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Comparison of existing equations for local scour at bridge piers: parameter influence and validation

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Abstract Local scour caused by the erosion or removal of sediment from bridge piers is a potential hazard to the safety of bridges. Numerous equations predicting local scour depth at bridge piers have been developed and compared over the past decades. However, little attention has been paid to the two widely used official equations in China. This study compared three types of commonly used equations, including the Chinese equations, HEC-18 equations, and Melville equations. Parameter influence analyses were firstly conducted to explore the effects of flow velocity, water depth, pier width, and sediment size on the calculated scour depth for each equation. The equations were then validated with 126 laboratory and 408 field data which were carefully screened. The analyses show that the effect degrees of each parameter on scour depths for the considered equations are significantly different, although the general trends are similar. The validation results show that the Chinese equations perform better with the field data than the laboratory data for which the equilibrium scour depths are significantly under-predicted by the equations. The HEC-18 equations predict the scour depths best for the laboratory data. The Melville equations over-predict the scour depth for both the laboratory data and the field data and are generally conservative.

Keywords Erosion hazards · Local scour · Bridge piers · Equilibrium scour depth · Parameter influence · Validation

1 Introduction

Local scour at bridge piers in alluvial rivers during large floods is one of the main causes of bridge failure (Deng and Cai 2010; Liang et al. 2015), and hence, correct prediction of the scour depths at bridge piers is of great importance to reduce hazards. Local scour is resulted from the interaction of three-dimensional, unsteady coherent flow structures and

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erodible river beds around the bridge piers (Graf and Istiarto 2002; Salaheldin et al. 2004; Dey and Raikar 2007; Kirkil et al. 2008; Keshavarzi et al. 2014). Because of the complex mechanisms involved in the local scour process (Dehghani et al. 2013), empirical equations based on dimensional analysis are still the most extensively used approach to estimate local scour depth at bridge piers (Hong et al. 2012; Brandimarte et al. 2012).

Over the past decades, numerous empirical pier-scour equations have been developed based on laboratory data. In order to check their accuracy in practice, these equations have been validated with field data by several investigations (e.g., Johnson 1995; Jackson 1997; Chase and Holnbeck 2004; Mohamed et al. 2005; Gulbahar 2009; Gaudio et al. 2010; Schuring et al. 2010; Ettema et al. 2011). Johnson (1995) found that most of these equations over-estimate the on-site scour depths under natural floods in the field and some uncertainties are existed when applying these equations into practice. Similar results were obtained by Gaudio et al. (2010) who noted the similitude effect between field and laboratory conditions. Recently, Sheppard et al. (2014) evaluated 23 pier-scour equations using perhaps the most comprehensive laboratory and field data set. They pointed out that these equations may provide, for the same case, quite different scour value due to the variability of parameters involved in these equations. However, few researches have considered the behavior of different equations with respect to their main parameters' impacts. In addition, there is an absence of evaluating the Chinese equations which have been written in national codes and widely used for more than 40 years in China by the civil engineers in design and administration of highway and railway bridges.

This paper compared three types of commonly used pier-scour equations for non-cohesive sediment, the revised 65-1 and 65-2 equations proposed in China, the HEC-18 equations (Richardson and Davis 2001; Arneson et al. 2012), and the Melville equations (Melville and Sutherland 1988; Melville 1997). In order to explore the differences of scour prediction among the equations, analyses of the main influencing parameters included in equations were carried out. In addition, the equations were validated with laboratory data and field data which are carefully screened to eliminate the unreasonable data. The results in this paper provide not only guidance for engineers to correctly use pier-scour equations in practice but also a better understanding of the physics of local scour at bridge piers.

2 Pier-scour equations

The functional relation between the local scour depth at bridge piers h_s and its pertinent parameters can be expressed as:

$$h_s = \text{function}\left[\text{flow}(\rho, v, h, V, g),\ \text{bedmaterial}\left(\rho_{\text{s}}, d_{\text{s}}, \sigma_{\text{g}}\right),\ \text{pier}(l, b, s, \alpha)\right] \tag{1}$$

where ρ and v = fluid density and kinematic viscosity, respectively; h and V = depth and depth-averaged velocity of approach flow, respectively; g = gravitational acceleration; ρ_{s} = sediment density; d_{s} and σ_{g} = sediment size and geometric standard deviation of the sediment size distribution; l and b = pier length and width, respectively; s = variable describing the pier shape; α = angle of the flow relative to pier alignment.

Assuming constant density of the flow and sediment as well as neglecting the influence of viscosity in highly turbulent flows, different equations for local scour can be established by considering different influencing degree of parameters in Eq. (1). It should be noted that the laboratory data used to fit equations are measured at the time when equilibrium scour is reached. Therefore, the scour depth predicted by each equation is the equilibrium depth of local scour.

2.1 Revised 65-1 equation

The revised 65-1 equation (termed 65-1R hereafter) in the Code for Survey and Design on Hydrology of Railway Engineering was proposed by the Ministry of Railways of the People's Republic of China (1999). It was developed by considering the influences of flow velocity, sediment size, and pier width and is expressed as:

$$h_s = \begin{cases} k_s k_{\eta 1} b_e^{0.6}\left(V - V_0'\right) & \text{for } V \le V_c \\ k_s k_{\eta 1} b_e^{0.6}\left(V_c - V_0'\right)\left(\dfrac{V - V_0'}{V_c - V_0'}\right)^{n_1} & \text{for } V > V_c \end{cases} \tag{2}$$

where $k_s =$ pier shape factor instead of s (see details in TB 10017-99), $k_{\eta 1} =$ sediment size factor, $b_e =$ projected width of the pier, $V_c =$ critical approach flow velocity for entrainment of bed sediment, $V_0' =$ incipient velocity for local scour at a pier, $n_1 = (V_c/V)^{0.25 d_s^{0.19}}$. In Eq. (2), the coefficients k_s and the exponent of b_e were determined based upon laboratory data, and $k_{\eta 1}$, n_1, and V_0' were determined by experiments as well as modified by field data collected from more than 300 bridges. The empirical expressions are as follows:

$$k_{\eta 1} = 0.8\left(\frac{1}{d_s^{0.45}} + \frac{1}{d_s^{0.15}}\right) \tag{3}$$

$$V_0' = 0.462 (d_s/b_e)^{0.06} V_c \tag{4}$$

The critical approach velocity of sediment is defined as:

$$V_c = 0.0246\left(\frac{h_p}{d_s}\right)^{0.14}\sqrt{332 d_s + \frac{10 + h_p}{d_s^{0.72}}} \tag{5}$$

where $h_p =$ flow depth after contraction scour. The projected width of pier is given by:

$$b_e = \begin{cases} (l - b)\sin\alpha + b & \text{if circular or sharp nose} \\ l\sin\alpha + b\cos\alpha & \text{if square nose} \end{cases} \tag{6}$$

2.2 65-2 equation

The 65-2 equation recommended by the Ministry of Transportation of People's Republic of China (2002) is expressed similarly in form as the 65-1R equation. The distinctions between them are: (1) flow depth is explicitly taken into account in 65-2 and (2) the determination methods of sediment size factor, critical velocity of sediment, incipient velocity for pier scour are different. The 65-2 equation is written as:

$$h_s = \begin{cases} k_{\eta 2} k_s b_e^{0.6} h_p^{0.15}\left(\dfrac{V - V_0'}{V_c}\right) & \text{for } V \le V_c \\ k_{\eta 2} k_s b_e^{0.6} h_p^{0.15}\left(\dfrac{V - V_0'}{V_c}\right)^{n_2} & \text{for } V > V_c \end{cases} \tag{7}$$

where $k_{\eta 2} =$ sediment size factor, $n_2 = (V_c/V)^{0.23 + 0.19 \lg d_s}$, and the remaining variables are determined as:

$$k_{\eta 2} = \frac{0.0023}{d_{\mathrm{s}}^{2.2}} + 0.375 d_{\mathrm{s}}^{0.24} \tag{8}$$

$$V_0' = 0.12(d_{\mathrm{s}} + 0.5)^{0.55} \tag{9}$$

$$V_{\mathrm{c}} = 0.28\sqrt{d_{\mathrm{s}} + 0.7} \tag{10}$$

The 65-1R and 65-2 equations were developed by using laboratory data and have been verified by a large amount of on-site measured data in China. However, it should be noted that the dimensions in both Eqs. (1) and (2) are inhomogeneity, and the unit of sediment size is millimeter, which differs from the other variable's scale unit of meter. Additionally, the influence of sediment grading for non-uniform sediment is neglected in both 65-1R and 65-2 equations.

2.3 HEC-18 equation

The Colorado State University (CSU) equation in the Federal Highway Administration (FHWA) Hydraulic Engineering Circular No. 18 (HEC-18) was developed by fitting laboratory data. This equation has been progressively modified over the years and is currently one of those recommended by the U.S. Department of Transportation for estimating local scour depths at bridge piers. The equation in the fourth version of HEC-18 (HEC-18 4th) (Richardson and Davis 2001) is expressed as:

$$\frac{h_s}{h} = 2.0 k_s k_\alpha k_b k_{\eta 3} k_w \left(\frac{b}{h}\right)^{0.65} F_r^{0.43} \tag{11}$$

where $F_r = V/(gh)^{0.5}$ = Froude number; and k_α, k_b, $k_{\eta 3}$, k_w = correction factors for angle of attack flow, state of bed-sediment motion, sediment size distribution, and wide piers, respectively (see Richardson and Davis 2001, for details).

The factor of sediment size distribution is:

$$k_{\eta 3} = \begin{cases} 0.4 V_R^{0.15} & \text{for } d_{50} \geq 2 \text{ mm and } d_{90} \geq 20 \text{ mm} \\ 1 & \text{for } d_{50} < 2 \text{ mm or } d_{90} < 20 \text{ mm} \end{cases} \tag{12}$$

where

$$V_R = \frac{V - V_{icd_{50}}}{V_{cd_{50}} - V_{icd_{90}}} > 0 \tag{13}$$

V_{icd_x} is the approach velocity required to initiate scour at the pier for grain size d_x, given by:

$$V_{icd_x} = 0.645 \left(\frac{d_x}{b}\right)^{0.053} V_{cd_x} \tag{14}$$

and V_{cd_x} is the critical velocity for incipient motion for grain size d_x, given by:

$$V_{cd_x} = 6.19 h^{1/6} d_x^{1/3} \tag{15}$$

The correction factor for very wide piers is applied when $h/b < 0.8$, $b/d_{50} > 50$, and $Fr < 1$, which is given as:

$$k_w = \begin{cases} 2.58\left(\dfrac{h}{b}\right)^{0.34} F_r^{0.65} & \text{for } V < V_\mathrm{c} \\ 1.0\left(\dfrac{h}{b}\right)^{0.13} F_r^{0.25} & \text{for } V \geq V_\mathrm{c} \end{cases} \tag{16}$$

It is recommended in HEC-18 4th that the upper limit of h_s/h is 2.4 for $F_r \leq 0.8$ and 3.0 for $F_r > 0.8$. The equation in the fifth version of HEC-18 (HEC-18 5th) (Arneson et al. 2012) is the same as HEC-18 4th except for neglecting the factor of sediment size distribution. However, an alternative equation for coarse bed is proposed in HEC-18 5th, which is only applicable to clear-water scour condition and to coarse bed materials with $d_{50} \geq 20$ mm and $\sigma_\mathrm{g} \geq 1.5$. To avoid repetition, the HEC-18 5th equation was only involved in the following validation of field data (section of 4.3).

2.4 Melville equation

Melville and Sutherland (1988) developed a pier-scour equation based upon envelope curves drawn to experimental data obtained mainly by laboratory experiments. This equation, termed as Melville and Sutherland (1988), is expressed originally as:

$$\frac{h_s}{b} = k_s k_\alpha k_I k_y k_{\eta 4} k_\sigma \tag{17}$$

where k_I, k_y, $k_{\eta 4}$, k_σ = factor of flow intensity, flow depth, sediment size, and sediment gradation ($k_\sigma = 1.0$), respectively.

The factor of flow intensity is recommended as:

$$k_I = \begin{cases} 2.4\left|\dfrac{V-(V_\mathrm{a}-V_\mathrm{c})}{V_\mathrm{c}}\right| & \text{for } \dfrac{V-(V_\mathrm{a}-V_\mathrm{c})}{V_\mathrm{c}} < 1 \\ 2.4 & \text{for } \dfrac{V-(V_\mathrm{a}-V_\mathrm{c})}{V_\mathrm{c}} > 1 \end{cases} \tag{18a}$$

where V_a = mean approach flow velocity at the armor peak (see details in Melville and Sutherland 1988), and for uniform sediment, Eq. (18a) can be simplified as:

$$k_I = \begin{cases} 2.4(V/V_\mathrm{c}) & \text{for } V < V_\mathrm{c} \\ 2.4 & \text{for } V > V_\mathrm{c} \end{cases} \tag{18b}$$

where $V_\mathrm{c} = 5.75 u_{*\mathrm{c}} \log(5.53h/d_{50})$, u_{*c} = critical shear velocity defined by Shields function.

The factor of flow depth is determined by:

$$k_y = \begin{cases} 0.78(h/b)^{0.255} & \text{for } h/b < 2.6 \\ 1.0 & \text{for } h/b > 2.6 \end{cases} \tag{19}$$

The factor of sediment size is recommended as:

$$k_{\eta 4} = \begin{cases} 1.0 & \text{for } b/d_{50} > 25 \\ 0.57\log(2.24b/d_{50}) & \text{for } b/d_{50} < 25 \end{cases} \tag{20}$$

Melville (1997) modified the determination method of these k factors values, which results in the estimation of scour depth being different from that of Melville and Sutherland (1988). The Melville (1997) equation is expressed as:

$$h_s = k_s k_\alpha k_I k_{yb} k_{\eta 4} k_\sigma \tag{21}$$

where k_{yb} = compositive factor of flow intensity and pier width recommended as (determinations of the other factors are same with that of Melville and Sutherland (1988)):

$$k_{yb} = \begin{cases} 2.4b & \text{for } b/h < 0.7 \\ 2.0\sqrt{hb} & \text{for } 0.7 < b/h < 5 \\ 4.5h & \text{for } b/h > 5 \end{cases} \tag{22}$$

The dimensions are homogeneity in the HEC-18 and Melville equations which were developed by dimensional analysis. From this point, these equations are more reasonable than the Chinese 65-1 R and 65-2 equations.

3 Parameter influence analysis

The flow velocity, flow depth, pier width, and sediment size are included commonly in the above equations. To illustrate their relative importance in determining the scour depth by each equation, a method of single-factor analysis was adopted. Each analysis was carried out by varying a selected parameter while keeping the other parameters constant. Four analyses were conducted to consider the flow velocity, flow depth, pier width, and sediment size, respectively. The input values of the analyzed parameters ranging from laboratory to field scale are listed in Table 1. In the following analyses, circular pier and uniform sediment were assumed.

The relations of scour depth with flow velocity, flow depth, and pier width can be expressed approximately as power functions when the value of each parameter is within an appropriate range (Table 1):

$$h_s = f(V^{a_1}, h^{a_2}, b^{a_3}) \tag{23}$$

here a_1, a_2, and a_3 are the exponents of flow velocity, depth, and pier width, respectively, which reflect the effects of different parameters in various equations. The relation between scour depth and sediment size can hardly be expressed as a power function, and hence, its effect will be discussed alternatively.

3.1 Flow velocity

When the approach flow velocity is much larger than the incipient velocity for local pier scour ($V \gg V_0'$), the power function for the flow velocity in both 65-1R and 65-2 equations can be written approximately as:

$$h_s = \begin{cases} f(V^{1.0}) & \text{for } V \le V_c \\ f(V^n) & \text{for } V > V_c \end{cases} \tag{24a}$$

Table 1 Range of the input values of parameters

No.	V (m/s)	h (m)	b (m)	d_s (mm)
I	0.1–5.0	4.11	1.07	1.30
II	1.77	0.1–10.0	1.07	1.30
III	1.77	4.11	0.01–5.5	1.30
IV	1.77	4.11	1.07	0.1–400

where n is a coefficient smaller than 1.0. Equation (24a) indicates that the influence of flow velocity on scour depth under live-bed condition is weaker than that under clear-water condition.

Flow velocity is included in HEC-18 4th mainly via Froude number, and its exponent is determined by sediment size which can also be seen as critical velocity of sediment:

$$h_s = \begin{cases} f\left(V^{0.43}\right) & \text{for } d_s < 20\ \text{mm} \\ f\left(V^{0.58}\right) & \text{for } d_s \geq 20\ \text{mm} \end{cases} \tag{24b}$$

The effect of flow velocity in both Melville and Sutherland (1988) and Melville (1997) is involved in the factor of flow intensity k_I, which is also distinguished as clear-water and live-bed conditions:

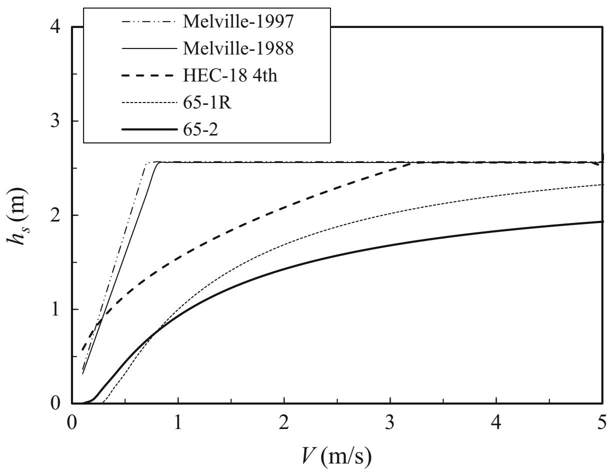
$$h_s = \begin{cases} f\left(V^{1.0}\right) & \text{for } V \leq V_c \\ f\left(V^{0}\right) & \text{for } V > V_c \end{cases} \tag{24c}$$

Comparison of the exponent for velocity in different equations shows that the influence of velocity is more significant in clear-water condition than that in live-bed condition. In order to display the influence of flow velocity intuitively, Fig. 1 shows the scour depths calculated by different equations using the data listed in the first row of Table 1. For each equation, the calculated scour depth shows an increasing tendency with the flow velocity. However, curves calculated by Melville and Sutherland (1988) and Melville (1997) equations as well as HEC-18 4th equations present apparent discontinuity points at the incipient velocity of sediment. Note that the critical velocity of sediment in each equation is determined by different methods. The increasing rate is different for each curve, suggesting that the effect degree of velocity is different.

3.2 Flow depth

In the 65-1R equation, the flow depth is not taken into account explicitly, although the critical velocity of sediment results in a slight dependence of scour depth on it. Therefore, the relation as a power function of scour depth and flow depth can be written approximately as:

Fig. 1 Influence of flow velocity on local scour depth



$$h_s = f\left(h^0\right) \tag{25a}$$

For the 65-2 equation, flow depth is included explicitly as a multiplicative factor and the power function can be expressed as:

$$h_s = f\left(h^{0.15}\right) \tag{25b}$$

The power function between scour depth and flow depth for HEC-18 4th equation is:

$$h_s = f\left(h^{0.14}\right) \tag{25c}$$

The effects of flow depth in the Melville and Sutherland (1988) and Melville (1997) equations are included via the factor of flow depth (k_y) and the compositive factor of flow intensity and pier width (k_{yb}), respectively, and they can be expressed separately as follows:

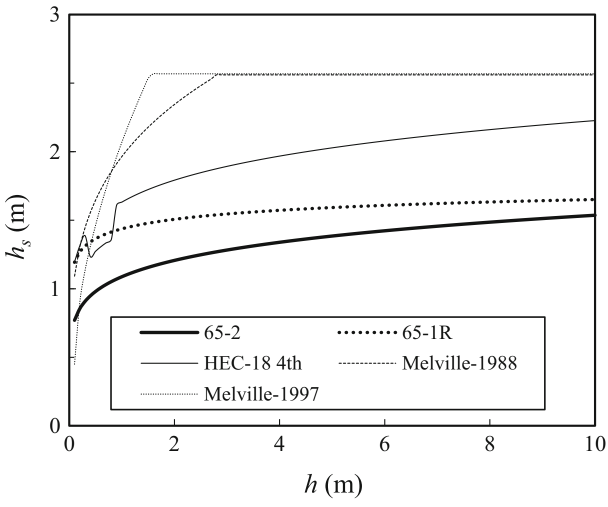
$$h_s = \begin{cases} f\left(h^{0.255}\right) & \text{for } h/b \le 2.6 \\ f\left(h^0\right) & \text{for } h/b > 2.6 \end{cases}, \quad \text{Melville (1988)} \tag{25d}$$

$$h_s = \begin{cases} f\left(h^{1.0}\right) & \text{for } h/b \le 0.2 \\ f\left(h^{0.5}\right) & \text{for } 0.2 < h/b \le 1.43 \\ f\left(h^0\right) & \text{for } h/b > 1.43 \end{cases}, \quad \text{Melville (1997)} \tag{25e}$$

Compared with the flow velocity, the flow depth exerts less effect on the scour depth except for the case of Eq. (25e) in relatively low flow depth condition. Equation (25d) shows that the scour depth is independent of flow depth in deep flow condition ($h/b > 2.6$), and similar result can be found in Eq. (25e). Chiew and Melville (1987) pointed out that scour depth increases with flow depth up to a limiting value of h/b, beyond which there is no influence of flow depth. They explained that, for shallow flows, the surface roller ahead of the bridge pier interferes with the scour action of the horseshoe vortex. With increasing flow depth, the interference reduces until there is no significant effect at $h/b \approx 3$.

Figure 2 depicts the variation of the calculated scour depth with the flow depth. All curves show that the scour depth increases with the flow depth in shallow flow ($h/b < 2.6$),

Fig. 2 Influence of flow depth on local scour depth



but the increasing rates are different. The increasing rate of 65-1R is the smallest, indicating the influence of flow depth is insignificant. The Melville (1997) equation shows the largest increasing rate when flow depth is relatively small, particularly in very shallow flow condition ($h/b < 0.2$). The increasing rate of 65-2 is similar to that of HEC-18 4th. The irregular variation exists on the curve of HEC-18 4th is due to the contribution of the correction factor k_w under the conditions of $h/b < 0.8$, $b/d_s > 50$, and $Fr < 1$.

3.3 Pier width

Pier width is an important parameter for local scour depth, and its influence on scour depth is significant, which can be seen from the relatively large exponents in the following power equations.

Both 65-1R and 65-2 equations share the following relation:

$$h_s = f\left(b^{0.6}\right) \tag{26a}$$

The HEC-18 4th equation includes a factor, k_w, for very wide pier, and the relation between the scour depth and the pier width in HEC-18 4th is:

$$h_s = \begin{cases} f\left(b^{0.65}\right) & \text{for } h/b \geq 0.8 \text{ or } b/d_s \leq 50 \text{ or } F_r \geq 1 \\ f\left(b^{0.31}\right) & \text{for } h/b < 0.8, \quad b/d_s > 50, \ F_r < 1 \text{ and } V/V_c < 1 \\ f\left(b^{0.52}\right) & \text{for } h/b < 0.8, \quad b/d_s > 50, \ F_r < 1 \text{ and } V/V_c \geq 1 \end{cases} \tag{26b}$$

The pier width is implied in the Melville and Sutherland (1988) equation via the factor of flow depth (k_y), and its relation with the scour depth is written as:

$$h_s = \begin{cases} f\left(b^{1.0}\right) & \text{for } h/b > 2.6 \\ f\left(b^{0.745}\right) & \text{for } h/b \leq 2.6 \end{cases} \tag{26c}$$

Melville (1997) classified the pier scour into three classes according to the value of b/h, namely scour at narrow piers ($b/h < 0.7$), intermediate piers ($0.7 < b/h < 5$), and wide piers ($b/h > 5$), and the scour depth at wide piers is independent of the pier width. The pier width is included in the Melville (1997) equation via the compositive factor of flow depth and pier width (k_{yb}), and its relation with the scour depth is as follows:

$$h_s = \begin{cases} f\left(b^{1.0}\right) & \text{for } b/h \leq 0.7 \\ f\left(b^{0.5}\right) & \text{for } 0.7 < b/h \leq 5 \\ f\left(b^{0}\right) & \text{for } b/h > 5 \end{cases} \tag{26d}$$

The variation of the calculated scour depth with the pier width is depicted in Fig. 3. It clearly shows that the scour depths calculated by both the Melville and Sutherland (1988) and Melville (1997) equations vary linearly when the value of pier width is small. For relatively wider piers, a smaller exponent of pier width is applied in Melville equations to extinct an over-prediction of scour depth; in particular, an upper limit for pier width is set ($b/h = 5$) in the Melville (1997) equation. Similarly, a reduction is also found in the HEC-18 4th equation when the pier width is very large. However, for the Chinese equations (65-1R and 65-2), the correction for wide pier is not taken into account.

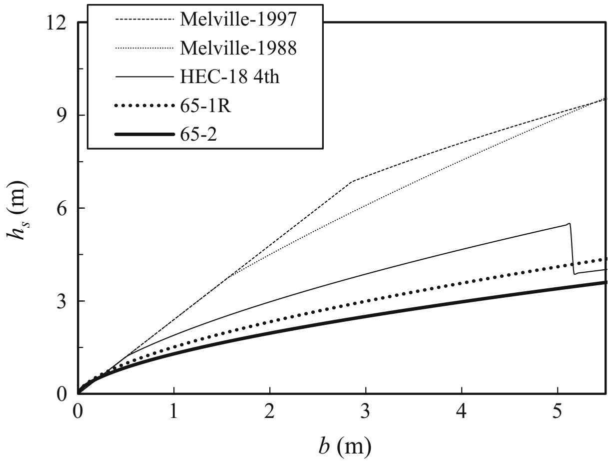


Fig. 3 Influence of pier width on local scour depth

3.4 Sediment size

The effect of sediment size on scour depth cannot be expressed simply as an exponential relation; however, the degree of influence can be obtained from the slope of curves in Fig. 4. It can be seen that the scour depth calculated by each equation shows almost the same decreasing tendency with the sediment size if the sediment size is larger than 10 mm. Melville and Sutherland (1988) explained that the down flow generated ahead of the pier is the main scouring agent, and the coarse particles may allow the down flow to penetrate the bed, which dissipates some of the flow energy and reduces the scour depth accordingly. But the variation trend is significantly different for the fine-sediment condition. The scour depth calculated by 65-1R or 65-2 decreases continuously with sediment size, and the decreasing rate is considerably high within the range of relatively small sediment sizes ($d_s < 0.5$ mm). This phenomenon implies that for the Chinese equations, the effect of sediment size is great in fine-sediment scour condition. However, no influence of sediment size is observed in the HEC-18 4th, Melville and Sutherland (1988), and Melville (1997) equations in the range of $d_s < 10$ mm.

4 Validation of pier-scour equations

4.1 Screening of scour data

Large quantities of equilibrium local scour data have been contributed by many researchers in recent years, from which the data source for single pier and non-cohesive sediment of 565 total data (listed in Table 2) were collected in this study, including 145 laboratory data and 420 field measured data.

In order to eliminate the unreasonable (negative or extremely large) scour depths these equations yield, a procedure screening the data was conducted before validation. The screening criteria are:

1. The values of relevant parameters are within the applicable range of all equations.

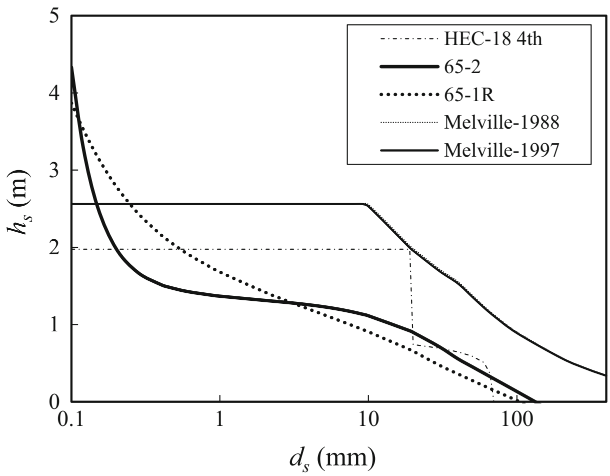


Fig. 4 Influence of sediment size on local scour depth

Table 2 Selected local scour data source and number of data points

Data source	Number of data points		
	Clear-water ($V < V_c$)	Live-bed ($V > V_c$)	Total number
Laboratory data			
Qi and Yin (1996)	9	0	9
Melville and Chiew (1999)	47	22	69
Sheppard et al. (2004)	9	5	14
Mohamed et al. (2005)	0	15	15
Lanca et al. (2013)	38	0	38
Total laboratory	103	42	145
Field data			
Wang et al. (1982)	0	9	9
Mueller and Wagner (2005)	119	292	411
Total field	119	301	420

The value of V_c in the above table was calculated by Eq. (5)

2. The laboratory scour data are the ultimate equilibrium scour depth, which means the tests durations should be long enough (>7 days).
3. The value of scour depth measured in the field is larger than the accuracy of the measurement instrument.

Through the screening procedure, the number of data is reduced to 534 (126 laboratory and 408 field data), and the range of each parameter is listed in Table 3. In laboratory condition, the sediment is uniform. Figure 5 shows the histograms of measured scour depth in laboratory and field conditions. As can be seen, there is no significant gap in both laboratory and field data, and most scour depths are within the range of 0.05–0.2 m and 0.2–0.6 m for laboratory and field data, respectively.

Table 3 Range of parameters used to validate equations

Date type	b_e (m)	V (m/s)	h (m)	d_s (mm)	σ_g	h_s (m)	Number of data points		
							Clear-water ($V < V_c$)	Live-bed ($V > V_c$)	Total
Laboratory	0.016–0.91	0.083–1	0.02–1.9	0.22–5.35	1–1.36	0.01–1.27	99	27	126
Field	0.5–16.48	0.1–8.7	0.2–22.5	0.1–400	1–6.16	0.1–7.7	126	282	408

The value of b_e in the above table was calculated by Eq. (6)

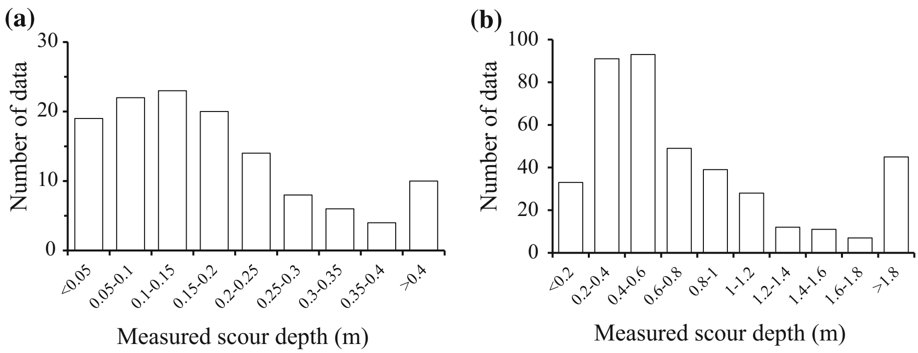


Fig. 5 Distribution of measured scour depth. **a** Laboratory data, **b** field data

4.2 Validation using laboratory data

Since the flow depth after contraction scour h_p is unknown, the approach flow depth h was alternatively used in the 65-1R and 65-2 equations. For the 65-1R, 65-2, and HEC-18 4th equations, $h_s = 0$ is assumed in the case of $V < V_0'$, corresponding to the situation where the approach velocity is not strong enough to initiate sediment transport around pier. The predicted results by the two HEC-18 equations are identical under the laboratory condition because of the uniform sand, and hence, to avoid repetition, only the HEC-18 4th equation is compared.

Comparisons of the predicted and measured scour depths in laboratory condition are shown in Fig. 6, with two dotted lines to indicate deviations of ± 30 % from the line of perfect agreement. The scour depths calculated by 65-1R (Fig. 6a) and 65-2 (Fig. 6b) equations are significantly smaller than measured ones, and these data (less than −30 %) occupy 98 and 80 % of the total data for 65-1R and 65-2, respectively. The reason may be that these two equations despite developed initially from laboratory data were modified based on large amounts of measured data of which the scour depths are usually smaller than the equilibrium scour depths. Because the duration of a natural flood is relatively short compared to the time required for equilibrium scour (Gaudio et al. 2010; Hager and Unger 2010). Therefore, 65-1R and 65-2 under-predict the scour depth in laboratory conditions. The HEC-18 4th equation performs the best, with 70 % of points fall inside the ±30 % bands. The Melville equations over-predict the scour depth, and the proportion of these data (>30 %) are 25 and 37 % of the total data for Melville and Sutherland (1988) and Melville (1997), respectively.

It is worth noting that different criteria for equilibrium scour have been proposed by different authors, which may result in the discrepancy in prediction of scour depth. Most criteria assume that effective equilibrium is achieved when the increment of scour depth in 24 h is below some given limits. These limits include 5 % of the pier diameter (Melville and Chiew 1999), twice the median sediment size (Lanca et al. 2013), and 2 mm (Qi and Yin 1996). Nonetheless, no systematic analysis about the possible errors introduced by these criteria has been reported in the literature.

4.3 Validation using field data

Comparisons of the measured and calculated scour depths using field data are presented in Fig. 7. It shows that the Chinese equations predict well, with 27.5 and 29.9 % of points fall

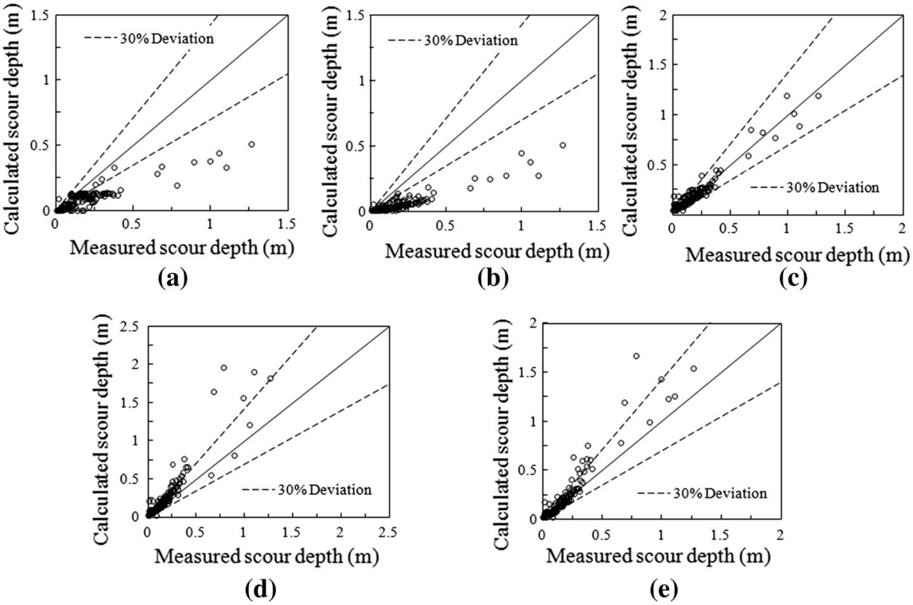


Fig. 6 Comparisons of equations with laboratory scour measurements: **a** 65-1R; **b** 65-2; **c** HEC-18 4th; **d** Melville and Sutherland (1988); **e** Melville (1997)

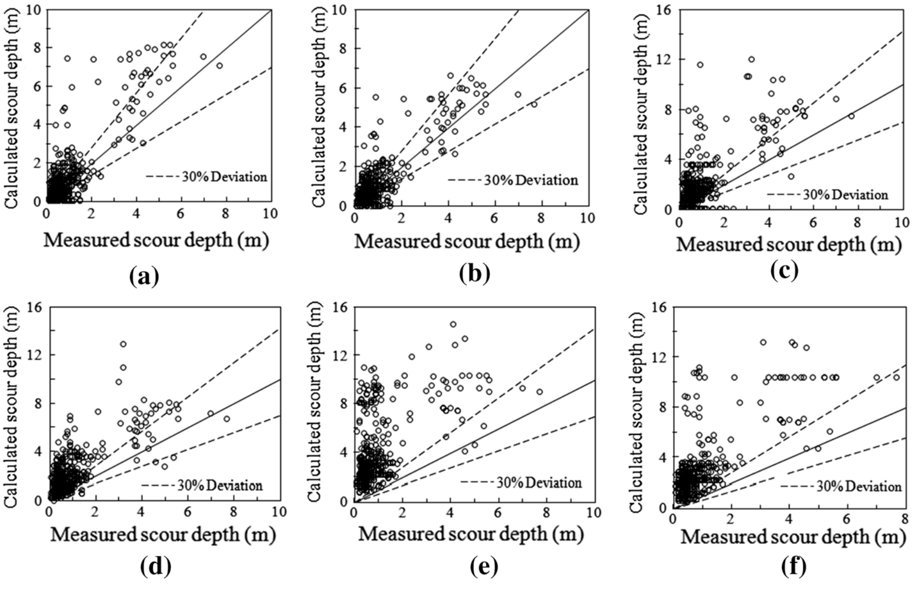


Fig. 7 Comparisons of equations with field scour measurements: **a** 65-1R; **b** 65-2; **c** HEC-18 4th; **d** HEC-18 5th; **e** Melville and Sutherland (1988); **f** Melville (1997)

inside the ±30 % bands for 65-1R and 65-2, respectively, and the data with large deviation are mostly characterized with small measured scour depth. Compared with the results predicted by the HEC-18 4th equation, the HEC-18 5th equation eliminates the data with zero value of calculated scour depths. The reason is that the incipient velocity for local scour at piers is not taken into account in HEC-18 5th. Moreover, the number of over-estimated points (>30 %) is relatively high, which occupy 82.1 and 91.2 % for HEC-18 4th and HEC-18 5th, respectively. The equations of Melville and Sutherland (1988) and Melville (1997) over-predict the scour depth significantly and are generally conservative, which is consistent with results obtained in previous studies (Johnson 1995; Mohamed et al. 2005). The overestimated points (>30 %) occupy 98.0 and 94.6 % for Melville and Sutherland (1988) and Melville (1997), respectively. Furthermore, significant scatter can be also observed in Fig. 7e, f.

Practically, the equilibrium scour depth is reached in quite a long duration (Hong et al. 2012), which, according to Simarro et al. (2011), is almost one to 2 weeks in laboratory observations. The corresponding flood duration in prototype may not be practical. Therefore, most existing equations based on laboratory experiments may generally over-estimate the scour depth in field (Deng and Cai 2010).

Further analysis of the variances between the equation predictions and the laboratory and field measurements remains to be conducted subsequently.

5 Summary and conclusions

This study compared several widely used equations for local scour at bridge piers, including the 65-1R and 65-2 equations in China, the HEC-18 equations (HEC-18 4th and HEC-18 5th), and the Melville equations (Melville and Sutherland 1988 and Melville 1997). The influences of primary parameters on the predicted scour depth for each equation were analyzed, and validations with screened laboratory and field data were conducted.

The parameter influence analysis indicates that the effect degree of each parameter on the scour depth in different equations is different, although the general trend is similar. The flow velocity shows different influences on the scour depth between clear-water and live-bed conditions. However, the critical point of velocity in each equation is different due to various determination method of V_c, and unreasonable discontinuities occur at critical points in Melville equations. Flow depth has relatively small influence on scour depth, particularly in deep-water condition ($h/b > 2.6$). Compared with the 65-1R and 65-2 equations, the reduction of pier width effects for wide piers is considered in the HEC-18 and Melville equations. In addition, the effects of sediment size in the 65-1R and 65-2 equations are significant for fine sediment ($d_s < 0.5$ mm), whereas the remaining equations only take into account the influence of sediment size under coarse-sediment condition ($d_s > 20$ mm).

The validation results through comparing the calculated and measured scour depth show that the 65-1R and 65-2 equations under-predict the scour depth in laboratory, while work well in field. The HEC-18 4th equation performs the best in laboratory condition while over-predicts the scour depth in field. The Melville equations significantly over-predict the scour depth and are generally conservative in laboratory and field conditions.

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