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A comparative study of local scour depth around bridge piers

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ABSTRACT

Scour is the leading cause of bridge collapse beneath any bridge pier located within the waterway. A numerical-based hydraulic model named the Hydrologic Engineering Centre River Analysis System and a mathematical model of the Florida Department of Transport were implemented to investigate their performance and accuracy in estimating the maximum scour depth beneath bridge piers where large and small-scale physical prototypes are used as a benchmark. The main findings are that a hydraulic model is an effective tool when employing the Colorado State University equation, which compares well with physical prototypes irrespective of the variation in piers' size and shape. Also, it has achieved more consistent results than the Froehlich and the Florida Department of Transport methodologies.

KEYWORDS

bridge scour, river analysis system, mathematical model, physical prototype, the Colorado State University equation, the Froehlich equation

1. INTRODUCTION

'Scour' can generally be defined as sediment erosion around an obstacle in the flow field's direction [1]. Scour can significantly break down structures like bridges, spillways, and weirs when their foundations have been undermined. Reference [2] reported that there had been several relatively recent bridge structure failures as a result of local scour around piers. Furthermore, the study concentrated on understanding the causes of pier scour causes and developed new methods for protecting bridges against scour effects. In this respect, the USA has estimated that the reasons for the failure of more than 500 bridges in the region between 1989 and 2000 were identified as scouring in 53% of the cases [3]. Reference [4] concluded that local scour at bridge foundations (piers and abutments) occurs due to river flooding, which is the main reason for the bridge collapse. As a result, bridge collapse causes human fatalities, injury, and economic losses for rehabilitation and reconstruction.

Although abundant studies have been reported since 1950, it remains a challenging problem due to the difficulties in understanding complicated flow and scouring processes in conjunction with intricate geometries of bridges.

Reference [5] stated that when the equilibrium of scour depth is under-estimated, it leads to bridge failure, whereas over-estimation increases construction costs. Researchers reported many experimental and numerical investigations to determine scour depth in different soils and river conditions. Studies employing the numerical-based hydraulic model of the Hydrologic Engineering Centre River Analysis System (HEC-RAS) for local scour prediction which was concluded that the HEC-RAS model is a practical methodology for using the Colorado State University equation (CSU) to evaluate the scour depth around bridge piers [6–8].

For contactless measurements, the scours must be assessed using short-range photogrammetry where the scours will be measured to see how practical the examined approaches

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are at reducing scour. A short-range photogrammetric approach was employed to capture scours in the downstream watercourse bed and banks, allowing the whole monitored region of the riverbed to be recorded [9]. This approach proved a rapid, dependable, and exact method for researching watercourse scouring on physical models. During flood flow, simulations and subsequent observations revealed that the suggested fortification significantly decreased scouring for the geometric operation in the streambed. In terms of minimizing sour depths and diameters and reducing turbulence in the riverbed, the examination of the longitudinal barrier yields the most remarkable results in contrast to the longitudinal barrier with a greater depth, which has a detrimental impact on the riverbed turbulence scours sizes. As a result, the longer the barrier, the greater the energy dissipated from the water in the riverbed, resulting in smaller sour sizes [10].

This study will calculate the maximum depth of local scour for a bridge foundation (pier) by using a one-dimensional HEC-RAS, [11] and make a comparison study with the Florida Department of Transport mathematical model based on the benchmark of the small and large physical model results. The HEC-RAS is considered the standard computer software package for local scour estimation. It is a one-dimensional hydraulic analysis program with scouring prediction modules that compute scour around bridge piers by empirical formulas. It is generally considered accurate, especially for uniform channel sections. Therefore, the model can be used in bridge studies and designs to evaluate bridge pier placement's approximate scour and depth. This study could be considered as a guide to the understanding of the scour components, fundamental and temporal developing of scouring, establishing a new methodology for accurately predict of local soil scour depth beneath piers, efficient bridge designs led to reducing rehabilitation and rebuilding fees, examining the performance of the HEC-RAS model and finally contributing to increasing the level of knowledge regarding the local scouring around bridge piers.

2. LOCALIZED SCOUR

2.1. Local scour

In local scour, the erosion action of sediments in the base of bridge piers occurs due to interfering with the flowing water. These obstacles lead to accelerating flow and making lots of vortices. These vortices are responsible for removing bed material around bridge piers or abutments. Local scour also divided into clear-water or live-bed scour [12]. Figure 1 shows the typical shape of local scour around bridge piers.

Fig. 1. The local scouring formulate around cylindrical piers (*Source*: Authors)

When the structure is placed in a current, the flow accelerates around this obstacle, and the vertical velocity gradient is converted to a pressure gradient acting on the structure surface. This pressure causes a downward flow, which impacts the bed. The downward flow velocity at the nose of bridge piers and vortex system is considered a basic module of flow fields. Indeed, at the bed of the structure, this flow produces vortices horseshoe and wake vortices and surface roller around and downstream of piers Fig. 2. The horseshoe vortexes tend to eliminate the soil around the foundation of piers, known as local bed scours. The transportation rate of bed materials away from the foundation of piers is more than the transportation rate to piers place.

As a consequence, scour depth increases. As the scour depth develops, the horseshoe vortex power decreases, decreasing the transportation level away from this region. Additionally, vertical vortices downstream of the bridge are known as the wake vortex. The power of wake vortices reduces quickly when the distance downstream of the pier increases. Then, there is often deposition of material nearly downstream of long piers (Fig. 2).

Reference [13] demonstrated that as the down-flow weakens, the vortex shedding (movement) of the large-scale convective structures (Horseshoe vortex) affiliated with more or more minor side to side in the pier flow field weakens, and the vertical alignment of unsteady flow

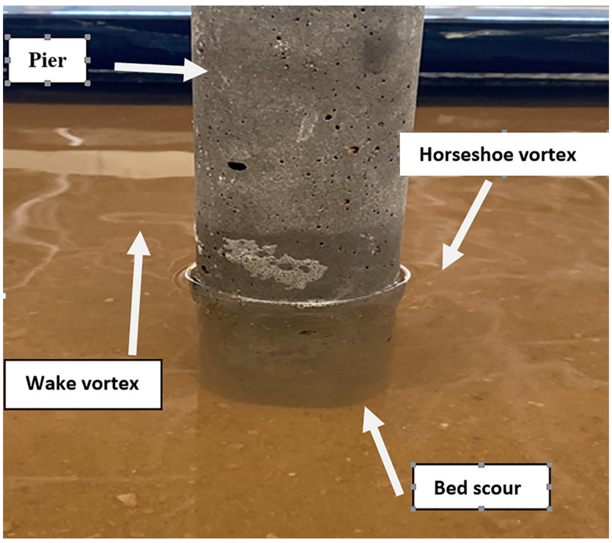

Fig. 2. Schematic of local scour showing horseshoe and wake vortices around cylindrical piers (*Source*: Authors)

structures (wake vortices) also destabilize due to the higher importance of bed contact pressure in a shallower flow. The vortices power per unit weight in the presence of piers depends on the mean velocity of the vortex, v, which can be expressed in the following form [14]:

$$power = \frac{dv^2}{dt} = A_P \frac{v^3}{l_v}, \quad (1)$$

where v is the mean velocity of the vortex; l_v is the length defined as the vortex size; A_P is the constant of the order one independent of the Reynolds number.

Around pier shape, the relationship between the vortex velocity and the flow velocity is practically constant. Therefore, the mean velocity U of the flow can be expressed as:

$$U = \frac{q}{y_0 + d_{se}}, \quad (2)$$

where y_0 is the water depth, m; d_{se} is the equilibrium scour depth calculated from the bed surface, m; q is the unit flow discharge, m^3 s^{-1}.

3. SCOUR PREDICTION

Three methods to estimate the maximum depth of local scour are described below. The first is a "stand-alone" empirical method that requires more miniature input modeling. The second two methods use the HEC-RAS for initial values and then apply empirical equations to estimate maximum depth. While most bridge engineers understand the nature and distribution of scouring "holes" around foundations, their formation and evolutions are very complex, dependent on local flow patterns around the foundation. These patterns change depending on the depth and velocity of channel flow, soil type and particle size of the riverbed materials, foundation geometry and streamlining, and the presence or absence of rip-rap and other armoring materials. A single equation will not capture all the nuances of scouring, but it will estimate the probable maximum depth.

3.1. Calculating pier scour with the Florida Department of Transport equation

Florida Department Of Transport (FDOT) equation [15] was established and improved over many years and by many researchers. For example, [16] considered more information about the local scour flow field and the size of bed materials. A National Cooperative Highway Research Program (NCHRP) study assessed around 30 local scour equations and established that, despite the Colorado State University (CSU) equation being considered the best, the FDOT equation achieved a good result compared to laboratory and field observation data. The FDOT equation comprises flow depth and velocity, pier size and shape, and the angle of attack and particle size. The NCHRP study slightly adjusted the FDOT equation to increase the performance in local scour prediction, which was linked to pier geometry, shape, and angle of attack to calculate an effective pier width (a^*) and differentiate between clear-water and live-bed flow conditions. This method was based on dimensional analysis more extensively than the CSU equation. Despite the CSU equation achieving accurate results in all conditions, the FDOT is an alternative method to predict local scour, especially for wide piers. The FDOT equation is expressed functionally as:

$$\frac{y_s}{a^*} = fn\left(\frac{y_0}{a^*}, \frac{V_0}{\sqrt{gy_0}}, \frac{\rho_s}{\rho}, \frac{V_0 a^* \rho}{\mu}, \frac{V_0}{V_c}, \frac{D_{50}}{a^*}\sigma, \theta\right), \quad (3)$$

where y_s is the equilibrium scour depth (maximum local scour depth after the flow duration is similar to the depth is no longer changing); ρ, ρ_s are the density of water and sediment, respectively; μ is the dynamic viscosity of water (depends primarily on temperature); g is the acceleration of gravity; D_{50} is the median diameter of the sediment; σ is the gradation of sediment; y_0 is the depth of flow upstream of the structure; V_0 is the average depth velocity upstream of the structure; a^* is the effective diameter of the structure; Θ is the parameter quantifying the concentration of fine sediments in suspension. The equations generated may be solved on a spreadsheet. However, different empirical factors are applied for different conditions of some parameters. Therefore, the full description would require several pages.

3.2. HEC-RAS method to predict scour

The HEC-RAS has two options to compute scour depth: (1) maximum velocity and flow depth at the bridge cross-section, or (2) compute scour around each pier separately by using the local flow conditions of each pier. Choice (1) was used in this study. Once flow conditions are computed, the CSU equation may be applied. It has a form similar to Eq. (1),

$$\frac{y_s}{y_0} = 2.0\ K_1\ K_2\ K_3\ K_4 \left(\frac{a^*}{y_0}\right)^{0.65} F_r^{0.43}, \quad (4)$$

where K_1–K_4 are the correction factors; F_r is the Froude number approaching a pier.

The Froehlich (FRO) equation may also be applied as alternativel. It has a form similar to that of the previous equations

$$\frac{y_s}{y_0} = 2.27\ K_5\ K_6 \left(\frac{a^*}{y_0}\right)^{0.43} F_r^{0.61} + 1. \quad (5)$$

HEC-RAS software will compute the scour depth for Eqs (4) and (5) as routine output. Typical inputs for HEC-RAS would include, pier shape (circular cylinder, round nose, and square), number (single or double or triple) and dimensions (a and L), flow depth upstream of bridge section (y_0), velocity (v), and discharge (Q) or river channel cross-sections and bottom slopes.

4. SMALL AND LARGE-SCALE PHYSICAL

The small-scale model consisted of a rectangular flume of 30 cm in width, 25 cm deep, and 7.5 m long with a 5 cm layer

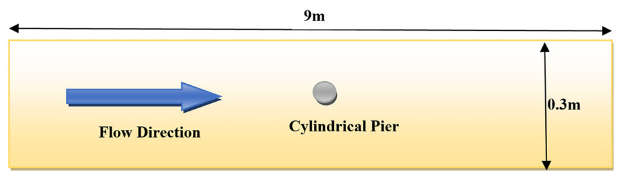

Fig. 3. Small-scale flume for scour study (*Source*: Author modified from [17])

of fine sand with the mean grain size, D_{50} = 0.27 mm, [17], as it is shown in Fig. 3. The velocity and the discharge of the water flow were calculated using an Acoustic Doppler Velocimetry (ADV) and a Moulinet. One or two piers with different cross-sections, shapes, and sizes were fixed on the flume base. Two circular-shaped piers and two oval cross-sections were tested. All piers were made of metal. The pertinent dimensions describe the pier shape and the diameter D for the circular piers and the parameters E and F for the oval cross-section piers. The circular had diameters D = 4.0 cm and D = 2.0 cm. The oval-shaped piers were E = 9.5 cm and F = 4.0 cm for the large piers, and E = 5.8 cm and F = 2.0 cm for the small piers. The flume was filled to 8 cm depth then the pump was turned on to start flow. Two different flow depths were applied. Furthermore, experiments were carried out using dual piers to study the impact of adjacent piers [15]. Finally, twelve experiments were conducted in this study, and the measured scour results are shown later.

The large-scale model (Fig. 4) was intended to study the problem of sediment accumulation and evaluate local scour around piers [18]. A rectangular flume with a width of 3.8 6 m, depth of 0.76 m, and straight length of 8 m, representing a scale of H 1:150 and V 1:30 and scale discharge 300–1,500 m^3 s^{-1}. An upstream stilling basin allowed for flow control and the channel could simulate flow and estimate scour depth around a bridge pier. Three square steel piers, 20 × 20 cm, and 80 cm in length were fabricated for the testing program. Pier dimensions represented transitional pier conditions. The piers were arranged and projected 52 cm above the sand surface. The 28 cm-thick bed was composed of medium sand with D_{50} = 0.5 mm.

5. RESULTS AND COMPARISONS

The results data of the small and large-scale physical models fabricated by [17] and [18] are used as the input data for the numerical HEC-RAS and mathematical model FDOT. The small model estimates are shown in Fig. 5 and Table 1,

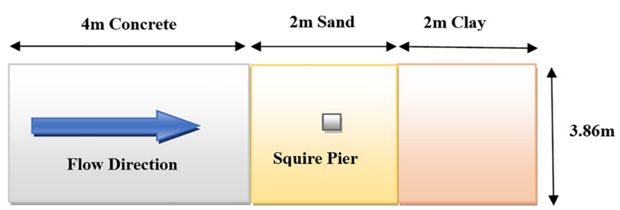

Fig. 4. Large-scale flume for scour study modified from (*Source*: Author modified from [18])

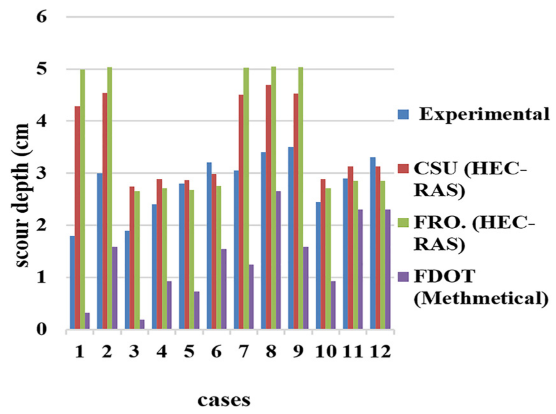

Fig. 5. The measured and estimated depth of scour small scale model

Table 1. The measured and estimated depth of scouring, C = circular, O = oval piers

Cases	Pier cross-section (cm)	Exp.	CSU (HEC-RAS)	FRO (HEC-RAS)	FDOT (Mathematical)
1	C	1.80	4.29	4.99	0.32
2	C4	3.00	4.54	5.03	1.59
3	C2	1.90	2.74	2.65	0.19
4	C2	2.40	2.89	2.71	0.93
5	C2	2.80	2.86	2.68	0.73
6	C2	3.20	2.99	2.75	1.54
7	O4 × 9.5	3.05	4.50	5.02	1.25
8	O4 × 9.5	3.40	4.69	5.05	2.65
9	O4 × 9.5	3.50	4.53	5.03	1.59
10	O2 × 5.8	2.45	2.89	2.71	0.93
11	O2 × 5.8	2.90	3.13	2.85	2.30
12	O2 × 5.8	3.30	3.20	2.91	2.29

where the three empirical predictions are presented directly below the measured scouring depth. The FDOT equation consistently under-predicts depth by 50% or more, while the HEC-RAS methods use the CSU and FRO equations over-predict by 30–50%. The CSU equation estimates were closest to the measured values for nearly every test.

Figures 6–8 show the error value in calculating scour depth using the HEC-RAS equations to compare the

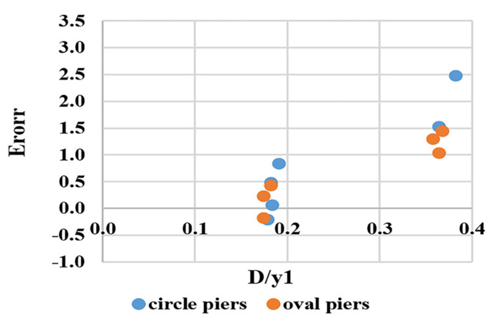

Fig. 6. Error value of CSU base HEC-RAS model with different pier shapes

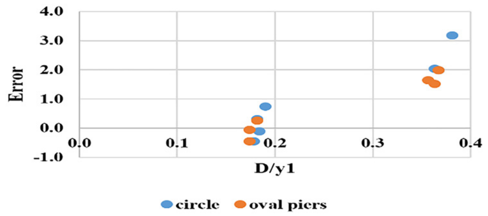

Fig. 7. Error value of FRO-based HEC-RAS model with different pier shapes

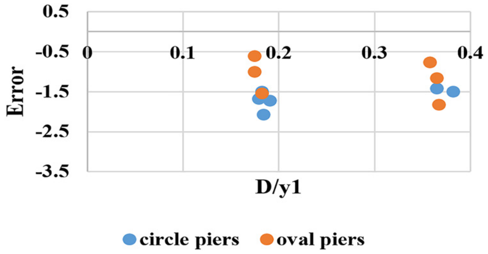

Fig. 8. Error value of the FDOT method with different pier shapes

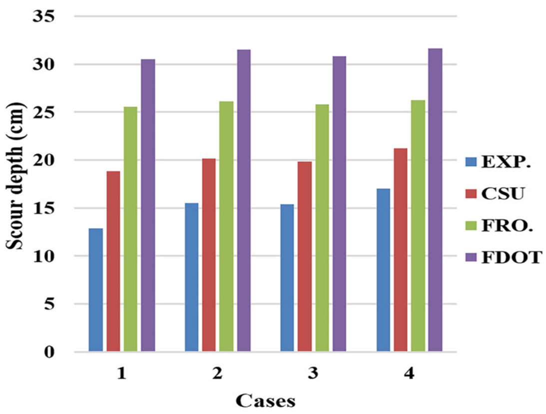

Fig. 9. The measured and estimated depth of scouring for the large-scale model

experimental and the empirical results concerning dimensionless (D/y_1). The HEC RAS software gives an over-estimated value, as mentioned before, with a maximum absolute error value equal to 3.3 cm corresponding to the circular pier with $D = 4$ cm, measured by the Froehlich equation while it

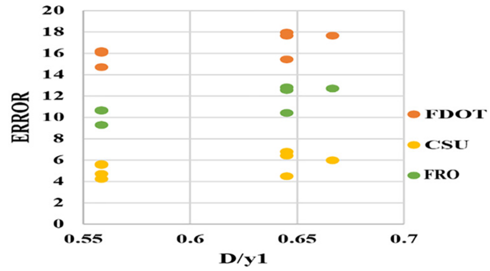

Fig. 10. Error value of the three prediction methods (FDOT, CSU, FRO)

was about 2.5 cm regarding the CSU equation. However, in some cases, the HEC-RAS equations recorded scour depth at almost the experimental value with the error below 1 cm, especially when pier diameter equals 2 cm for circular and oval shapes. To sum up, it can be concluded that all piers (circular and oval) with pier width equal to 4 cm give over-estimated scour depth more than those with a width equal to 2 cm. Finally, the FDOT method, generally, gives an under-estimated value with a maximum absolute value equal to 2 cm.

The FDOT equation consistently over-estimated scour depths by a large margin (>100%) for the large-scale model. However, the HEC-RAS estimates were closer, with the CSU equation performing better than the Froehlich equation (30–40% vs., 60–90%, respectively) (Fig. 9 and Table 2). Figure 10 shows the error value in calculating scour depth using the HEC-RAS equations to compare the experimental and the empirical results concerning dimensionless of (D/y_1), which shows that HEC RAS equations give an over-estimated value where the maximum absolute error is 12.6 cm corresponding to the Froehlich equation. Furthermore, the CSU equation recorded scour depth almost to the experimental value with an error equal to 4.5 cm. Finally, the FDOT method, generally, gives a huge-estimated value with the maximum absolute error value of 17.7 cm.

6. CONCLUSIONS

An accurate, safe and efficient bridge pier design is associated directly with calculating the local scour depth around bridge piers. Therefore, this project compares the bridge scour depth calculation results with a one-dimensional

Table 2. The measured and estimated scouring depth for the large-scale model S, for the square nose pier

Cases	Pier cross section	Exp.	CSU (HEC-RAS)	FRO (HEC-RAS)	FDOT (Mathematical)
1	20 × 20 cm S	12.9	18.84	25.58	30.51
2	20 × 20 cm S	15.5	20.17	26.12	31.54
3	20 × 20 cm S	13.2	19.6	25.75	30.82
		15.4	19.85	25.804	30.82
		12.9	19.65	25.7	30.82
4	20 × 20 cm S	15.5	21.1	26.1	31.68
		17	21.21	26.25	31.68
		15.5	21.03	26.15	31.68

hydraulic model HEC-RAS and the mathematical model FDOT employing the large and small-scale physical models as a benchmark data input. The close agreement between the calculated and measured methods confirms that the HEC-RAS software is an effective technique for calculating scour depth around bridge piers which can be used to estimate pier scour with different shapes, dimensions, geometries, and different flow regime conditions, especially when employing the CSU equation because it infrequently predicts under-estimation of the scour depth. The FDOT methodology obtains under-estimation scour depth when the small-scale model data is employed while achieving over-estimation scour depth values corresponding to the extensive model input data. In contrast, the FRO equation obtains higher results, mainly when applied to large pier cross-sections.

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