abutment length perpendicular to the flow direction;
L_R	combined term to take into account effect of pier or abutment size and flow depth;
R	correlation coefficient;

T_d	dimensionless time term used by Oliveto and Hager;
T_s	dimensionless time;
t	time;
u	mean approach flow velocity;
V_e	experimentally determined scour hole volume;
V_m	predicted scour hole volume using test results of scour depth;
V_{OH}	predicted scour hole volume using scour depth of Oliveto-Hager approach;
V*	dimensionless scour hole volume;
Δ	relative density.

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