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Evaluating Various Factors in Calculation of Scour Depth around Bridge Piers using HEC-RAS Software, CSU2001 and Froehlich Equations

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ABSTRACT: Today, scour is one of the important issues in river and coastal engineering science. Most of the existing structures exposed to the flowing water are destroyed by this phenomenon. Determining relationship between parameters influencing scour depth and maximum depth of scour, and also finding dominant function of them is one of the important issues in hydraulic engineering. Many equations and software have been presented by researchers to calculate local scour, such as Hec-Ras software. Ignorable errors of this software in vitro test make it one of the nominated options in evaluating local scour depth. Hec-Ras software uses CSU and Froehlich equations to calculate local scour. In this study, software output and manual calculation output of CSU and Froehlich equations were compared. Results of empirical equations and Hec-Ras in the scattering length of Haraz River were compared with each other to create equal hydrological and hydraulic conditions. Reviewing the Froude number, its measurement, and the effective coefficients of common empirical equations and software has significant effect on changes of these parameters in the results. The study also indicate that equations used in Hec-Ras will have acceptable results if their coefficients are examined with sufficient engineering , accurate perspective and controlling use or non-use of coefficients in ranges closer to the defined boundary.
Keywords: Local Scour, Empirical Equations Of Local Scour, Froude Number, Bridge Pier, Hec-Ras

INTRODUCTION

Scour is a phenomenon which occurs due to water flow in rivers and streams. Determining scour depth is important because it represents flow demolition potential around the structure and plays key role in designing foundation of structures exposed to treated water.

Bridges are one of the main river structures with significant role in road construction. Every year, many bridges are damaged due to the scour after flood, which represents the importance of study to estimate scour depth in bridge pier. The main vortex system is formed by flow collision to the forward and its deviation to down (Figure1).

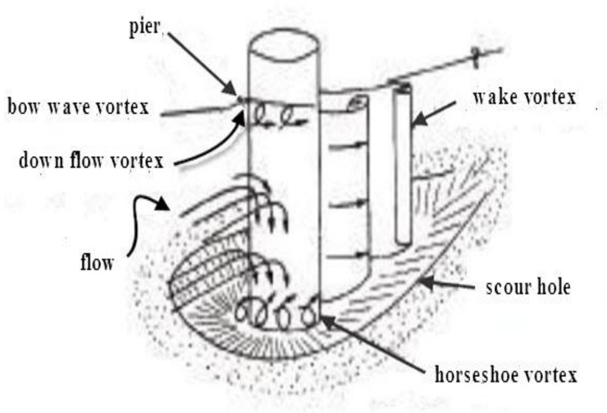

Figure 1. downstream flow and vortex system around cylindrical bridge pier.

Reviewing evidences indicates that most of the bridges are destroyed by scour or other hydraulic factors. For instance, during last 30 years in USA, one in a thousand of the 500,000 bridges constructed on the rivers are destroyed, 60% of which is due to the scour, while, the share of earthquake in these destructions is only 2%. Ghalardi (2004) evaluated long-term bridge pier scour with adhesive soil. EFA/SRICOS and Hec-Ras software were used to calculate the bridge pier scour, and EFA/SRICOS indicate scour depth more than Hec-Ras (Ghelardi, 2004).

Azizian et al (2010), evaluated bridge pier scour using HEC-RAS 4.0 numerical model and empirical results. Results of numerical model represent that in discharges with larger return period, scour increases, especially in lateral piers of the bridge, due to the increasing discharge and flow velocity and also increasing vortex flow around bridge pier. Although in some cases HEC-RAS model estimate the scour more than in vitro model, but in general results of both models are in good agreement, therefore, the model can be used in bridge studies and designs to evaluate accurate amount of scour and depth or bridge pier placement (Azizian et al., 2010).

Sheikh al-Eslami et al (2010) estimated scour depth around bridge pier using FASRET mathematic model. To calculate scour depth, 16 empirical equations were added to the model as a sub-program. Result of their study indicate Froehlich (1988) and Johnson (1995) equations are more accurate than other relations, and equations of Jin Fisher (1977), Melvil (1977), and

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Melvil and Saterland (1988) evaluated scour depth considerably more than other equations (Sheikh al-Eslami et al, 2010).

Apaydin M. (2010) evaluated vulnerable bridge scour risk. In the study, Hec-Ras software was used to study local scour; otherwise, with sufficient data, HYRISK software can be used to calculate annual scour risk and bridge destruction. Results of the study indicate appropriate sensitivity of Hec-Ras software in calculating scour (Apaydin, 2010).

The importance of determining scour depth is because it indicates flow destruction potential around the structure, and play significant role in designing foundation of structures that are exposed to water treat.

If the pier is vertical to the river bed, water flow creates instability and a series of vortex streams. These vortex systems are considered as the main mechanism of scour which create hole in bridge pier in long term and may lead to collapse of bridge.

According to the type of pier and flow condition, vortex system can be a combination of the following systems:

- Horseshoe vortex system
- Grooved or rising vortex system
- Trailing vortex system
- Downward vortex system
- Bow wave vortex system (Ministry of energy, 2011).

MATERIALS AND METHODS

Hec-Ras software was developed by U.S. army corps of engineering and is widely used by engineers all around the world. In 2006, simulation and sediment transferring capability was added to it. Hec-Ras is a set of different numerical models designed to be used in multi-purpose problems. The software includes a graphic user link. Final version of the software include three one-dimension hydraulic analysis parts:

1) calculation of permanent flow water level profile,

2) simulation of non-persistent flow, and

3) simulation of sediment transfer along with bed changes.

The current version of the software (late 2009), is able to simulate permanent, non-persistent and quasi non-persistent flow, and model sediment transfer and bed changes. Therefore, the software can be used to investigate the scour more proper than previous versions. The software is able to model current networks and simulate different structures in flow path such as culvert, bridge and tank. Dominant hypothesis on this model is like HEC-2 model, except that this model is able to simulate the flow in non-persistent condition. Furthermore, the software is able to simulate under-critical and super critical flow or a combination of them.

To analyze bridge pier scour, first a hydraulic model of river spans on which the bridge is placed should be developed. This model should include cross-sections in downstream of the bridge, so that the downstream boundary condition defined by the user does not affect the results of the hydraulic bridge just upstream it. However, to evaluate the long-term effects of bridge on water level profile in upstream, model should include some cross-sections in bridge upstream. If observable data are not provided, the model should be calibrated as much as possible. After calibration of hydraulic model, in the presence of observable data, design events required to scour analysis may be entered. In general, design event (design discharge) for scour analysis is usually 100 years (with 1% probability). Moreover, it is suggested to use a 500 year discharge (with 0.2% probability) to evaluate the bridge foundation in great flood condition (HEC_RAS, 2010).

Evaluating local scour in bridge pier:

Bridge pier scour can be calculated by CSU equation of Colorado state university (Richardson et al., 1990). The equation is a default of Hec-Ras. Another equation has been presented by Froehlich to be used in scour evaluation, instead of CSU. CSU and Froehlich equations have been discussed as follow:

$$\frac{d_s}{y} = 2k_1k_2k_3k_4\left(\frac{b}{y}\right)^{0.65} F_r^{\,0.43} \qquad (1)$$

Where, k_1 is correction factor for the bridge deck shape (ranged between 0.9-1.1), k_2 is the correction factor of flow hit angle with bridge pier, calculated as:

$$k_2 = (\cos\theta + \frac{1}{b}\sin\theta)^{0.65} \qquad (2)$$

Where, L: bridge pier length in flow path, θ: flow hit angle to bridge pier, if L/a>12, the model considers 12 as its maximum, and if θ>5, model considers 1.0 for k_2, k_3: correction coefficient of bed, k_4: coefficient used when a cover layer is formed on scour hole, b: bridge pier width, and Fr: Froude number in bridge pier upstream.

Bridge pier scour is calculated by Froehlich formula as:

$$d_s = 0.32\phi(b')^{0.62} y^{0.47} Fr^{0.22} D_{50}^{-0.09} + b \qquad (3)$$

Where, b: pier width (m), y: flow depth in pier upstream (m), D_{50}: average diameter of bed particles (m), L: pier length (m), and Fr: Froude number of pier upstream, d_s: scour depth (m), ϕ: correction coefficient of bridge pier form, varying from 0.7-0.31 according to bridge pier form. b`: considers the effect of pier and water hit the pier, and is calculated as (Brunner,2010):

$$b' = (b\cos\theta + L\sin\theta) \qquad (4)$$

CSU equation of the software is used after every editing the software and its final version is CSU2001 equation. The equation have been edited four times from 1975-2001.

Haraz River

Mazandaran province, due to its specific climate is having numerous rivers. One of the important rivers is Haraz River. Haraz River originates from Lar and passes through Amol City and leads to the Caspian Sea. It is a permanent river in Mazandaran province around Nour and Amol city. Its length is 185 km, its origin height is 3450 m, outfall height is 25 m and average river slope is 1.9%. River was first directed to east, and then changed to north. According to the statistics of Kharsang, the mean annual discharge of the river is 1150 million m^3 [6]. Study area of this paper include ZiarYagh, Ab Ask and Bayjan bridges located in 92+395, 83+166.5, and 62+322 km of Haraz river, respectively (Haraz Rah advisory co, 2009-2010)

Modeling process of three bridges in Hec-Ras is similar and flood discharge of design is equal for three bridges, because they are in one direction. The bridges are located on the main branch of the Haraz River along with each other. Return periods of 2, 5, 10, 20, 50 and 100 years are equal to 97, 158, 205, 253, 321, and 375 m^3/s, respectively.

In this study, first the water level profile and scour depth was modeled using required hydraulic and hydrological data of Hec-Ras. Then, Hec-Ras output was evaluated according to the Froude number and depth and flow rate taken from water level profile model, and using identical empirical equations and Hec-Ras results.

Cross-sectional data extracted using topographic maps in AutoCAD land. After preparing topographical maps, cross-sections in river upstream and downstream was created and cross-sectional data, including main water channel and numerical cross-sectional data, were extracted and entered to Hec-Ras.

Hec-Ras input data include not only cross-sectional data, but bed slope as border data, Manning coefficient, discharge with different return periods, expansion and contraction coefficient and geometric characteristics of bridge. In this paper, according to executive maps, data extracted and geometric data of bridge were entered to Hec-Ras, then, after entering consistent flow data, scour was modeled by HEC-RAS .

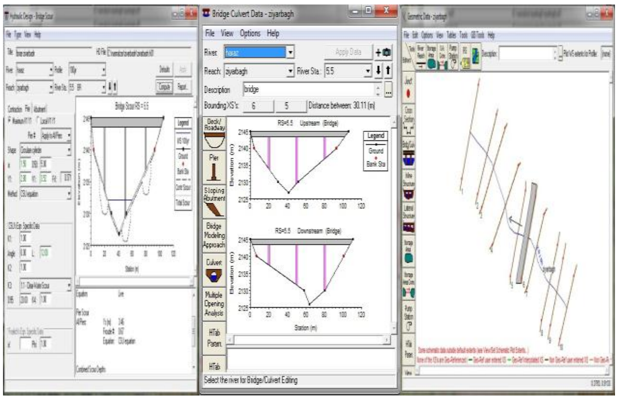

Figure 2. schematic plan of river, bridge and scour depth.

Scour modeling by empirical equations

CSU and Froehlich equations are selected as the calculation base of scour in Hec-Ras. Flow depth and velocity are used in Hec-Ras as the results of water level profile. Froude number of these bridges is studied in both trapezoidal and rectangular modes using empirical equations with 6 return periods.

Table 1. Empirical equations of bridge pier local scour calculation.

d_s	CSU 2001 Ziarbagh	Froehlich Ziarbagh	CSU 2001 Ab ask	Froehlich Ab ask	CSU 2001 Bayjan	Froehlich Bayjan
d_s (Q100)	3.737	2.525	3.504	2.551	4.523	2.5
d_s (Q50)	3.649	2.494	3.394	2.511	4.412	2.458
d_s (Q20)	3.518	2.447	3.23	2.453	4.177	2.39
d_s (Q10)	3.57	2.43	3.094	2.404	3.926	2.3
d_s (Q5)	3.272	2.364	2.932	2.346	3.798	2.276
d_s (Q2)	3.062	2.285	2.632	2.244	2.721	2.228

Table 2. scour depth for trapezoidal and rectangular waterways with different discharges in Ziar Bagh bridge.

ZiarBagh	CSU (HEC-RAS)	Froehlich HEC-) (RAS	CSU2001 (Fr trapezoid)	Froehlich (Fr trapezoid	CSU2001 (Fr rectangular)	Froehlich rectangular) (Fr
ds(Q100)	3.46	2.49	3.737	2.525	3.456	2.486
ds(Q50)	3.39	2.46	3.649	2.494	3.389	2.456
ds(Q20)	3.28	2.41	3.518	2.447	3.285	2.415
ds(Q10)	3.18	2.38	3.57	2.43	3.184	2.378
ds(Q5)	3.06	2.34	3.272	2.364	3.056	2.339
ds(Q2)	2.88	2.26	3.06	2.36	2.881	2.3

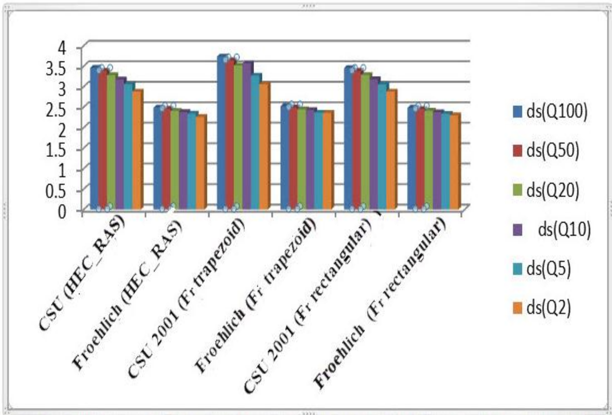

Figure 3. scour depth for trapezoidal and rectangular waterways with different discharges in Ziar Bagh bridge.

Table 3. scour depth for trapezoidal and rectangular waterways with different discharges in Ab Ask bridge.

Ab Ask	**CSU (HEC -RAS)**	**Froehlich (HEC-RAS)**	**CSU2001 Fr trapezoid**	**Froehlich trapezoi Fr d**	**CSU2001 Fr rectangular**	**Froehlich rectangula Fr r**
ds(Q100)	3.36	2.53	3.504	2.551	3.356	2.527
ds(Q50)	3.26	2.49	3.394	2.511	3.263	2.491
ds(Q20)	3.11	2.44	3.23	2.453	3.107	2.437
ds(Q10)	2.99	2.39	3.094	2.404	2.995	2.389
ds(Q5)	2.84	2.33	2.932	2.346	2.837	2.331
ds(Q2)	2.56	2.23	2.632	2.244	2.564	2.235

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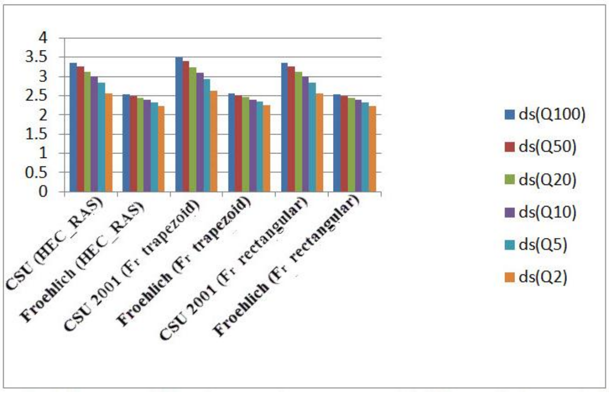

Figure 4. scour depth for trapezoidal and rectangular waterways with different discharges in Ab Ask bridge.

Table 4. scour depth for trapezoidal and rectangular waterways with different discharges in Bayjan bridge.

Bayjan	CSU (HEC-RAS)	Froehlich (HEC-RAS)	CSU2001 (Fr trapezoid)	Froehlich trapezoid Fr)	CSU2001 (Fr rectangular)	Froehlich (rectangular Fr)
ds(Q100)	4.4	2.49	4.523	2.5	4.407	2.486
ds(Q50)	4.28	2.44	4.412	2.458	4.277	2.442
ds(Q20)	4.09	2.38	4.177	2.39	4.087	2.38
ds(Q10)	3.93	2.33	3.926	2.3	3.927	2.329
ds(Q5)	3.72	2.27	3.798	2.276	3.716	2.268
ds(Q2)	2.65	2.22	2.721	2.228	2.655	2.219

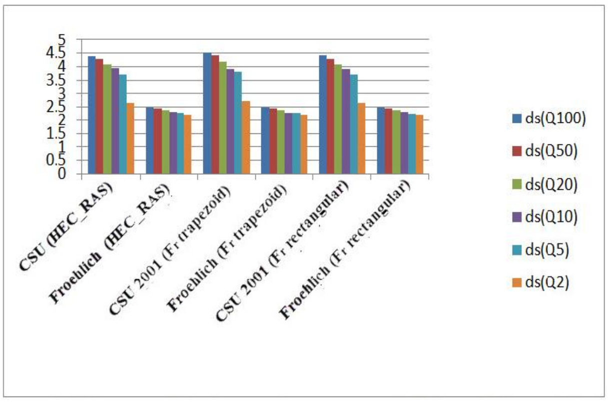

Figure 5. scour depth for trapezoidal and rectangular waterways with different discharges in Bayjan bridge

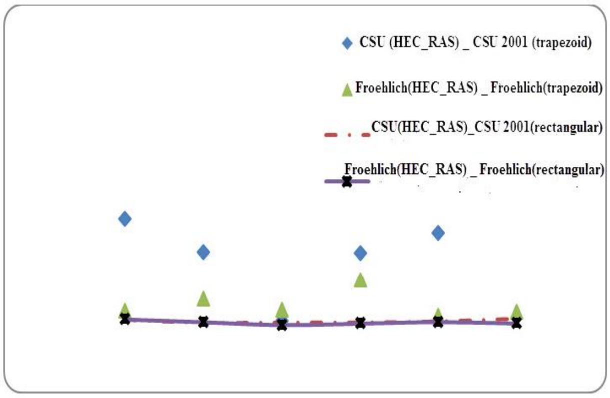

Figure 6. relative error of empirical methods to Hec-Ras in Bayjan bridge.

RESULTS AND DISCUSSION

Carefully observing the figures and tables indicate that scour depth will increase with discharge, and the maximum scour belongs to CSU method. The minimum error belongs to the Froude number calculation method in rectangular model. Therefore, it can be inferred that Hec-Ras software uses rectangular model to evaluate Froude number and scour depth.

Results of CSU2001 and Hec-Ras comparison indicate the equation used in Hec-Ras can be suitable to achieve scour depth, since one-dimensional modeling of water level profile along the flow is not far away from the reality, and the river flow is mostly longitudinal along the slope. Hec-Ras software with csu2001 equation as the default, models the scour depth after receiving input parameters, analyzes the permanent flow based on accuracy of modeling, draws water level profile, and extracts results such as Froude number, velocity and depth.

Based on the instruction of the software, it was observed that empirical equation used in Hec-Ras 4.1 default, is csu2001, but in calculation of local scour, there is no icon for correction coefficient of kw, and there is no comment about it in instruction of Hec-Ras4.1 software and is referred to instruction of Hec-18 software. Finally, it was clear that this coefficient should be combined to one of the three correlation coefficients, and this combined coefficient should be placed in the desired icon to be used in local scour calculation of the software. In empirical equations of this factor, if the flow depth/bridge pier thickness is less than 0.8, then the correction factor should be used. But in software instruction, if the flow depth/bridge pier thickness is less than 0.8, and the thickness of bridge/d50 is larger than 50, then this correction factor is calculated and used in calculation of local scour depth of bridge pier.

CSU2001 is applicable in calculation of live bed scour and pure water scour; on the other hand, CSU2001 responses give larger numbers than Froehlich equation that considers a certainty coefficient. These can be reasons of usingCSU2001 as the default of Hec-Ras software.

This equation, regardless of its completeness than other equations, should be considered with engineering view and necessary reviews should be done about boundary of determined ranges for these coefficients, otherwise, results will have many errors and investigating the study show that after preparing water level profile, etc. scour depth can be calculated manually and more controlled results achieve. Bridge pier scour, regardless of many equations, may need new, controlled and modified equations or coefficients.

CONCLUSION

- CSU2001 is the default equation of Hec-Ras
- CSU2001 give numbers larger than Froehlich equation, and is considered as a certainty coefficient because of complexity of scour and its dependency to many hydraulic parameters, etc.
- Comparing Hec-Ras output based on CSU, Froehlich equations and manual output of the equations indicate that software default for evaluating Froude number is

based on rectangular channel, while Froude number should be calculated based on main form of the channel.

- Based on HELP of Hec-Ras software, range of correction factor of k_4 is:

If D50<2mm, or D95<20mm, then $k_4=1$, otherwise, correction factor of k_4 should be calculated before using in the equation. During modeling, it was observed that k_4 correction factor range is different: if $D_{50} \leq 2$mm, and $D_{95} \leq 20$mm, then $k_4=1$, otherwise it should be calculated before using in the equation.

- To use Hec-Ras software, not only it is required to learn the software, but sufficient engineering view is needed to prevent error in calculated output of correction coefficients (for instance, k_w).

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