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A Probabilistic Quantile Regression-Based Scour Estimation Considering Foundation Widths and Flood Conditions

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Abstract: Scour has been widely accepted as a key reason for bridge failures. Bridges are susceptible and sensitive to the scour phenomenon, which describes the loss of riverbed sediments around the bridge supports because of flow. The carrying capacity of a deep-water foundation is influenced by the formation of a scour hole, which means that a severe scour can lead to a bridge failure without warning. Most of the current scour predictions are based on deterministic models, while other loads at bridges are usually provided as probabilistic values. To integrate scour factors with other loads in bridge design and research, a quantile regression model was utilized to estimate scour depth. Field data and experimental data from previous studies were collected to build the model. Moreover, scour estimations using the HEC-18 equation and the proposed method were compared. By using the "CCC (Calculate, Confirm, and Check)" procedure, the probabilistic concept could be used to calculate various scour depths with the targeted likelihood according to a specified chance of bridge failure. The study shows that with a sufficiently large and continuously updated database, the proposed model could present reasonable results and provide guidance for scour mitigation.

Keywords: bridge scour; scour estimation; quantile regression; probabilistic model; deterministic models

CLC number: U442.59

1 Introduction

The process of scour around river-crossing bridges is usually affected by extensive potential factors, relating to various research fields. During the past years, interdisciplinary problems are often concerned, which are usually proposed by one project with raw data, while research in other fields provides analytic framework or tools, usually mathematic and statistic concepts, to solve the problem[1-3]. Our study follows this trend to highlight the phenomenon identified as the key factor that causes bridge failures[4-6], and the statistic analytic method, namely quantile regression. Caused by the erosion process during scour, the scour hole that has a great impact on the bearing capacity of bridge foundations[7] will be formed. Bridge foundations can be undermined if the scour depth exceeds a threshold as shown in Fig.1. More than 500 bridges in Georgia has been damaged during floods, and these deficiencies led to approximately $130 000 000 direct losses due to scour[8].

This physical process is related to three main fields: hydraulic engineering, geotechnical engineering, and structural engineering. Furthermore, data analysis becomes important with the increasing number of field measurements. Previous studies show that the development of

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scour is closely associated with foundation width, flow velocity and depth, as well as sediment characteristics. Over the past decades, significant amounts of studies have been carried out on this topic, from macro view and micro view[9-17]. These efforts can be summarized into two categories: 1) the Observation-Driven Approach, which is a preliminary evaluation that connects parameters and scour results qualitatively by observation or simplified geo-hydraulic tests; and 2) the Mechanism-Based Approach, which focuses on the mechanism of scour phenomenon to build a predictive model. As an extension of the Observation-Driven Approach, empiric models[4,8], whose coefficients are usually from data fitting, are incorporated into regional or national design codes because they can provide relatively accurate estimations.

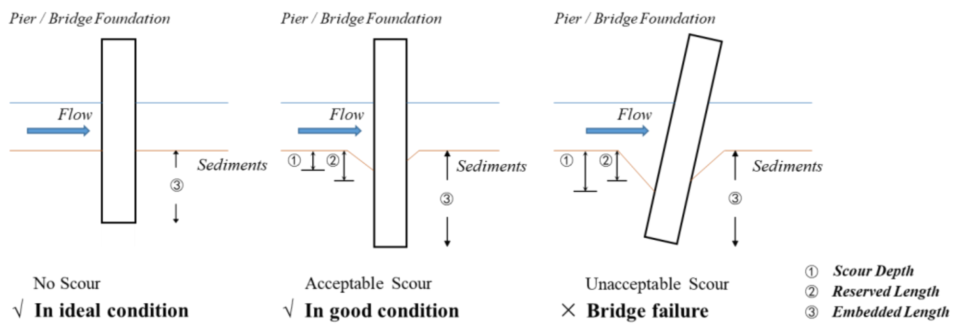


Fig.1 Working conditions and scour status for bridge pier and foundations

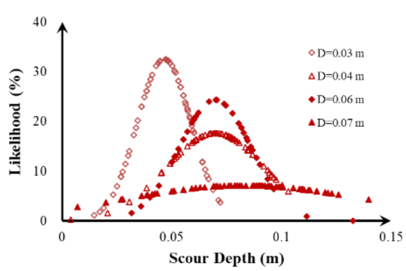
Recently, emerging foundation types and advanced design techniques that are utilized in bridge constructions encourage engineers to build bridges with long span under complex environmental conditions. However, when being applied in the field, existing methods show their deficiencies in accuracy and practicality. First, some of the estimations carried out by current design standards are found to be not accurate enough or invalid when being used in practice[18], especially for wide piers[19]. Second, most of the current estimations provide a deterministic value (e.g., the maximum scour depth), while other loads in bridge design (such as seismic influence and wind impacts) are always regarded as probabilistic values[20]. Recent studies indicate that the influence of scour-related parameters can be analyzed probabilistically[21-23], and AASHTO LRFD bridge design codes have been applied to treat scour probabilistically[24]. However, it is hard for designers to consider the influence of scour with a determined value, while other loads are treated probabilistically.

Similar to pavements, railways, and offshore structures, the design and analysis of geotechnical engineering are also complex, because they employ materials that are heterogeneous, time-dependent, rate-dependent, and anisotropic. The goal of this study is to establish a probabilistic framework based on a quantile regression model and parameter uncertainties for scour design and reduction. First, data were described and preliminarily analyzed, which were collected from previous research and the Nationwide Database. By using the present model, the relationship between scour-related parameters and the maximum scour depth was investigated. Then, the model concept was explained and the relationships between parameters were briefly discussed. Due to the stochastic nature, quantile regression theory was considered as an alternative to the conventional deterministic model and for analyses. With this model, scour depth as well as its probability, rather than a deterministic estimation, could be provided. The model could provide a flexible and powerful tool for designers to address problems related to dispensing rates (either high or low), even in the preliminary stage.

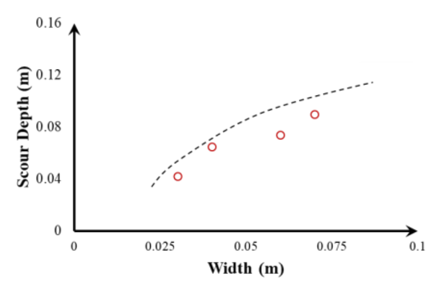
2 Database Used to Develop Probabilistic Quantile Regression-Based Estimation for Bridge Scour

For a typical real-world problem, there are many sources of uncertainties rather than determinate parameters in predicting scour at bridges, such as pier width, flow velocity, and particle size. In addition, even with same parameters, scour depths can be different. For example, the maximum scour depths around two square piers, which are with the same geometry (pier width = 0.29 m; pier length = 7.32 m) under the same flow condition (flow velocity = 0.7 m/s; flow depth = 0.58 m) in one area (median particle size, d_{50} = 0.94 mm), were monitored as 0.21 m and 0.43 m, respectively[25]. When the conditions of prototype are different from those under which the predictive method was proposed and verified, it will provide unreliable results. Different from deterministic methods, a probability framework can become a powerful tool to calculate the likelihood of bridges with different scour depths and probabilities of bridge failure, considering foundation widths and flood events. With this concept, scour depth for various design service period and structure importance can be calculated.

Data acquired from laboratory were analyzed first to confirm the probabilistic pattern of scour depth because the conditions in experiments are simpler than fieldwork. Together with our previous studies which investigated foundations with various arrangements[26], a small database populated by piles with a range of diameters (from 0.03 m to 0.07 m) was built[27-29]. Using normal regression methods, it was confirmed that the scour depth around different foundation widths could be described as probabilistically distributed (Fig.2(a)). Meanwhile, the scour depth with high possibility increased with the foundation width, and the uncertainty of the scour depth also increased under the same condition (Fig.2(b)). The wider the foundation was, the larger the range of the possible equilibrium scour depth would be. It also confirmed that the wider the foundation is, the harder it is to estimate the scour depth accurately.



(a) Probabilistic distribution of scour results



(b) Scour depth with highest likelihood

Fig. 2 Results of scour around foundation models in flume tests

Field data from bridges in sandy riverbed were then collected and analyzed for further investigation. During the past decades, a good deal of field data has been collected[25,30-36], which augments the National Bridge Scour Database of the U.S. In total, 1 343 field measurements were selected as the source database to construct the quantile regression-based model in this study. To fully analyze the raw data and extract practical knowledge, the idea of data mining (DM) was used to divide the process into three steps: 1) data collection and preparation; 2) data transformation and quantile regression; and 3) data mining and weight determination. The commonly used approach is the cross-validation method, in which the data can be divided into *k* different subsets. Among these subsets, *k-1* subsets were engaged to build the model and the remaining subset was used to test if the model worked in *k* times successively. Hence, 30 items were randomly picked in the database beforehand to test the quantile regression-based model, which was established by using the rest of the data. At last, all the data were fully used in building and testing the model.

The Froehlich database is composed of 83 onsite measurements, including scour depths around three pier shapes, namely, round, sharp, and square[18]. The diameters of the bridge foundations in this database are from 0.98 m to 19.5 m, while the particle sizes of the river sediments range from 0.008 mm to 90 mm. The flow velocities were measured upstream the bridge pier, ranging from 0.15 m/s to 3.67 m/s. The flow depths around the testing area are from 0.43 m to 19.5 m. The Landers-Mueller database has 352 scour depth measurements from fifty-six bridge sites in the U.S.[25] The piers are consisted of round, sharp, and square types, whose diameters range from 0.29 m to 4.27 m and median particle sizes are from 0.17 mm to 108 mm. The flow velocity and water depth recorded for this database were derived when the scour depth was measured. The flow velocities are between 0.18 m/s and 3.93 m/s, and the water depths are from 0.34 m to 11.73 m. Since these parameters are usually measured during the last period of flood events, it is hard to know if the velocity is the peak velocity, or if the scour reaches its equilibrium state under this condition. It partially contributes to the uncertainty of flow if the designers treat these parameters equally. Soils in this database are non-cohesive and flow parameters were recorded until the flood ended, so it is likely that the field measurements are almost the maximum scour depths under the condition. As mentioned above, other field data collected by researchers were also involved to expand the database, and the conditions were elaborated in previous publications[31-36].

The matrix in Fig.3 graphically shows the relationship of measurements for all the related primary parameters in the database, which indicates that the scour problem is quite complicated with the interaction between factors. The relationships between the response variable (i.e., scour depth in this study) and the independent variables as well as those between independent variables can be analyzed preliminarily. Flow velocity and water depth can be estimated to be linear with scour depth according to Fig.3. It can also be partially concluded that the two variables were not independent of each other, which was opposite to our previous experimental strategies. In fact, the relationship between flow velocity and water depth is controlled by the evolution of a river channel, which can be described as a real-world problem, instead of being randomly decided or selected as we usually do in the laboratory. Meanwhile, pier width and the median particle size (d_{50}) cannot be directly regarded as linear with the response variable. In the DM process, different techniques for model adjustment can be used, including the traditional multiple regression, the non-parametric methods of regression trees, and *k*-nearest neighbors. Due to the data characteristics revealed in the matrix, data related to these parameters were adjusted to a linear quantile regression model in this study.

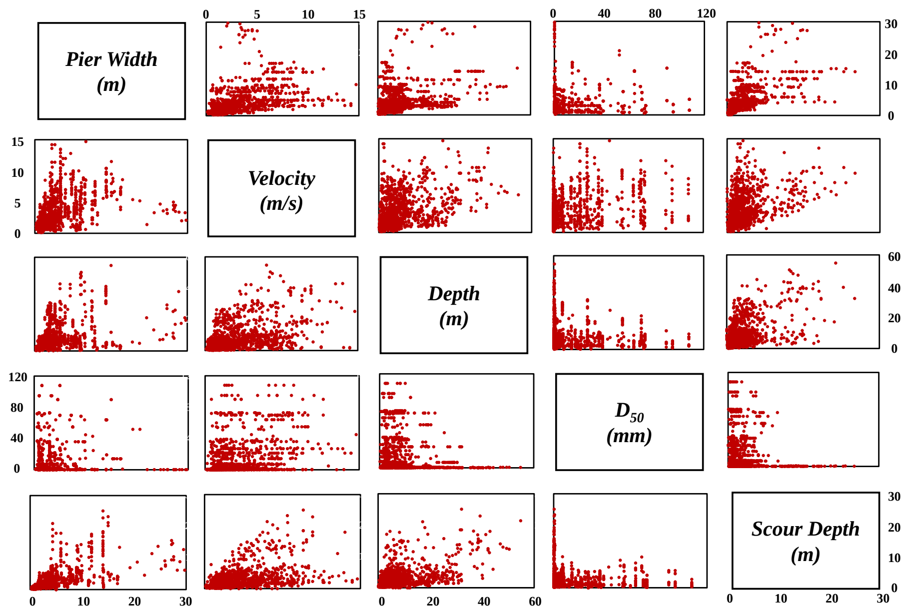


Fig.3 Relationship matrix between variables for bridge scour in practice (Each of the figures shows the relationship between its row variable and column variable)

3 Model Using Quantile Regression for Scour Prediction

Consider Y a random variable. The most conventional quantile is usually used as the median value, namely $Q_{0.5}$, which means the probabilities of Y is larger or smaller than $Q_{0.5}$ that equals to 0.5. Similarly, Q_τ was defined for those whose probability value Y below Q_τ is τ. In quantile regression method, Q_τ ($0 < \tau < 1$) can be addressed as a linear combination of several unknown regressors and coefficients[37-38]. The model can be expressed as follows:

$$Q_\tau(Y|\boldsymbol{x}_i) = \boldsymbol{x}_i{}^T\boldsymbol{\beta}(\tau),\ 0 < \tau < 1 \qquad (1)$$

where $\boldsymbol{\beta}(\tau)=(\boldsymbol{\beta}_1(\tau), \ldots, \boldsymbol{\beta}_p(\tau))^T$ is the quantile coefficient that may depend on τ; $\boldsymbol{x}_i$ (i = 1, 2, 3, 4, 5) are the scour-related regressors; and Y is the scour depth.

Let Y be a random variable with cumulative distribution function CDF $F_Y(y) = P(Y \leqslant y)$, and then the τ th quantile of Y can be written as

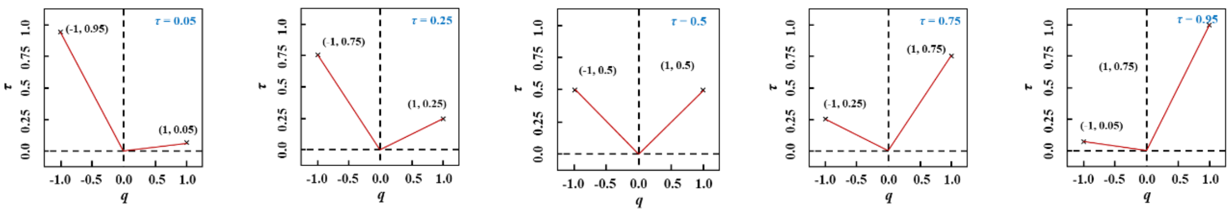
$$Q_\tau(Y) = \inf\{y: F_Y(y) \geq \tau\} \qquad (2)$$

where $0 < \tau < 1$ is the quantile level. In this study, $Q_{0.05}$ (Y) is the first quintile, namely, the 5th percentile; $Q_{0.25}$ (Y) is the second quintile, namely, the 25th percentile; $Q_{0.5}$ (Y) is the third quintile, namely, the median; $Q_{0.75}$ (Y) is the fourth quintile, namely, the 75th percentile; and $Q_{0.95}$ (Y) is the fifth quintile, namely, the 95th percentile. Given the check function as

$$\rho_\tau(q) = \begin{cases} \tau q, & q \geq 0 \\ (\tau - 1)q, & q < 0 \end{cases} \quad (3)$$

Fig.4 presents the check function for τ. Estimations can be derived by using linear programming techniques[37-39]. The quantile regression model can also be calculated using a simplex method, which complies with linear programming theory:

$\min_{\theta \in R^m} \boldsymbol{\theta}^T \boldsymbol{\omega}$, subject to $\boldsymbol{\theta}^T \boldsymbol{A} \geq c^{\mathrm{T}}$, and $\theta_i > 0$, where $\boldsymbol{A}$ is m × n matrix, $\omega \in R^m, c \in R^q$. (4)



(a) τ = 0.05 (b) τ = 0.25 (c) τ = 0.5 (d) τ = 0.75; (e) τ = 0.95

Fig.4 The check function ρτ (*q*)

As mentioned above, the key parameters that influence the scour results are from three aspects, i.e., hydraulic (flow velocity, water depth), geotechnics (median particle size, soil characteristics), and structure (pier width, pier geometry, and attack angle). In this model, the structural aspects are simplistically represented by pier width (*PW*, which is easy to be quantified), the hydraulic aspects are represented by Froude Number (*Fr*, which integrates flow velocity and water depth), and the geotechnics aspects are represented by Sediment Index (*SI*). These parameters are the primary factors that influence the maximum scour depth. The model can thus be written as

$$Q_Y(\tau|x) = \boldsymbol{\beta}_0(\tau) + PW\boldsymbol{\beta}_1(\tau) + Fr\boldsymbol{\beta}_2(\tau) + SI\boldsymbol{\beta}_3(\tau) \quad (5)$$

$$Fr = V \cdot (g \cdot h_p)^{-0.5} \quad (6)$$

$$SI = \ln(D/d_{50}) \quad (7)$$

and can be estimated for any $\tau \in (0,1)$ by solving the problem

$$\widehat{\beta}_n(\tau) = \arg\min_{b \in \boldsymbol{R}^p} \sum_{i=1}^{n} \rho_\tau(y_i - x_i^{\mathrm{T}} \boldsymbol{\beta}) \quad (8)$$

where τ is the quantile level, $\boldsymbol{\beta}$ is the quantile coefficient, *PW* is the pier width (m), *Fr* means the Froude Number, *SI* means the Sediment Index, *g* is the acceleration of gravity, *V* is the mean velocity of the coming flow upstream the foundation (m/s), h_p is the flow depth directly upstream the foundation (m), *D* is the pier diameter (m), and d_{50} is the mean particle size of soil.

The estimated quantile regression parameters and their confidence intervals are listed in Table 1. During the scour process, these variables can be handled as probabilistic loads and their influences are shown in Fig.5. These factors can be classified into two categories, i.e., design and environment. Factors from the aspect of design, including pier width and scour mitigation methods, are usually determined by designers.

Table 1 Variables in Quantile Regression Model

Quantile Level	Variables	Coefficients	Value	Standard Error	*T* Value	*Pr* (> |*t*|)
$\tau_{0.05}$	Pier Width	Intercept	0.079	0.028	2.772	0.0.006
		β	0.152	0.017	9.056	0
	Fr	Intercept	0.221	0.022	9.984	0
		β	0.233	0.046	5.031	0
	Sediment Index	Intercept	0.004	0.055	0.075	0.940
		β	0.051	0.008	6.052	0
$\tau_{0.25}$	Pier Width	Intercept	0.188	0.036	5.218	0
		β	0.291	0.020	14.493	0
	Fr	Intercept	0.511	0.048	10.695	0
		β	0.578	0.105	5.506	0
	Sediment Index	Intercept	-0.330	0.094	-3.529	0
		β	0.190	0.017	11.234	0
$\tau_{0.5}$	Pier Width	Intercept	0.216	0.063	3.448	0
		β	0.474	0.032	14.899	0
	Fr	Intercept	1.317	0.106	12.392	0
		β	0.576	0.223	2.585	0.010
	Sediment Index	Intercept	-0.662	0.134	-4.936	0
		β	0.380	0.028	13.734	0
$\tau_{0.75}$	Pier Width	Intercept	0.269	0.077	3.485	0
		β	0.770	0.053	14.634	0
	Fr	Intercept	3.055	0.206	14.860	0
		β	1.197	0.426	2.811	0.005
	Sediment Index	Intercept	-1.446	0.196	-7.379	0
		β	0.746	0.050	15.015	0
$\tau_{0.95}$	Pier Width	Intercept	0.25	0.159	1.574	0.116
		β	1.5	0.069	21.610	0
	Fr	Intercept	8.110	0.928	8.742	0
		β	5.142	0.722	7.122	0
	Sediment Index	Intercept	-3.229	0.751	-4.301	0
		β	1.686	0.128	13.164	0

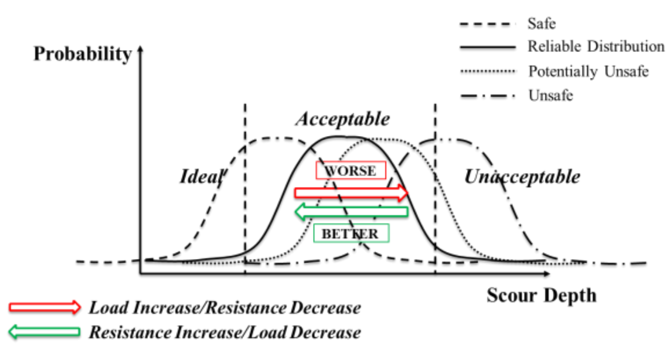
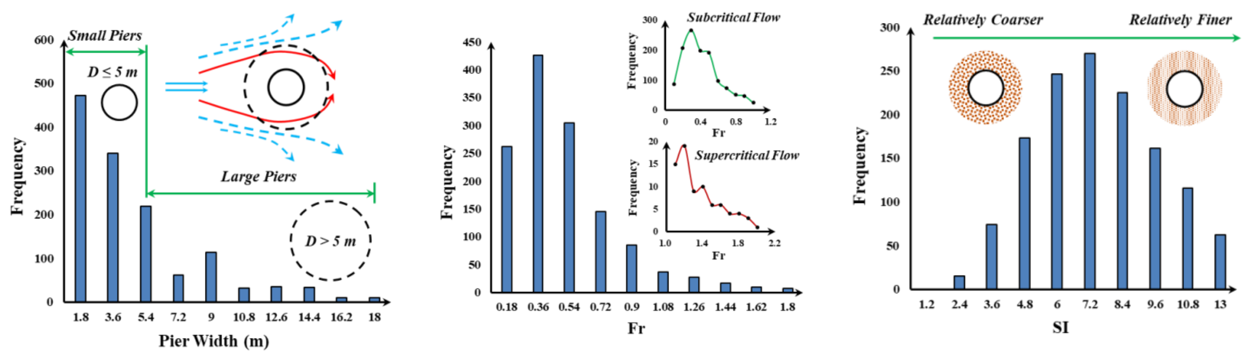


Fig.5 Concept and strategy of probabilistic design method for scour estimation

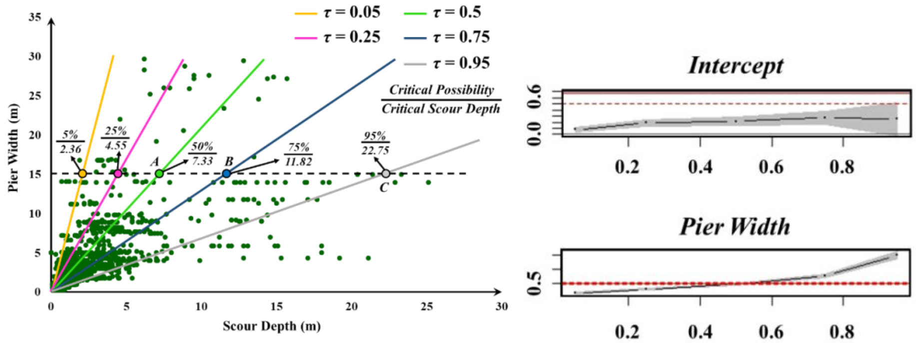
Fig.6(a) presents the distribution of pier width in the database. Previous studies indicate that the scour behaviors of underwater structures with various widths are quite different. Recently, an increasing number of bridge foundations are built with large widths (more than 5 m), while the existing predictive equations behave worse when the piers become larger[40]. In addition to the structure selection, countermeasures have also been used to mitigate scour depth. Factors from the aspect of environment, including the characteristics of flow and sediments, are stochastic as real-world problems. A frequency histogram of *Fr* for both supercritical and subcritical flows is depicted in Fig.6(b). When the Froude Number is greater than one, it is regarded as supercritical, and when it is less than one, it can be treated as subcritical. Generally, supercritical flows are faster than subcritical flows. In fact, flow conditions in practice are usually subcritical, and bridge failures are predominated by long-term scour. The histogram suggests that it is a normal distribution when *Fr* is smaller than one and larger than one, respectively. Fig.6(c) shows a frequency histogram of *SI*, which is also a normal distribution. As mentioned above (Fig.5), factors from the aspect of design are crucial to reducing the risk of bridge failure because environmental factors are not determined by designers. For a certain site, the occurrence of floods can be identified as a probabilistic problem for a long duration. The scour depth is closely related to the likelihood of a catastrophic flood. It is similar for the distribution of soil characteristics, because the sediments on site are not selected by designers but naturally stochastic. When environmental factors are propitious to bridge safety, e.g., riverbed sediments have high scour resistance, and/or water flows slowly, designers can provide a bold plan (such as, large foundation with less or without countermeasures). On the contrary, the choice of foundation shape and type is limited, while the budget of countermeasures will be increased.



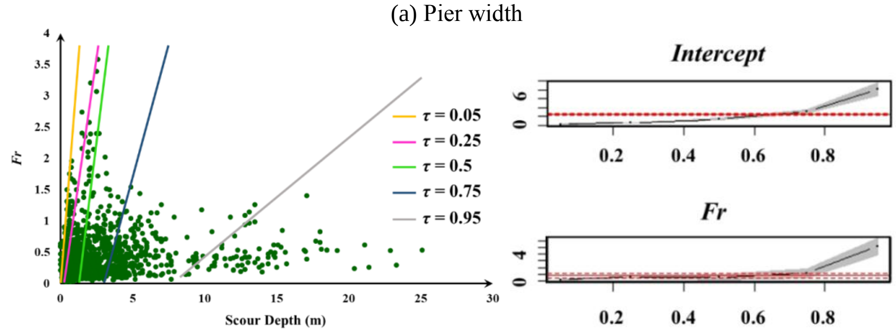
(a) Pier Width (b) *Fr* (c) *SI*

Fig.6 Distribution of Pier width, *Fr*, and *SI* in present database

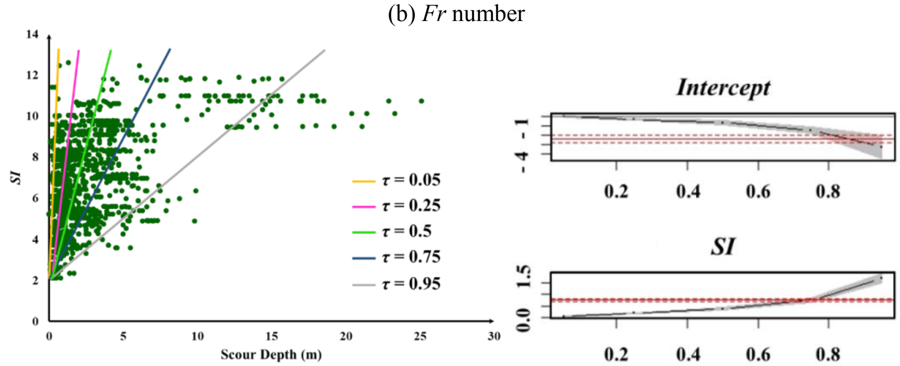
Fig.7 shows the model for each of the quantiles, which describes the results of quantile regression built with three variables and the trend of each coefficient. Critical Scour Depth (CSD) represents the maximum scour depth for a pier that occurs with its Critical Possibility (CP). For example, when *PW* = 15 m, by using the quantile regression model, the probability for the occurrence of a scour depth less than 7.33 m was 50% (Point *A*). Similarly, Point *B* shows the scour depth (11.82 m) whose nonexceedance probability of occurrence was 75%, while Point *C* had the probability of 95% that the scour depth would not be more than 22.95 m. Results calculated by *Fr* and *SI* could be derived using the same method. The comparing column diagram for the influence of each variable is shown in Fig.8, which indicates the changing importance of these variables.



(a) Pier width



(b) *Fr* number



(c) *SI*

Fig.7 Quantile regression results using pier width, *Fr* number, and *SI*

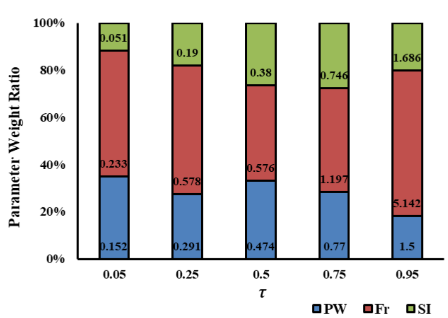


Fig.8 Comparison of the influence of each variable when predicting scour depth

In general, flow plays the most important role in scour, especially for low nonexceedance probability (5%) and high nonexceedance probability (95%). To mitigate scour, more attention needs to be paid to flow altering and energy dissipating instead of merely enhancing the riverbed. The embedded depth, as which the foundations should be constructed, as well as how strict the countermeasures should be installed, is required to maintain acceptable reliability or probability of collapse during the service life of the bridge. These depend on the service period, e.g., a bridge designed to serve a period of 50 years requires less embedded depth (and/or simpler countermeasures) than those designed for 200 years, because the probability of a 100-year flood that occurs during the 50 years is quite small. By using this concept, the design of the bridge can be more appropriate and economical. The importance of *PW* increases when the nonexceedance probability becomes larger, while *SI* shows the opposite trend. Normally, conventional methods focus on median conditions (τ = 0.5), which can be handled almost equally. However, according to Fig.8, it would be different when predicting scour depth consisting of extreme conditions (τ = 0.95), which also explains why existing equations have deficiencies when predicting scour depth with large piers, extreme floods, or weak riverbed. It demonstrates the relation between string force density and bar force density in expansion.

4 Comparison and Comments on Deterministic Method and Probabilistic Method

4.1 Deterministic estimations of scour depth using HEC-18 equation

The Hydraulic Engineering Circular No. 18 (HEC-18) report provides different estimations for sand and clay[8]. The HEC-18 equation recommended in this work is the most commonly used guideline applied in alluvial sand-bed channels. A time-dependent method, known as the Scour Rate in Cohesive Soils method (SRICOS), for estimating scour in cohesive soils was proposed by Briaud et al.[41] In this study, measurements that are under sandy bed condition were only collected and analyzed. The HEC-18 equation is based on the equation that was originally proposed at the Colorado State University (CSU) from the laboratory data of scour around circular piers. Modifications to the equation have been made progressively over the years to account for more complex pier shapes and flow conditions[8,42]. The equation is widely used to estimate local scour depth, both live-bed and clear-water scours. The current HEC-18 deterministic equation can be written as

$$\frac{Y}{h_p} = 2.0K_1K_2K_3K_4\left(\frac{D}{h_p}\right)^{0.65} Fr^{0.43} \tag{9}$$

where Y is the scour depth (m); h_p is the flow depth upstream the foundation (m); D is the pier diameter (m); K_1, K_2, K_3, and K_4 are the correction factors for the foundation shape, attack angle, bed configuration, and sand characteristics; and Fr is the Froude Number.

For designers, the overestimation of scour depth will bring excess costs for bridge constructions, while underestimation will lead to potential safety hazard. Similar to the HEC-18 equation, most of the widely used predictive methods, as well as their correction, are deterministic[12,14,43], which can directly figure out a deterministic scour depth, while ignore the uncertainties in the models. Since the parameters (e.g., flow velocity) are stochastic, the scour depth should also be stochastic. In addition, as mentioned above, other load factors in bridge design are regarded as probabilistic loads, and it is necessary to treat all loads equally. Therefore, a probabilistic approach is needed to extend the existing scour estimation system.

4.2 Comments on deterministic method and probabilistic method

In this study, the idea that the scour depth should be determined as probabilistic value is borrowed from different approaches. Briaud et al.[21] proposed a site-specific method, which presents the scour depth using statistic concept with a cumulative density function. Bolduc et al.[22] analyzed databases for local scour and developed probabilistic prediction models using the bias for the model uncertainty. Briaud et al.[23] continued to use a set of database to quantify the statistical parameters, which were utilized to develop a reliability-based load and resistance factor design for local scour around shallow and deep foundations. By using the concept of quantile regression, the maximum scour depth can be predicted as a range with various possibilities, with which the bridge designer can adjust the safety factors or avoid waste caused by the excessive embedded length. In this study, when environmental factors are propitious to bridge safety, it allows designers to provide a bold plan, e.g., large foundation with less (or without) countermeasures. In practice, to ensure the safety of a bridge during its service, more attention should be paid for extreme conditions. Therefore, 50%, 75%, and 95% nonexceedance probabilities of occurrence were calculated. In total, 30 items (four of them were repeated items and deleted) were selected randomly in advance to compare the behaviors of the present quantile regression-based model with the HEC-18 equation (Table 2).

Table 2 Results calculated by deterministic method (HEC-18) and quantile regression model (QR) using randomly selected items

Pier Width (m)	Velocity (m/s)	Water Depth (m)	d_{50} (mm)	Measured Depth (m)	Calculated by HEC-18 (m)	Calculated by QR (m)		
						Probability = 50%	Probability = 75%	Probability = 95%
1.20	0.10	1.10	0.38	0.70	0.57	0.78	1.19	2.05
0.90	0.20	1.80	0.06	0.20	0.68	0.64	0.96	1.60
3.50	1.30	17.40	0.39	1.60	5.01	1.37	2.96	5.50
3.00	0.50	7.10	0.01	0.70	2.66	1.35	2.58	4.75
2.10	2.70	12.30	0.12	2.30	4.69	1.21	1.89	3.40
3.30	0.70	4.30	0.48	0.50	3.06	1.38	2.81	5.20
1.17	3.42	0.60	21.30	0.60	2.36	0.77	1.17	2.01
1.50	0.15	0.60	0.50	1.20	0.72	0.93	1.42	2.50
0.99	1.41	0.30	21.30	0.33	1.32	0.69	1.03	1.74
2.58	3.00	2.31	36.10	0.78	4.48	0.96	1.74	3.97
3.00	0.50	7.10	0.01	0.70	2.66	1.35	2.58	4.75
5.04	1.86	0.93	14.30	1.14	4.98	1.57	2.93	6.66
14.00	6.50	2.20	64.00	2.20	18.62	1.39	2.57	5.86
5.00	0.70	5.90	0.48	0.90	4.18	1.37	3.17	7.75
4.00	0.29	3.60	0.38	2.20	2.32	1.35	3.11	6.25
1.70	1.10	8.00	6.90	1.70	2.62	1.02	1.58	2.80
11.80	4.50	3.00	0.20	10.5	14.84	1.80	4.05	12.38
0.30	0.70	0.60	0.94	0.20	0.49	0.36	0.50	0.70
4.70	1.80	16.70	0.60	6.50	6.93	1.40	3.22	7.30
7.70	2.40	4.60	7.20	3.90	9.09	1.52	3.48	8.53
2.50	0.60	4.80	0.18	1.50	2.42	1.37	2.19	4.00
4.48	3.63	4.10	39.00	3.00	7.52	1.14	2.09	4.77
2.46	0.99	1.74	2.50	1.02	2.59	1.38	2.16	3.94
1.10	0.40	1.80	0.17	0.20	1.05	0.74	1.12	1.90
3.20	1.90	23.00	6.90	4.10	5.77	1.39	2.73	5.05
1.53	0.84	2.10	0.60	1.02	1.82	0.94	1.45	2.55

As shown in Fig.9, results predicted by the HEC-18 equation were usually larger than field data, sometimes even several times more than the field data. The present method provides several critical scour depths, relating to different probabilities. If the service period of a bridge is long or the environmental conditions are extreme, designers can use results calculated with the probability of 95%. Otherwise, designers can apply the results from the probability of 50%. In addition, if the conditions are moderate, the results calculated with the probability of 75% can be good choices.

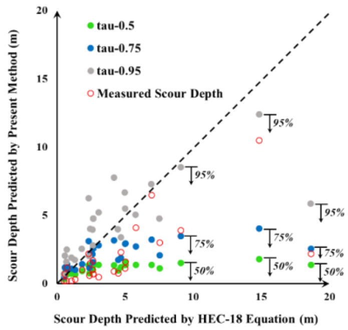


Fig.9 Scour prediction for randomly selected terms using HEC-18 and present method

In practice, the maximum scour depth for a bridge pier can be designed with the following steps (i.e., "CCC" procedure): 1) calculate the critical scour depth using quantile regression-based model; 2) confirm the acceptable probability for scour depth according to building importance and environment parameters; and 3) check if the scour depth is acceptable and use scour countermeasures to mitigate it.

5 Conclusions

In this paper, a probabilistic model based on quantile regression method for predicting scour depth at bridge foundations is proposed. The results of scour depth were calculated as CSD using the "CCC" procedure, with which designers can control potential loss under the conditions of different bridge importance and lifespan. The three factors, namely, pier width, *Fr* number, and *SI*, have their own contributions to the results and were analyzed. Both *Fr* and *SI* are uncertainties that can be treated as stochastic variables. Under extreme conditions, hydraulic parameters play the most important role among these factors. By comparing the calculated results of randomly selected data, both the HEC-18 equation and the quantile regression-based model could provide reasonable predictions. The primary benefit of this method, although in a preliminary stage, is that it can provide several scour depths according to various probabilities, instead of only one deterministic value provided by traditional methods.

Although the concept of predicting scour depth through the aspect of probability is a preliminary trial, it can be a good complement to the probabilistic system of scour estimation. By involving more data and gathering more variables, the model will behave better. Besides, the quantile regression-based model is renewable when new data are involved. A limitation of this model at the present stage is that the range of each variable is not comprehensively covered, especially for the increasing pier diameter in current practices. Another limitation is the fact that the scour hole refilling and the measurement of field data may cause the underestimation of field data, which are the basis of the quantile regression model. To overcome these limitations, further study will be carried out, and a more and wider range of field data will be involved in this model to extend the concept.

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