Live-bed scour experiments with 45° wing-wall abutments

M H MAZUMDER¹ and A K BARBHUIYA^{2,*}

¹Department of Civil Engineering, Silchar Polytechnic, Silchar 788 010, India

²Department of Civil Engineering, National Institute of Technology,
Silchar 788 010, India
e-mail: akbarbhuiya@yahoo.com

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Abstract. Live bed scour experiments were conducted using four types of non-cohesive bed sediments with median diameters $d_{50} = 0.26$ mm, 0.42 mm, 1.06 mm and 1.92 mm and five 45° wing-wall abutments of lengths $l = 0.04$ m, 0.06 m, 0.08 m, 0.10 m and 0.12 m. The tests were conducted in the range of flow velocity varies from 0.71 to 5 times of the critical velocity. The plotting of non-dimensional scour depths (scour depths/abutment lengths) vs non-dimensional flow intensity (flow intensity/critical velocity) show one peak value of scour depth close to the threshold velocity and thereafter, it reduces and again attain a live-bed maximum in the range of flow intensity 3 to 5 times of the critical velocity. It is also observed that the scour depth increases with the increase in sediment sizes up to threshold value of flow for all sediment sizes and abutment lengths. Further, the scour depth decreases with the increase of non-uniformity under all flow conditions. A design equation is proposed for estimating maximum scour depth at 45° wing-wall abutment under live-bed condition. The calculated values of scour depths using proposed equation, and also with three different live-bed local scour equations, are compared with the measured values of scour depths.

Keywords. Scour; bridge foundation; abutments; hydraulics; rivers.

1. Introduction

Protrusion of bridge abutments into the main channel causes obstruction of main channel flow. The flow accelerates around the obstructions and also develops turbulences causing the scour of its foundations. Scour of bed sediments around bridge abutments and piers can lead to structural collapses of the bridge. Estimation of scour depths near bridge abutments and piers for design storm conditions, are very important. Under-prediction can result in costly bridge failure and possibility of loss of lives, while over-prediction can result in unnecessary increase in construction cost.

*For correspondence

The flow and the scouring process is complex, involving separation of flow to develop three-dimensional vortex flow; and the complexity increases with the development of the scour hole. Exact theoretical analysis of the problem is not possible. The typical approach to analysis of bridge scour is based on physical modelling aimed at deriving prediction formulas or methodologies for the estimation of maximum scour depths. Most of the previous studies were done under clear water scour condition even though the majority of bridge failures due to scour of its foundation occur during floods, where a significant sediment flux is carried by the flow in rivers. Therefore, the dominant scour process is essentially due to the live-bed scour, which is well known to be different from that under a clear-water condition due to faster arrival of an equilibrium scour hole, where the scour depth fluctuates around a mean equilibrium value (Breusers & Raudkivi 1991; Hoffmans & Verheji 1997; Lim & Cheng 1998; Melville & Coleman 2000; Ballio *et al* 2010). The fluctuations of scour depths are due to the passage of bed forms and transport of sediment mass into and out of the scour hole. When the mass of sediment transported into the scour hole is equal to the sediment scoured from the scour hole, there exists a state of equilibrium condition known as dynamic equilibrium.

Very few studies on scour at bridge abutments under live-bed are available in the literature. Laursen (1963) and Gill (1972) analysed the problem based on an analogy to scour in a long contraction. Kandasamy (1989) and Dongol (1994) studied some aspects of the scouring mechanism. Lim & Cheng (1998) proposed one semi-empirical equation based on the flow and sediment mass continuity equations. Sheppard & Miller Jr (2006) conducted pier scour experiments and compared their results with some of the local scour equations. Ballio *et al* (2010) studied the temporal scales for scour at abutments. Available live-bed prediction equations give widely varied results for a given flow, abutment and sediment conditions indicating that more research on this problem is required for better understanding and prediction of scour depth.

In the present studies, live-bed scour experiments at 45° wing-wall abutments were conducted to understand the effect of different parameters on equilibrium scour depth. A design equation is proposed based on the experimental data. The proposed equation is compared with other three different live-bed local scour equations under the present conditions of the tests.

2. Experimental set-up and procedure

Experiments were conducted at the Hydraulics Engineering Laboratory at National Institute of Technology Silchar, India. A rectangular flume 17 m long, 0.8 m wide and 0.8 m deep was used for all the experiments. The test section was located 9.15 m from the upstream end of the flume. At the inlet section, there was a vertical steel screen covering the full cross-section for damping the flow disturbances through which water entered into the flume. The schematic diagram of the experimental setup, top view of the flume and test section is shown in figure 1. Flow depths were controlled using an adjustable tailgate located at the downstream end of the flume. The flume was connected to the water supply system in the laboratory. A sediment trap was constructed in the downstream side, having a length of 1.5 m to arrest the scoured sediments. Three sizes of 45° wing-wall abutments made of transparent Perspex sheet, with lengths perpendicular to the flow $l = 0.04$ m, 0.06 m, 0.08 m, 0.10 m and 0.12 m were used. Both uniform and non-uniform sediments were used in the experiments. The median grain sizes d_{50} of uniform sediments were 0.26 mm, 0.42 mm, 1.06 mm and 1.92 mm and geometric standard deviation σ_g , of particle size distribution of sediments given by (d_{84}/d_{16}) were 1.35 for 0.26 mm, 1.32 for 0.42 mm, 1.3 for 1.06 mm and 1.24 for 1.92 mm. The median grain sizes d_{50} of non-uniform sediments were

Figure 1. Schematic diagram of experimental set-up.

0.26 mm and 0.42 mm and σ_g were 1.8, 2.25 and 2.65 for 0.26 mm and 1.61, 1.81, 2.08, 2.55 and 3.15 for 0.42 mm.

The durations of experimental runs for different experiments were different. For clear water scour experiments, it took around 30 h to reach the equilibrium of scour depth whereas, for live-bed scour, it was around 8 hours to reach the dynamic equilibrium. The scour depths were measured with the help of a point gauge with an accuracy of ± 0.1 mm. However, measured and calculated data were rounded off to mm. In order to avoid the undesirable scour, which otherwise would happen by the action of sheet flow with inadequate flow depth, the flume was first slowly filled with the water at a low rate. The pump was allowed to run for 10 min to stabilize the flow in the flume. Once the water level reached the desired depth, the experiments were started by adjusting water inflow to the required rate and maintaining the required flow depth by downstream gate. The sediment was fed manually at the upstream during the experiments through a hopper as shown in the figure 1 and the bed level outside the influence zone of local scour was tried to keep at pre-experimental level. It may be mentioned that markings were made on the wall of the flume at the level of sediment bed before starting the flow. During the experiments, when it was found that the upstream bed level was lowered by 3–4 mm, sediment was spread uniformly on the hopper, and bed level was brought to its original level. However, it may be mentioned that it was very difficult to maintain the bed level exactly at pre-experimental level.

In order to get uniform flow, the flow discharge and the flow depth were controlled by a gate valve and a tailgate respectively. However, it is important to mention that a perfect uniform flow is very difficult to achieve in the experimental flume study. Sometimes, it was observed that the flow depths varied approximately ± 3 mm about the predetermined value. The reason may be due to the degradation of bed level and change of flow discharge. The change of discharge was caused due to the fluctuation of electric voltage which subsequently affected the discharge of

Table 1. Experimental conditions.

Sediment size (d_{50}) (mm)	Flow depth (h) (m)	Flow velocity (V) (m/s)	Flow intensity (V/V_c)	Froude no. (Fr)	Reynolds no. (Re)
0.26	0.05–0.26	0.197–1.25	0.71–4.99	0.140–1.33	39375–112500
0.42	0.05–0.25	0.205–1.28	0.71–4.96	0.146–1.38	41000–111250
1.06	0.05–0.20	0.297–1.29	0.71–3.52	0.212–1.40	59375–112500
1.92	0.08–0.20	0.400–1.40	0.71–2.93	0.286–1.59	80000–112500

pumps lifting the water from the underground reservoir to constant head reservoir. The discharge was measured using a calibrated V-notch weir fitted at the inlet tank; and the depth of flow was recorded by a point gage. During the experiments the maximum scour depths were monitored using a periscope. The detailed experimental conditions are given in table 1.

3. Results and analysis

In the present study, most of the experiments were conducted on live-bed scour condition. However, some experiments were conducted under clear-water scour condition to maintain the continuity in the data set for assessing the effect of flow intensity on scour depth. Although, at the dynamic equilibrium condition of scour hole, there were fluctuation of scour depths due to passage of bed forms past the scour hole during live-bed scour experiments, the equilibrium scour depth d_{se} was recorded when the bed forms were out of the scour hole. Detailed study on generation and passage of the bed forms within the scour hole is not done, however; some observations were made during experiments. It is found that ripples were started to develop at $V/V_c = 0.97$ for $d_{50} = 0.26$ mm and 0.42 mm and transformed to next bed forms dunes at flow intensity range $V/V_c = 2.0$ to 3.5. It migrated towards downstream and during the passage through scour hole, the scour depth reduces temporarily. At the tail of the dunes, small ripples were also observed. For sediment sizes $d_{50} = 1.06$ mm and 1.92 mm, there was no formation of ripples but dunes were formed at $V/V_c = 2.0$ to 3.5. The process of migration was similar to that of ripples and dunes formed on $d_{50} = 0.26$ mm and 0.42 mm. At higher flow intensity $V/V_c = 5.0$, experiments were conducted only with bed sediment sizes $d_{50} = 0.26$ mm and 0.42 mm. It was observed that the bed forms migrated towards upstream indicating the formation of antidunes. However, the size and movement of the bed forms were not affected by the length of the abutments. The effect of abutment length, flow intensity, sediment size, flow depth and sediment gradation on scour depth are discussed below:

3.1 Effect of flow intensity on scour depth

The normalised scour depth (d_{se}/l) as a function of flow intensity, (V/V_c) is presented in figure 2. It is found that the scour depth increases with the increase in flow intensity and then decreases, reaching a minimum value, and again increases reaching the equilibrium live-bed scour depth, as was found by many researchers (Ettema 1980; Chiew 1984; Melville & Chiew 1999; Sheppard and Miller 2006). Under clear-water conditions, the maximum scour depth occurs at flow velocity close to V_c and the scour depth is known as threshold peak.

Figure 2. Normalized scour depth (d_{se} / l) versus flow intensity (V / V_c).

Under live-bed conditions, initially the scour depth reduces and then increases towards a second maximum value. The second maximum scour depth, known as live-bed peak, probably occurs at upper plane bed flow regime condition. The scour depths shown in figure 2 are the

maximum values corresponding to that flow intensity. The presentations of experimental data show that the live-bed peak scours depth occur at $V/V_c = 3$ to 5. For ripple forming uniform sediments, ($d_{50} = 0.26$ mm and 0.42 mm), live-bed maximum scour exceeds the thresholds peak, but for other two types of uniform sediments ($d_{50} = 1.06$ and 1.92 mm), it is found that the live-bed maximum scour depth and threshold peak scour depth, are almost same. However, from figure 5, it is seen that for non-uniform sediment, the equilibrium scour depth increases with the increase of flow intensity even beyond the critical velocity.

3.2 Effect of abutment length-sediment diameter ratio on scour depth

The equilibrium scour depth d_{se} at abutments under live-bed scour condition is influenced by the ratio of abutment length to median sediment diameter, (l/d_{50}). The presentation of normalized equilibrium scour depths (d_{se}/l) vs normalized sediment sizes (l/d_{50}) in figure 3, show that d_{se}/l decreases with the increase of l/d_{50} , but the decreases are not linear and the curves fitted to the data are almost asymptotic to l/d_{50} axis. The decrease of d_{se}/l is sharp at smaller value of normalized sediment size ($l/d_{50} < 100$) but at larger values of normalized sediment size ($l/d_{50} > 100$), d_{se}/l decreases, but the decrease is not significant. This observation is not in conformity with the findings of Ettema (1980) for clear water scour and Chiew (1984) for live-bed scour for circular piers. Their data show, that scour depth increases with the increase in l/d_{50} up to $l/d_{50} = 50$. For $l/d_{50} > 50$, d_{se} is independent of the sediment size. However, Dey & Barbhuiya (2004) and Wong (1982) reported observations similar to the present findings for a constant value of V/V_c , which was close to the unity. Figure 3 shows that d_{se}/l is smaller for larger abutment length and finer sediment size. The probable reason may be due to the presence of some cohesive force in the sediments and formation of ripples in the bed. Also, the scour depth d_{se} may not be too small, but the effect of normalization of scour depth d_{se} by the larger abutment length l makes d_{se}/l smaller. Further, if the length of the abutment is increased, the strength of the down flow may not increase after certain minimum length and the increase of scour depth will be only due to the increased accelerated flow.

3.3 Effect of flow depth on scour depth

Experiments were conducted to study the effect of flow depth (h) on equilibrium scour depth (d_{se}). Flow depths were varied from 0.05 m to 0.26 m at approaching flow condition $V/V_c \approx 1.50$. Two sizes of abutments with length $l = 0.06$ m and 0.08 m and three sizes of uniform bed sediments with $d_{50} = 0.26$ mm, 0.42 mm and 1.06 mm were used in the experiments. Presentations of data (figure 4) show that the scour depth increases with the increase in flow depth at shallow flow depth, but become independent at higher flow depths. Similar observations were made by Raudkivi & Ettema (1983) for pier scour under clear water scour condition. It is seen from figure 4 that the scour depths become independent at $h/l > 2$ for sediment sizes 0.26 mm and 0.42 mm. Experiments could not be conducted at higher flow depths with sediment size 1.06 mm due to constrain in the laboratory flow discharge. The results may be justified due to the fact that the transportation of sediment due to flow depends on the shear stress developed at the particle level, in the present study shear velocity ratio was kept constant at $v_*/v_{*c} \approx 1.5$ and thus the effect of flow depths were incorporated in calculating v_* . However, under constant v_*/v_{*c} , probably the formation of primary vortex is effected by the flow depths and thus at shallow depths the scour is little less. For sediment size $d_{50} = 1.06$ mm it is found that the range of influence of flow depths is more compared to sediment sizes 0.26 mm and 0.42 mm.

Figure 3. Normalized scour depth (d_{se}/l) versus normalized sediment size (l/d_{50}).

3.4 Effect of sediment gradation on scour depth

Effect of sediment gradation is studied using two sizes of sediments tested with a single abutment of length 0.08 m under the approaching flow condition of $V/V_c \approx 0.97, 2.0$ and 3.5. The median

Figure 4. Normalized scour depth (d_{se}/l) versus normalized flow depth (h/l).

grain sizes d_{50} of non-uniform sediments were 0.26 mm and 0.42 mm and geometric standard deviations σ_g were 1.8, 2.25 and 2.65 for 0.26 mm and 1.61, 1.81, 2.08, 2.55 and 3.15 for 0.42 mm. Figure 5 is plotted using the experimental data.

Figure 5. Normalised scour depth (d_{se}/l) versus geometric standard deviation of the sediment (σ_g).

Figure 5 represents the dependency of normalized equilibrium scour depth (d_{se}/l) on geometric standard deviation σ_g of sediments. The particle size distribution has a pronounced influence on the scour depth. Non-uniform sediments ($\sigma_g > 1.4$) consistently produce lower scour depths than that in uniform sediments. Further, for the same non-uniformity coefficient, the scour depths are higher at higher flow intensity. The plots demonstrate a drastic decrease in scour depth that occurs for widely graded sediments. Experimental data of Wong (1982) for a 45° wing-wall abutment under clear water scour condition are also plotted on the same figure. The trends in the data are similar to the present observation but the data are lying below the data of present experiments. The reason may be explained due to the fact that Wong conducted the experiments with an abutment of length 0.6 m which is much longer than the length of abutment of present experiments. Moreover, Wong conducted the experiments under clear-water conditions only. From the figure, it is apparent that the effect of σ_g on scour depth is prominent up to $\sigma_g = 2.25$ and 2.5 for $d_{50} = 0.26$ mm and 0.42 mm respectively. However, the effect of non-uniformity on scour depths reduces for $\sigma_g > 2.5$. In non-uniform sediments, a process of armouring in the scour hole commences resulting in an exposure of coarser particle due to washing out the finer fraction. The armour-layer gradually increases the effective bed shear resistance, which restricts the development of scour hole.

4. Maximum equilibrium local scour depth around 45° wing-wall abutment

Maximum equilibrium local scour depth at 45° wing-wall abutment in non-cohesive bed sediments depends on the variables characterizing the fluid properties, flow conditions, bed sediment properties, size of the abutment and alignment of the abutment with respect to flow direction. The following functional relationship describes the maximum equilibrium local scour depth:

$$d_{se} = f_1 (U, \rho, \rho_s, g, l, \nu, h, d_{50}, \sigma_g, \theta), \quad (1)$$

where U = average velocity of approach flow, ρ = mass density of the fluid, ρ_s = mass density of the sediment, g = acceleration due to gravity, l = projected length of abutment measured perpendicular to the flow, ν = kinematic viscosity, h = approaching flow depth, d_{50} = median grain size, σ_g = geometric standard deviation of sediments, θ = inclination of the abutment with the direction of flow and d_{se} = equilibrium scour depth.

Since, ρ , ρ_s , g and ν are constant for given sediment and fluid, the relationship between d_{se} and its dependent variables can be expressed as:

$$d_{se} = f_2 (l, h, d_{50}, U, \sigma_g, \theta). \quad (2)$$

Eq. (2) can be evaluated using experimental data by writing in terms of factors:

$$d_{se} = K_l K_h K_d K_I K_\sigma K_\theta, \quad (3)$$

where, K_l = abutment length factor, K_h = approaching flow depth factor, K_d = bed sediment size factor, K_I = flow intensity factor, K_σ = bed sediment gradation factor and K_θ = abutment alignment factor.

Figure 6 is a plot of data from the present experiments and live-bed scour data of Dongol (1994) and Kandasamy & Melville (1998). The measured scour depths for different sizes of the sediments have been adjusted by dividing scour depths by sediment size factor (described later

The correlation coefficients between the experimental data and the best fitted curve, which is used to draw the envelope curve, defining factor K_d , is 0.971. According to this equation, the scour depths under live-bed scour condition increases with the increase in sediment size.

Figure 7. Coefficient (K_d) versus sediment size (d_{50}).

Figure 2 shows that when flow velocity becomes more than the threshold value, there are very little variation of maximum scour depths with uniform bed sediment size. But, for non-uniform sediment, the scour depth increases with the increase in flow intensity. The effect of non-uniformity on scour depth is considered separately. Thus, the factor K_I accounting velocity of approach flow for flow velocity beyond threshold value may be taken equal to 1. Although, it is found that under live-bed condition, particularly for V/V_c in the 1–2 range, the scour depths are little less than both the clear-water and live-bed maximum, it is considered appropriate to use $K_I = 1$ for design purposes, because the prediction of design flood involves uncertainties and there are possibilities of occurrences of high flow intensity.

Experimental data for non-uniform sediments with $d_{50} = 0.26$ mm and 0.42 mm, and $\sigma_g = 1.8, 2.25$ and 2.65 for 0.26 mm and 1.61, 1.81, 2.08, 2.55 and 3.15 for 0.42 mm are plotted in figure 5 for flow intensity $V/V_c \approx 0.97, 2.0$ and 3.5. The measured scour depths are normalized by the maximum scour depth obtained for uniform sediments corresponding to that flow intensity. Envelope curves in figure 8 define the factor K_σ accounting non-uniformity of bed sediments on maximum scour depth at 45° wing-wall abutment for the corresponding flow intensity. Linear interpretation may be done to obtain value of K_σ between any two flow intensities.

The values of K_θ , recommended by Melville (1992), for different inclination of the abutment with the direction of flow are widely used and are given in table 2. Melville plotted an envelope curve using the experimental data of Ahmad (1953), Laursen & Toch (1956), Sastry (1962), Zaghloul (1983), Kwan (1984) and Kandasamy (1985) to determine the values of K_θ for design purpose. The experimental conditions under which these data were obtained are similar to the present experimental conditions. Thus these values may be used for estimating the maximum scour depth at 45° wing-wall abutment under live-bed scour condition.

Figure 8. Coefficient (K_σ) versus geometric standard deviation of the sediment (σ_g).

Table 2. Flow alignment factor for different angles of attack (after Melville 1992).

θ (deg)	Flow alignment factor, K_θ
30	0.90
60	0.97
90	1.00
120	1.06
150	1.08

Now, substituting the values of different K s in Equation (3), maximum equilibrium local scour depth d_{se} is given by

$$d_{se} = 4.5l^{0.6}d_{50}^{0.28}K_\sigma K_\theta, \quad (6)$$

where d_{se} is in centimetre

The above equation is based on laboratory data; where the experiments were conducted under controlled conditions. Field data are not available to validate the equation. In actual field under live-bed scour condition, the flow may not be uniform. Further, during flood flow, the sediment continuity equation may not be valid in all the stretches of river due to variation of bed condition. Moreover, the proposed equation is not free from the inherent limitations of laboratory models experiments, particularly in river model involving sediment transport where the scale model is not possible. Actual field situation should be considered in the estimation of local scour depth in addition to general and contraction scour to estimate the design scour depth.

5. Comparison of experimental results with the proposed equation and also with three scour prediction equations from the literature

Following recently published scour prediction equations under live-bed scour conditions were evaluated for the conditions of the experiments:

Froehlich (1989) analysed the scour data of different researchers using statistical method and developed the following equation of live-bed scour depths:

$$\frac{d_{se}}{h} = 2.27K_s K_\theta \left(\frac{l}{h}\right)^{0.43} F_r^{0.61} + 1, \quad (7)$$

where $K_s = 0.75$ for 45° wing-wall abutments, $K_\theta = (\theta/90)^{0.13} = 1$ if $\theta =$ angle of inclination of the abutment with respect to the main flow $= 90^\circ$ and $F_r =$ approaching flow Froude number.

Melville (1992, 1995, 1997) proposed a design method to estimate the scour depth at abutments based on empirical relationships containing different factors or coefficients.

The proposed equation for 45° wing-wall abutment placed perpendicular to the flow in a rectangular channel is

$$d_{se} = K_{hl} K_I K_d, \quad (8)$$

where,

$$K_{hl} = 2l \text{ if } l/h \leq 1, K_{hl} = 2(hl)^{0.5} \text{ if } 1 < l/h < 25, K_{hl} = 10h \text{ if } l/h \geq 25$$

$$K_I = V/V_c, \text{ if } V/V_c < 1, K_I = 1 \text{ if } V/V_c > 1$$

$$K_d = 0.57 \log(2.24l/d) \text{ if } l/d \leq 25, K_d = 1 \text{ if } l/d > 25$$

Table 3. Comparison of measured and computed equilibrium scour depths.

Abutment length (l) (cm)	Sediment size (d_{50}) (mm)	Flow intensity (V/V_C)	Measured (d_{sc}) (m)	Proposed equation (m)	Froelich (1989) (m)	Melville (1997) (m)	Lim and Cheng (1998) (m)
4	0.26	1.5	0.066	0.071	0.231	0.060	0.111
4	0.26	2.0	0.069	0.071	0.247	0.060	0.105
4	0.26	3.5	0.070	0.071	0.208	0.060	0.076
4	0.26	4.98	0.070	0.071	0.196	0.060	0.063
6	0.26	1.5	0.078	0.090	0.247	0.090	0.134
6	0.26	2.0	0.081	0.090	0.266	0.090	0.127
6	0.26	3.5	0.086	0.090	0.230	0.090	0.091
6	0.26	4.98	0.086	0.090	0.221	0.090	0.075
8	0.26	1.5	0.09	0.107	0.260	0.120	0.154
8	0.26	2.0	0.094	0.107	0.281	0.120	0.144
8	0.26	3.5	0.098	0.107	0.248	0.120	0.103
8	0.26	4.98	0.098	0.107	0.241	0.120	0.084
10	0.26	1.5	0.105	0.123	0.271	0.150	0.170
10	0.26	2.0	0.107	0.123	0.294	0.150	0.159
10	0.26	3.5	0.110	0.123	0.264	0.150	0.113
10	0.26	4.98	0.110	0.123	0.258	0.142	0.092
12	0.26	1.5	0.113	0.137	0.281	0.180	0.185
12	0.26	2.0	0.115	0.137	0.306	0.180	0.173
12	0.26	3.5	0.119	0.137	0.278	0.180	0.122
12	0.26	4.98	0.121	0.137	0.274	0.156	0.099
4	0.42	1.5	0.075	0.081	0.233	0.060	0.109
4	0.42	2.0	0.076	0.081	0.245	0.060	0.102
4	0.42	3.5	0.078	0.081	0.205	0.060	0.074
4	0.42	4.96	0.077	0.081	0.195	0.060	0.061
6	0.42	1.5	0.085	0.103	0.249	0.090	0.131
6	0.42	2.0	0.090	0.103	0.264	0.090	0.123
6	0.42	3.5	0.091	0.103	0.227	0.090	0.088
6	0.42	4.96	0.091	0.103	0.219	0.090	0.073
8	0.42	1.5	0.097	0.123	0.262	0.120	0.150

Table 3. (continued).

Abutment length (l) (cm)	Sediment size (d_{50}) (mm)	Flow intensity (V/V_C)	Measured (d_{sc}) (m)	Proposed equation (m)	Froehlich (1989) (m)	Melville (1997) (m)	Lim and Cheng (1998) (m)
8	0.42	2.0	0.103	0.123	0.279	0.120	0.140
8	0.42	3.5	0.103	0.123	0.245	0.120	0.099
8	0.42	5.0	0.102	0.123	0.239	0.120	0.082
10	0.42	1.5	0.110	0.141	0.273	0.150	0.166
10	0.42	2.0	0.118	0.141	0.292	0.150	0.154
10	0.42	3.5	0.119	0.141	0.261	0.150	0.109
10	0.42	5.0	0.120	0.141	0.257	0.140	0.090
12	0.42	1.5	0.132	0.157	0.283	0.180	0.180
12	0.42	2.0	0.137	0.157	0.304	0.180	0.167
12	0.42	3.5	0.145	0.157	0.275	0.178	0.117
12	0.42	5.0	0.144	0.157	0.273	0.153	0.096
4	1.06	1.5	0.089	0.105	0.237	0.060	0.099
4	1.06	2.0	0.090	0.105	0.216	0.060	0.083
4	1.06	3.5	0.091	0.105	0.195	0.060	0.061
6	1.06	1.5	0.116	0.134	0.257	0.090	0.120
6	1.06	2.0	0.118	0.134	0.237	0.090	0.099
6	1.06	3.5	0.120	0.134	0.220	0.090	0.073
8	1.06	1.5	0.130	0.159	0.272	0.120	0.129
8	1.06	2.0	0.137	0.159	0.254	0.120	0.097
8	1.06	3.5	0.137	0.159	0.241	0.120	0.058
10	1.06	1.5	0.146	0.182	0.235	0.150	0.128
10	1.06	2.0	0.150	0.182	0.224	0.150	0.106
10	1.06	3.5	0.151	0.182	0.244	0.134	0.085
12	1.06	1.5	0.171	0.203	0.298	0.180	0.163
12	1.06	2.0	0.167	0.203	0.283	0.180	0.134
12	1.06	3.5	0.183	0.203	0.274	0.153	0.096
4	1.92	1.5	0.118	0.124	0.216	0.060	0.068
4	1.92	2.0	0.119	0.124	0.203	0.060	0.061
4	1.92	2.93	0.122	0.124	0.194	0.060	0.047

Table 3. (continued).

Abutment length (l) (cm)	Sediment size (d_{50}) (mm)	Flow intensity (V/V_C)	Measured (d_{se}) (m)	Proposed equation (m)	Froehlich (1989) (m)	Melville (1997) (m)	Lim and Cheng (1998) (m)
6	1.92	1.5	0.130	0.158	0.237	0.090	0.082
6	1.92	2.0	0.135	0.158	0.225	0.090	0.073
6	1.92	2.93	0.137	.158	0.220	0.104	0.056
8	1.92	1.5	0.148	0.188	0.254	0.120	0.115
8	1.92	2.0	0.152	0.188	0.244	0.120	0.096
8	1.92	2.93	0.156	0.188	0.241	0.120	0.078
10	1.92	1.50	0.161	0.215	0.269	0.150	0.127
10	1.92	2.01	0.172	0.215	0.261	0.150	0.105
10	1.92	2.93	0.174	0.215	0.259	0.134	0.085
12	1.92	1.50	0.200	0.240	0.283	0.180	0.111
12	1.92	2.01	0.206	0.240	0.275	0.172	0.097
12	1.92	2.93	0.210	0.240	0.275	0.147	0.073

Lim & Cheng (1998) introduced a semi-empirical equation for the time-averaged equilibrium live-bed scour at vertical-wall abutments as

$$\left(1 + \frac{d_{se}}{2h}\right)^{4/3} = \frac{1 + 1.2\sqrt{l/h}}{\sqrt{\frac{v_{sc}^2}{v_*^2} + \left(\frac{l \tan \phi_b}{d_{se}} + 1\right)^{2/3} \left(1 - \frac{v_{sc}^2}{v_*^2}\right)}}, \quad (9)$$

where ϕ_b = side slope angle of scour hole.

Eqs. (7)–(9) are used to predict the equilibrium scour depths under the conditions of experiments. As recommended by Melville (1992), scour depths calculated using Equation (9) are multiplied by 0.75 to apply them for 45° wing-wall abutment. The computed results along with flow intensity and measured values are given in table 3. From the table, it is seen that Froehlich's equations over-predict the scour depths for all sizes of abutment length and sediments. This may be due to the addition of 1 on the right hand side of the equation particularly at higher depth of flow. Melville's and Lim and Cheng's equations give results close to the measured values. However, Melville's equation slightly over-predicts when the abutment length is large and sediment size is small, but under-predicts when sediment sizes are large and abutment lengths are small. Lim and Cheng's equation gives the maximum scour depths at flow intensity $V/V_c = 1$, the scour depth decreases with the further increase of flow intensity and thus under-predicts at higher flow intensity.

6. Summary and conclusions

The results of laboratory experiments on local scour at 45° wing-wall abutments in uniform and non-uniform sediments under a live-bed scour condition have been used to analyse the effect of abutment lengths, flow intensity, sediment sizes, flow depths and sediment gradation. It is observed that scour depths increases with the increase of abutment length but the increase is not linear for all lengths of abutment. The increase is more for short abutment lengths compared to long abutment. The normalized equilibrium scour depths (dividing scour depth by abutment length) have been related to the flow intensity. The equilibrium scour depth increases with increase in flow intensity up to threshold value ($V/V_c = 1$) and reaches the clear water peak. It then decreases, again increases and reaches the live-bed maximum at flow intensity in the range $V/V_c = 3$ to 5. It is found that the live-bed maximum scour and clear water peak are almost same for bigger size sediments. However, for ripple forming sediments, live-bed scours are little more than clear-water scour. Scour depth increases linearly with the increase of sediment size under clear water scour conditions for all sediment sizes at constant flow intensity ratio whereas, under live-bed condition, the increase of scour depths are not linear. For bigger size of sediments ($d_{50} > 1$ mm) the increase is small. The effect of approach flow depths under live-bed condition is almost negligible. Scour depths decreases with the increase of nonuniformity coefficient.

A design equation is proposed based on experimental data. The proposed equation is conservative as all the measured data is a little less than the computed value. Thus, the computed value is acceptable for design purpose. Comparison of computed scour depths, for the range of conditions covered by the experiments, with the three other equations show that Froehlich's equations over predicts the scour depths for all sizes of abutment length and sediments. Melville's and Lim and Cheng's equations give results close to the measured values. However, Melville's equation slightly over-predicts when the abutment lengths are large and sediment sizes are small but

under-predicts when sediment sizes are large and abutment lengths are small. Lim and Cheng's equation under-predicts at higher flow intensity.

List of symbols

d_{50} median diameter of sediment particles;
 d_{16} 16% finer particle diameter;
 d_{84} 84% finer particle diameter;
 d_{se} maximum scour equilibrium depth;
 F_r Froude number, $V/(gh)^{0.5}$;
 g gravitational acceleration;
 h approaching flow depth;
 K_d particle size factor;
 K_{hl} flow depth-abutment length expression;
 K_I flow intensity factor;
 K_s abutment shape factor;
 K_θ abutment alignment factor;
 K_σ function depending on σ_g ;
 R_e Reynolds number, Vh/ν ;
 s relative density of sediment particles;
 V average approaching flow velocity;
 V_c critical velocity for sediment particles;
 v_{*c} critical shear velocity of bed sediment;
 θ angle of attack;
 ν kinematic viscosity of water;
 ρ mass density of water;
 ρ_s mass density of sediment particles;
 σ_g geometric standard deviation;
 ϕ angle of repose of sediment;
 ϕ_b side slope angle of scour hole;

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