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Article

HEC-RAS simulation of scour in circular piers using a sediment transport demonstration channel

Simulación con HEC-RAS de la socavación en pilas circulares empleando un canal de demostración de transporte de sedimento

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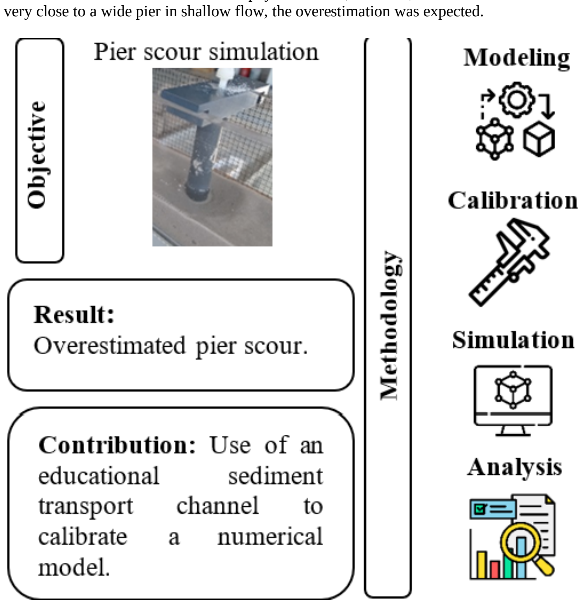
Abstract

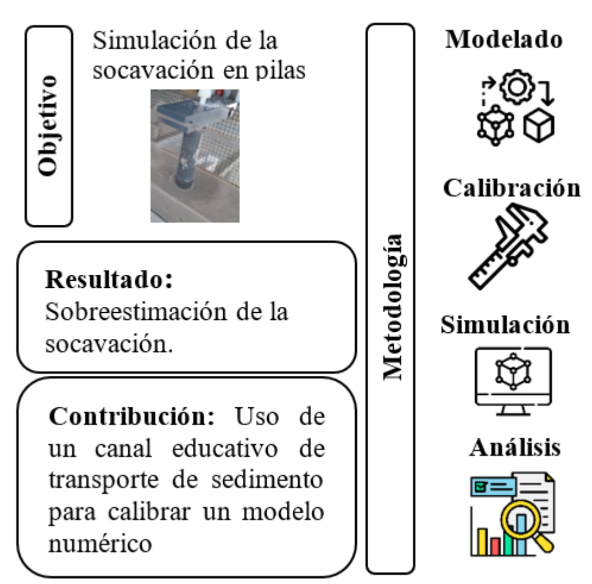
Intending to take advantage of the implementation of two very affordable resources, a sediment transport demonstration channel for teaching and a very versatile open-source software (HEC-RAS), the present work develops the numerical simulation of the scour in a circular pier. The numerical modeling (HEC-RAS) was calibrated with the tests of the physical model (sediment transport demonstration channel). The reduced dimensions of the channel limited the number and precision of the tests; however, they were sufficient to provide the information required by the numerical model. The work details the physical and numerical modeling in such a way that a clear and simple guide is obtained, to simulate the scour of piers in bridges. The result obtained in the first instance exceeds the scour of the physical model, however, due to the simulated conditions, very close to a wide pier in shallow flow, the overestimation was expected.



Bridge, Calibration, Numerical modeling

Resumen

Con el objetivo de aprovechar la implementación de dos recursos muy asequibles, un canal de demostración de transporte de sedimento para docencia y un software de acceso libre muy versátil (HEC-RAS), el presente trabajo desarrolla la simulación numérica de la socavación en una pila circular. El modelado numérico (HEC-RAS) y se calibró con los ensayos del modelo físico (canal de demostración de transporte de sedimento). Las dimensiones reducidas del canal limitaron el número y la precisión de los ensayos, sin embargo, resultaron suficientes para brindar la información requerida por el modelo numérico. El trabajo detalla el modelado físico y el numérico, de tal forma que, se obtiene una guía clara y sencilla para simular la socavación de pilas en puentes. El resultado obtenido en una primera instancia supera a la socavación del modelo físico, sin embargo, por las condiciones simuladas, muy cercanas a una pila ancha en flujo somero, era de esperarse la sobreestimación.



Puente, Calibración, Modelado numérico

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Introduction

"Scour is a natural phenomenon caused due to the erosive action of flowing stream on alluvial beds which removes the sediment around or near structures located in flowing water. It means the lowering of the riverbed level by water erosions such that there is a tendency to expose the foundations of a structure. It is the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around the piers and abutments of bridges" (Khwairakpam and Mazumdar, 2006).

Thanks to this, there are many methods for calculating this phenomenon; however, most of these are based on data obtained in the laboratory, so they only manage to obtain an estimate of the scour depth, and none is completely accurate due to the variability of conditions in each case. Most authors agree that the variables that influence the local scour phenomenon of bridge piers in order of importance are the transverse dimensions of the pier, the speed of the current and its depth, and finally the granulometry of the material in the channel.

The relevance of calibration in the accuracy of numerical simulations is implemented in the present study using a sediment transport demonstration channel. The peculiarity lies in the limitations of the channel's small dimensions. However, the aim is to demonstrate the efficiency and contribution of a teaching channel to numerical modeling.

The research is presented under the following scheme. In the Physical Modeling section, the characteristics of the sediment transport demonstration channel and the circular pier used are described. The software used, the calculation equations, the boundary conditions, and the selection of parameters for setting up the model are presented in the Numerical Modeling section. In the Simulation section, the values are presented and analyzed. Finally, in Conclusions, the most relevant results are summarized and opportunities for improvement are defined.

Physical Modeling

The tests were carried out in the Hydraulics laboratory of the University of Guanajuato, Celaya-Salvatierra Campus.

Sediment transport demonstration channel.

The main characteristics of the Sediment transport demonstration channel are listed below as mentioned by the manufacturer, Armfield. These characteristics can be seen in Figure 1, as well as in the rest of the channel figures presented in the document.

- A transparent, inclinable flow channel through which water can be recirculated by a pump over a mobile bed to demonstrate the whole range of bedforms from incipient particle movement to bed washout.
- Three different discharge rates can be selected and measured within the range of 0.2 to 0.6 liters/sec.
- The channel slope can be adjusted within the range of 0-10%.
- The working section of the channel is 1.55m long, 78mm wide, and 110mm deep.
- The equipment is self-contained and may be bench-mounted in either the classroom or laboratory by virtue of its portability.
- A model undershot weir and bridge pier are included for local erosion demonstrations.
- A water level gauge is supplied to calibrate the overshot weir.

The original slope adjustment mechanism, consisting of a fine screw jack to which an accurate slope indicator is attached, was replaced by an automatic system (GUTIERREZ-VILLALOBOS, et al., 2022).

Box 1

Figure 1
Sediment transport demonstration channel
Source: Own elaboration

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Sediment

A 2.5 cm thick sediment bed was placed using the sediment included with the channel (Figures 2 and 3).

Box 2

Figure 2
Sediment placement

Source: Own elaboration

The sediment was characterized by the sieving granulometric method. According to the granulometric curve presented in Figure 3, the characteristic diameters $D10$, $D30$, and $D60$ have a value of 0.224, 0.265, and 0.328, respectively. While the uniformity coefficient, Cu, has a value equal to 1.464 (Equation 1) and the curvature coefficient, Cc, of 0.956 (Equation 2). Therefore, the sediment is classified as poorly-graded sand (SP).

$$Cu = \frac{D_{60}}{D_{10}} = 1.464 \tag{1}$$

$$Cc = \frac{{D_{30}}^2}{D_{60}D_{10}} = 0.956 \tag{2}$$

Box 3

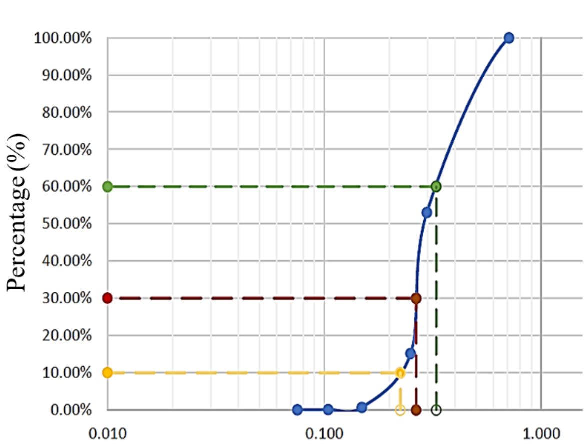

Figure 3
Granulometric curve

Source: Own elaboration

Pier

The study scenario was established with the bridge pier included with the channel. The pier has a diameter of 2 cm and is fixed through a support which in turn is anchored to the top of the channel walls as shown in Figure 4.

As for the length of the channel, the pier was placed 80 cm from the inlet, which corresponds to 30 cm within the gridded area (0.5 x 0.5 cm) for monitoring (Figure 4).

While, regarding the cross-section of the channel, 7.8 cm wide, the pier was placed in the center.

Channel slope (S) and flow rate (Q)

Based on several preliminary tests, where intense erosion was observed, the minimum possible slope and flow rate were established as a test scenario. These being, $S = 0.1\%$, and $Q = 0.00035\ m^3/s$ (0.35 liters/seconds).

Box 4

Figure 4
Scouring process

Source: Own elaboration

Physical Modeling Result

Figure 4 shows the scour process while Figure 5 shows the final scour. The scour diameter runs from wall to wall in the cross-section and longitudinally is 8 cm, slightly greater than the channel width (7.8 cm). The scour depth at the foot of the pier (maximum depth) was 2 cm. It should be noted that the final scour condition was established shortly (less than one minute) after the flow stabilized.

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Box 5

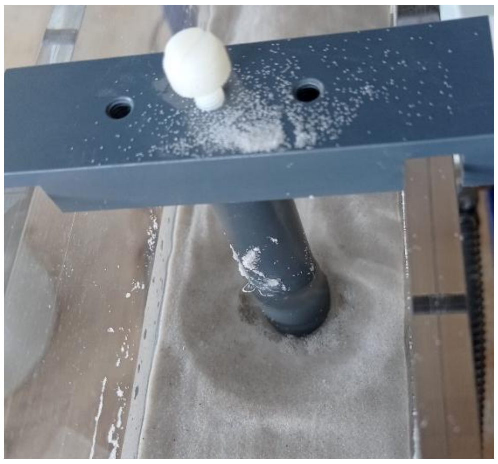

Figure 5
Resulting scour
Source: Own elaboration

Numerical Modeling

HEC - RAS (Hydrologic Engineering Centers River Analysis System) is a hydraulic modeling software that, through the one-dimensional steady flow computation component, determines water surface profiles for steady and gradually varying flow. The system can handle a complete channel network, a dendritic system, or a single river reach. The steady flow component is capable of modeling flow surface profiles in subcritical, supercritical, and mixed regimes. The basic computational procedure is based on the solution of the one-dimensional energy equation (Brunner, 2022).

This software, in addition to being able to simulate floods (CHÁVEZ-CÁRDENAS, et al., 2022) and perform sediment transport analysis, also computes scour in bridge piers (Cordova Bances, 2024).

However, to compute scour at bridges, it is necessary to develop a hydraulic model and this model in turn requires geometric and channel flow data.

Geometry

The channel was modeled keeping the width of 7.8 cm; however, the length was increased by 1 m concerning the sediment transport demonstration channel, 50 cm upstream and 50 cm downstream of the pier, with the sole intention of keeping possible calculation fluctuations away from the area of interest.

Twenty-seven cross sections were defined, spaced every 10 cm, except for the 4 mandatory sections for the correct hydraulic modeling of the bridge (Figure 6). These four cross sections are separated by 0.85 cm, 0.3 cm, and 0.85 cm in the flow direction.

Flow

The flow condition necessary to implement the scour calculation is permanent. Therefore, $Q = 0.00035\ m^3/s$ was established, using the depths recorded at the beginning and end of the channel as a boundary condition.

Hydraulic design- Bridge scour

To use the *Hydraulic design- Bridge scour* module, it is necessary to run the permanent flow simulation by activating the flow distribution option, subdividing the cross-section, and computing the hydraulic information for each slice, thus allowing determining the scour with greater precision along the cross-section. For this study, the cross-section was divided into 8 slices.

Box 6

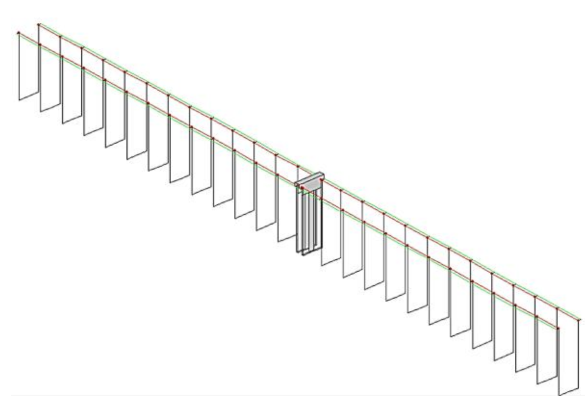

Figure 6
Profile perspective
Source: Own elaboration

Simulations

To calibrate the model, various simulations were carried out to finally achieve the scour obtained with the physical model.

The calibration work focused on finding the values for the energy loss coefficients, due to friction (Manning's n) and those related to the pier. Therefore, a first analysis was carried out without sediment and then with sediment.

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Without sediment

To find Manning's n the following procedure was performed without the pier.

Since the numerical model does not consider the falling discharge as in the sediment transport demonstration channel, a supercritical flow condition is established, thus ensuring that uniform flow is achieved, a condition that is used as a boundary condition.

A slope high enough to guarantee supercritical flow was established (S=1.5%), finding in the numerical model that n=0.01 is the value with which the same depth recorded in the channel was obtained.

Once Manning's n was known, the pier was placed and the bridge model was configured, selecting the energy, momentum, and Yarnell methods for low flow, indicating that the highest energy answer should be considered. It should be noted that the drag coefficient was set at 1.2 and the pier shape coefficient at 0.9. On the other hand, for high flow, the Energy Only option was chosen.

With this configuration, the computed depths before and after the pier were 1.9 cm and 1.4 cm, respectively (Figure 7), which are acceptably close to those recorded at the channel (Figure 8).

Box 7

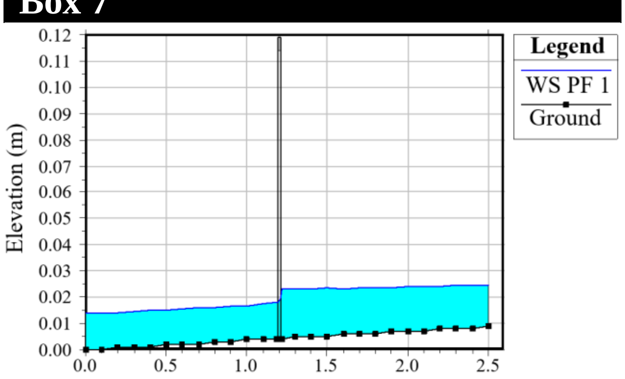

Figure 7
Numerical simulation, without sediment, but with pier (WS= water surface)
Source: Own elaboration

Box 8

Figure 8
Physical simulation, without sediment, but with pier
Source: Own elaboration

With sediment

Finally, the test scenario was simulated with the physical model ($S = 0.1\%$ and $Q = 0.00035\ m^3/s$).

After some tests and starting from the known value of Manning's n for the condition without sediment, it was found that with sediment n is equal to 0.015.

The Hydraulic design- Bridge scour module automatically loads the maximum water depth and velocity obtained from the hydraulic model. While the shape ($K1$), width (a), and length (L) of the pier are taken from the geometric data of the bridge. It is up to the user to choose between the Colorado State University (CSU) equation (Richardson, et al, 1990) or the Froehlich (1988) equation for the scour computation.

Regardless of the method chosen, the $D50$ is required. The CSU equation is the default. The user is only required to enter the pier nose shape, the angle of attack for flow hitting the piers (α), the condition of the bed ($K3$), and a $D95$ size fraction for the bed material. On the other hand, when selecting the Froehlich equation, the only value that is required is the projected pier width with respect to the direction of the Flow (a^*) and is calculated with equation 3.

$$a^* = a\ cos\alpha + L\ sin\alpha = 0.02\ m \tag{3}$$

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$D50$ and $D95$ were obtained from the granulometric curve (Figure 3), being 0.28 mm and 0.6 mm, respectively. Clear water scour corresponds to $K3$.

The result was very similar using the CSU or Froehlich equation. The scour depth (Y_s) was equal to 0.03 m and the diameter was 0.1 m, see Figure 9. Compared to the result of the physical model, the scour was greater (0.03 m > 0.02 m and 0.1 m > 0.08 m).

In order to adjust the results of the numerical simulation to those of the physical simulation, a factor (K4) of 0.6 was applied to reduce the scour, as shown in Figure 10. In this way, the scour coincides with the maximum depth, $Y_s = 0.02$ m, while the diameter slightly exceeds the width of the cross-section, resembling that presented in Figure 5.

Box 9

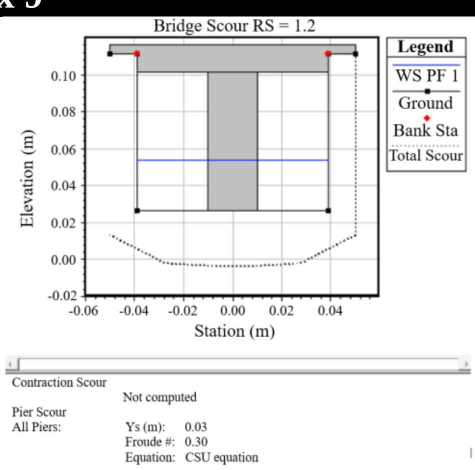

Figure 9
Pier scour computed with CSU equation
Source: Own elaboration

Box 10

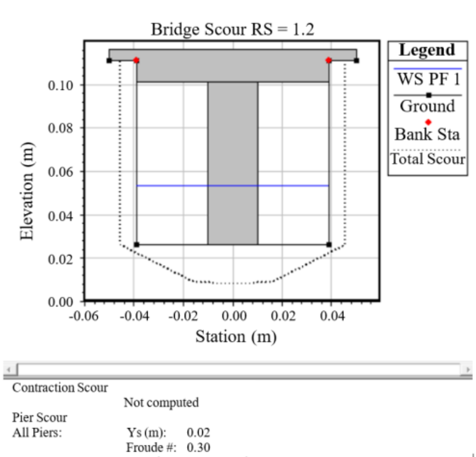

Figure 10
Pier scour computed with CSU equation and affected by a factor to decrease scour depths
Source: Own elaboration

Conclusions

The objective of simulating scour in a circular pier using HEC-RAS was met. However, the direct result overestimated scour, because the evaluated scenario approximates the condition of wide pier in shallow flow, it has been identified that in this condition there are equations, including the CSU equation, that overestimate scour depth. (Arneson, et al., 2012).

Combining a tool as versatile as HEC-RAS with a channel that is primarily educational can, despite its limitations, especially in terms of size, enhance research studies.

To complement the present study, it would be worthwhile to carry out further tests with different flow rates and pier shapes to define the scenarios that require adjustment in the calculated scour and to normalize the adjustment factors.

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Chávez-Cárdenas, Xavier: Contributed to the project idea and research method. He supported the design of the physical and numerical models. He carried out the analysis of data and results, as well as writing the article.

Gutiérrez-Villalobos, José Marcelino: Implemented an automatic control system for the channel slope and contributed to data acquisition.

Moralez-Garibay, María Cristina: Supported the physical model design, and characterized the sediment. She also contributed to the writing of the article.

Availability of data and materials

All data presented in this research are of own elaboration.

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Abbreviations

CSU	Colorado State University
HEC-RAS	Hydrologic Engineering Centers River Analysis System
WS	Water Surface

References

Antecedents

Froehlich, D.C., (1988). Analysis of Onsite Measurements of Scour at Piers. Proceedings of the ASCE National Hydraulic Engineering Conference, Colorado Springs, CO.

Khwairakpam, P. and A. Mazumdar (2006). Local Scour Around Hydraulic Structures. International Journal of Recent Trends in Engineering, 1(6).

Richardson, E.V., D.B. Simons and P. Julien, (1990). Highways in the River Environment, FHWA-HI-90-016. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Basics

Brunner, Gary W. (2022). HEC-RAS Hydraulic Reference Manual. US Army Corps of Engineers, Version 6.0.

CHÁVEZ-CÁRDENAS, X., ARROYO-CHAVEZ, H., GUTIERREZ-VILLALOBOS, J. M., & MORALEZ-GARIBAY, M. C. (2022). Preliminary assessment of the risk of river overflow in the presence of a bridge using HEC-RAS and LiDAR topography. Journal of Research and Development, Vol. 8, No. 22, pp. 23-30.

GUTIERREZ-VILLALOBOS, J. M., MARTÍNEZ-CENTENO, J. M., CHÁVEZ-CÁRDENAS, X. and TALAVERA-VELÁZQUEZ, D., (2022). Control system for automation of a didactic testbench water canal. Journal Civil Engineering, Vol. 6, No. 15, pp. 1-6.

Supports

Arneson, L. A., Zevenbergen, L. W., Lagasse, P. F., & Clopper, P. E. (2012). Evaluating scour at bridges (No. FHWA-HIF-12-003). National Highway Institute (US).

Discussions

Cordova Bances, G. (2024). Estimación de la socavación en las pilas del puente del río Yuracyacu en Nueva Cajamarca. UNAM.
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