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Live-Bed Local Scour around Wing-wall Abutments

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Abstract

Local scour experiments were performed with four different uniform cohesionless sediment diameters d_{50}= 0.26 mm, 0.42 mm, 1.06 mm and 1.92 mm and three wing-wall abutments with projected lengths perpendicular to the flow l = 0.06 m, 0.08 m and 0.10 m. The tests were performed in the flume located in the Hydraulics Engineering Laboratory at National Institute of Technology Silchar, Assam. These tests were conducted in the range of velocity ratio V/V_c values 0.71 to 5. The plotting of scour depths d_{se} *vs* V/V_c show two peak values of d_{se}, one at V/V_c value near 1 and the other between 3 to 5. It is found that the scour depth increases with the increase of sediment sizes up to threshold value of flow (V/V_c = 1). The measured values of scour depth are compared with calculated values using three different live-bed local scour equations for the conditions of the tests.

Key words: Scour, Abutments, Hydraulics

1. Introduction

When natural flow is disturbed by placing some obstruction in the form of bridge abutments, bridge piers or any other structures, the flow accelerates around these 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. Brice and Blodgett (1978) studied 383 bridge failures caused by catastrophic floods. Approximately half of these failures were caused by local scour. Although, some of the scour was attributed to the increased local and contraction scour, due to accumulation of ice and debris, a large numbers resulted from erroneous prediction of scour depth during engineering design. These studies underscore the importance of prediction of scour depths near bridge abutments and piers under design storm conditions. Under-prediction can result in costly bridge failure and possibly in the loss of lives, while over-prediction can result in unnecessary increase in construction cost.

The flow and the scouring process are complex in details 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 restricted to clear water scour condition even though the majority of bridge failures due to scour 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 from the viewpoint of a faster arrival of an equilibrium scour hole, where the scour depth fluctuates around a mean equilibrium value (Breusers and Raudkivi 1991, Hoffmans and Verheij 1997; Lim and Cheng 1998; Melville and Coleman 2000; Ballio et al. 2010).

Very few studies on live-bed scour at bridge abutments are available in the literature. Lursen(1963) and Gill (1972) analysed the problem based on an analogy to scour in a long contraction. Kandasamy(1989) and Dongol(1994) described some aspects of the scouring mechanism. Lim and Cheng (1998) proposed one semi-empirical equation based on the flow and sediment mass continuity equations. Sheppard and Miller Jr (2006) have conducted some experiments on bridge pier 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.

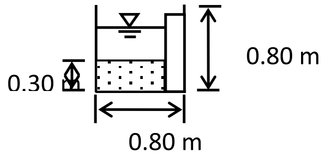
In the present studies, live-bed scour experiments at wing-wall abutments are done to understand the effect of different parameters on equilibrium scour depth. The results are compared with calculated values using three different live-bed local scour equations for the conditions of the tests.

2.Experimental setup and procedure

Experiments were conducted at the Hydraulics Engineering Laboratory at National Institute of Technology Silchar, Assam. A rectangular horizontal 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 Fig. 1. An adjustable tailgate was installed at the downstream end of the flume to control the flow depth. The choice of the flume and the location of the test section were made in such a way that— (a) the width of the flume was wide enough to have three-dimensional flow and (b) the flow became fully developed before it reaches the test section. 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 projected lengths perpendicular to the flow l =0.06 m, 0.08 m and 0.10 m were used. The bed sediments used in the experiments were near uniform with median grain sizes d_{50} of 0.26 mm, 0.42 mm, 1.06 mm and 1.92mm.The non-uniformity co-efficient 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 pump was allowed to run for different durations for different experiments. For clear water scour experiments it was allowed to run around 30 hours to reach the dynamic equilibrium of scour depth whereas, for live bed scour it was around 8 hours. The scour depth is measured with the help of point. 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 minutes 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 at the upstream during the experiments and bed level outside the influence zone of local scour was tried to maintain 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. 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.



Section A-A

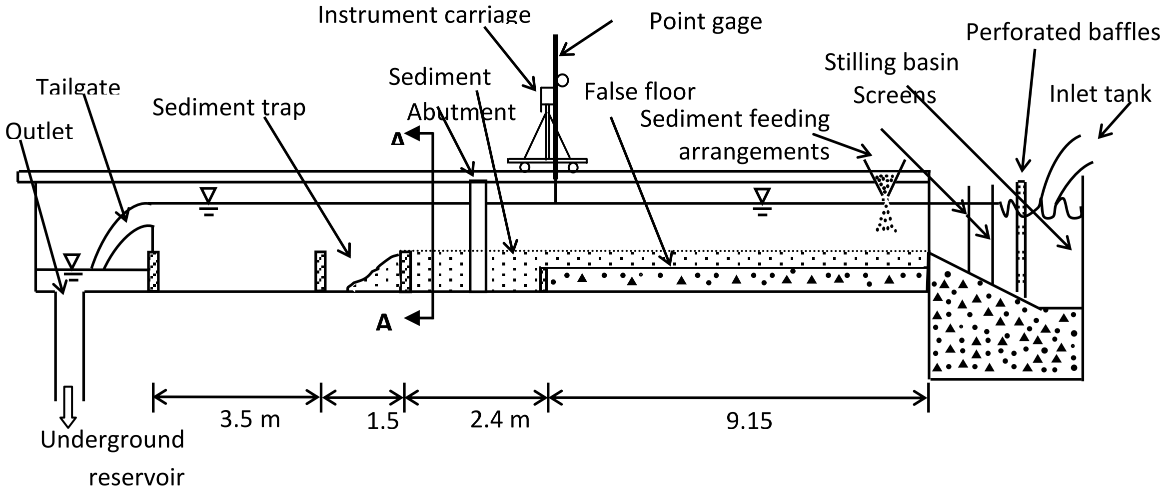


Fig 1: Schematic diagram of experimental set-up

Sediment size (d_{50}) (mm)	Flow depth (*h*) (m)	Flow velocity (*V*) (m/s)	Flow intensity (V/V_C)	Froude No. (F_r)	Reynolds No. (R_e)
0.26	0.09-0.2	0.197-1.25	0.71-4.98	0.140-1.33	39375 - 112500
0.42	0.087-0.2	0.205-1.28	0.71-5.0	0.146-1.38	41000 -111250
1.06	0.087-0.2	0.297-1.29	0.71-3.52	0.212 - 1.40	59375 - 112500
1.92	0.08-0.2	0.40-1.40	0.71-2.93	0.286- 1.59	80000 - 112500

Table 1. Experimental conditions

3. Results and Analysis

In the present study, most of the experiments were conducted on live-bed condition. Few experiments were conducted on clear-water condition to maintain the continuity in the data set for assessing the effect of flow intensity on scour depth. The detailed experimental conditions are summarised in Table 1. 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. The effect of flow intensity and sediment size are discussed below:

3.1 *Effect of flow intensity on Scour Depth*

The influence of flow intensity, (V/V_c) on equilibrium scour depth (d_{se}) is shown in Fig. 2. The normalised scour depth (d_{se}/l) as a function of flow intensity, (V/V_c) is presented in Fig. 3. From the figures it is found that the scour depth increases with the increase of flow intensity and then decreases and again reaches a second peak as was found by many researchers (Ettema 1980; Chiew 1984; Melville and Chiew 1999, Sheppard et al. 2006). The first peak scour depth is known as threshold peak and occurs at flow velocity V_c. The second maximum scour depth known as live-bed peak probably occurs at about the transition flat bed stage of sediment transport on the channel bed. The presentations of experimental data show that the live-bed peak scours depth occur at V/V_c between 3 to 5. In all the experiments it is found that the live bed maximum scour depth is greater than threshold peak for sediment sizes (d_{50}) 0.26 mm and 0.42 mm, whereas, for sediment sizes 1.06 mm and 1.92 mm the threshold peak scour depth is almost closed to live-bed scour depth. The reason may be due to the formation of ripples in the bed with sediment sizes less than 0.6 mm.

3.2 *Effect of sediment sizes on Scour Depth*

The effect of sediment size (d_{50}) on equilibrium scour depth (d_{se}) is shown in Fig. 4. Normalized scour depth (d_{se}/l) *vs* normalized sediment size (l/d_{50}) is plotted in Fig. 5. From the Fig. 3, it is found that d_{se} increases with the increase of sediment sizes under clear water scour conditions. The increase of d_{se} with the increase of d_{50} is significant for d_{50} = 0.26 mm and 0.42 mm, but the increase is very small for d_{50} = 1.06 mm and 1.92 mm. Similar results were reported by Dey and Barbhuiya (2004). The trend is similar for all lengths of abutments tested. Under live-bed conditions, d_{se} is little less for 0.26 mm sediments then the d_{se} for d_{50} = 0.42 mm, 0.1.06 mm and 1.92 mm. The differences of scour depths d_{se} for d_{50} = 0.42 mm, 0.1.06 mm and 1.92.mm are negligible under live-bed scour. The presentation of normalized equilibrium scour depth (d_{se}/l) vs sediment size (l/d_{50}) show that d_{se}/l decreases with the increase of l/d_{50} at smaller value of normalized sediment size ($l/d_{50} < 100$). At larger values of normalized sediment size ($l/d_{50} > 100$), d_{se}/l decreases, but the decrease is not very significant. This observation is not in conformity with the findings of Ettama (1980) for clear water scour and Chiew (1984) for live-bed scour for circular piers. Their data show that scour depth increases with the increases of l/d_{50} up to $l/d_{50} = 50$. For $l/d_{50} > 50$, d_{se} is independent of the sediment size. However, Wong (1982) reported an observation similar to the present findings for a constant value of V/V_c, which was close to the unity. The smaller scour depths at d_{50} = 0.26 mm may be due to the presence of some cohesive force in the sediments and formation of ripples in the bed.

4. Comparison of experimental results with three scour prediction equations under live-bed condition from the literature

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

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

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

Where, $K_s = 0.75$ for wing-wall abutments, $K_\theta = (\theta_a/90)^{0.13} = 1$ if θ_a = angle of inclination of the abutment with respect to the main flow = 90^0 and F_r = approaching flow Froude number.

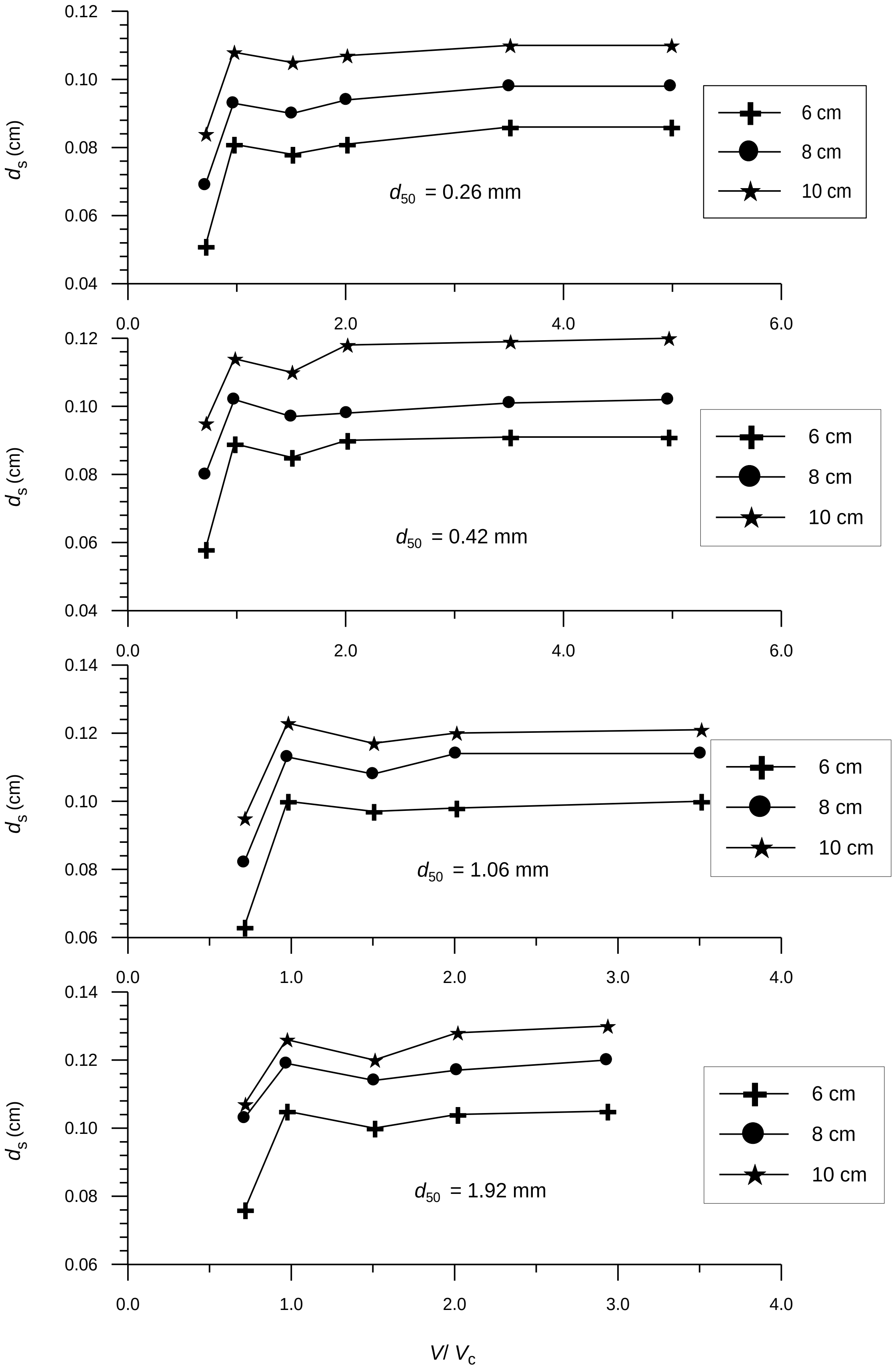


Fig 2: Scour depth (d_s) versus flow intensity (V/V_c)

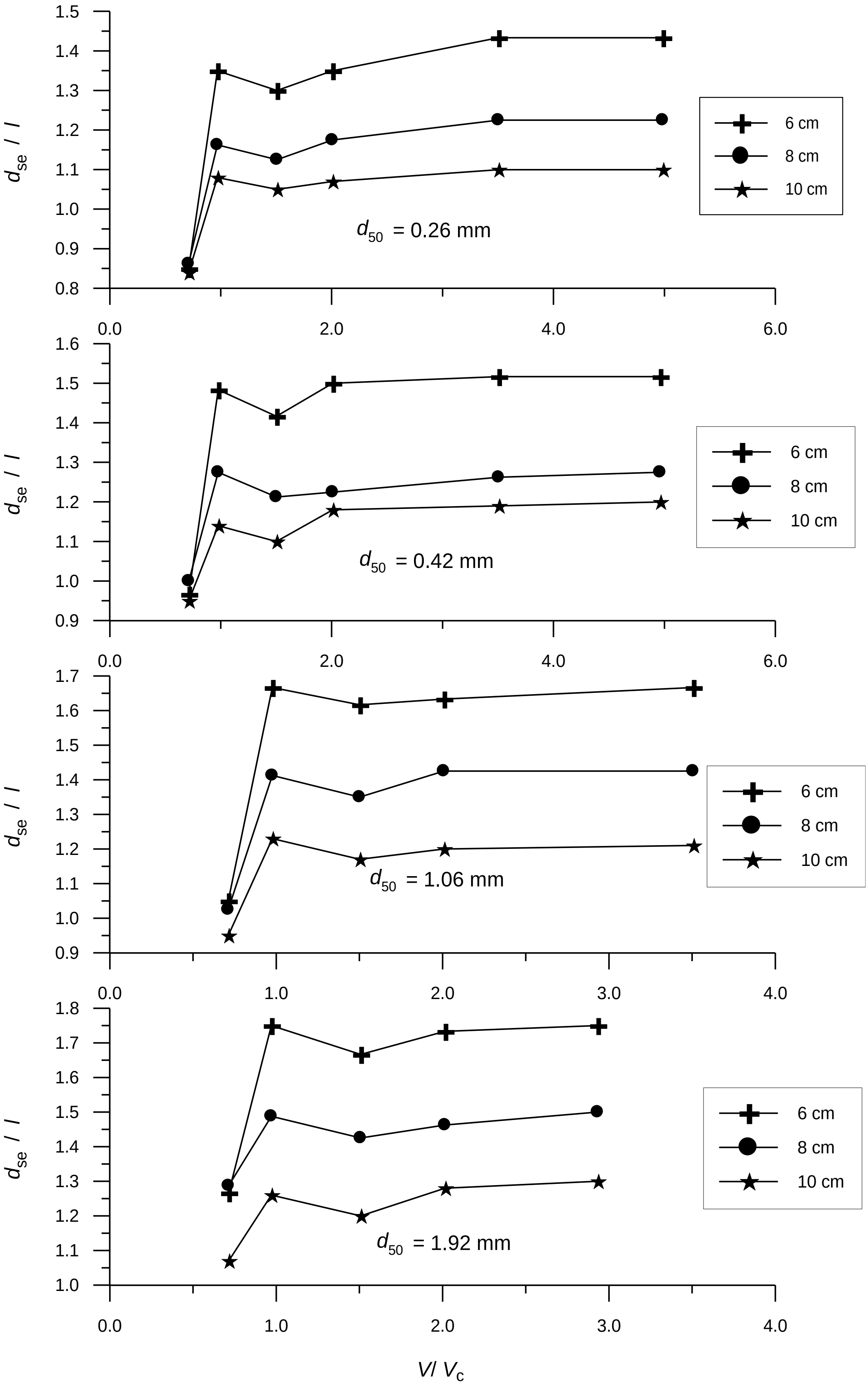


Fig 3: Normalized scour depth (d_{se} /l) versus flow intensity (V/Vc)

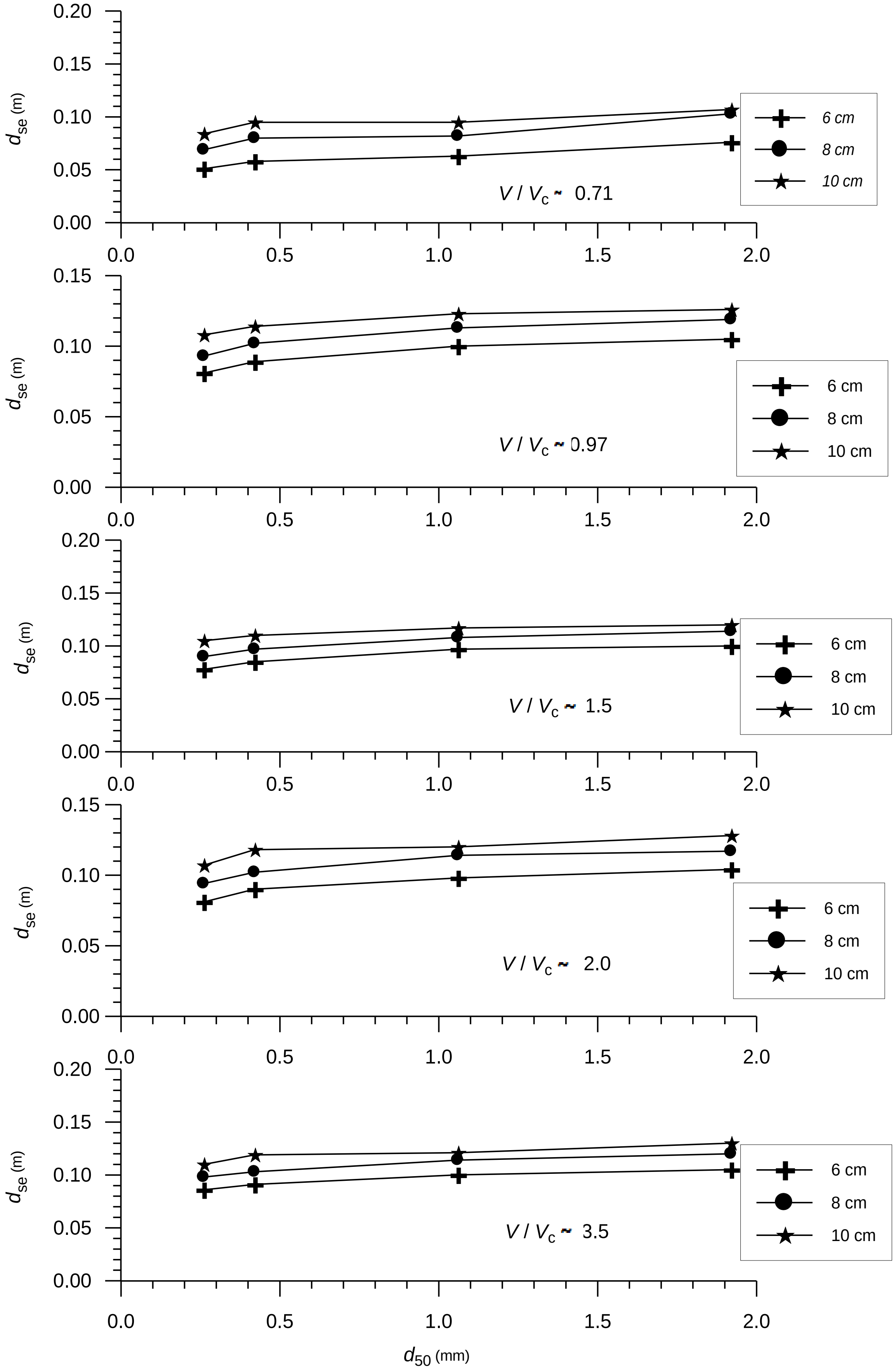


Fig 4: Scour depth (d_s) versus sediment size (d_{50})

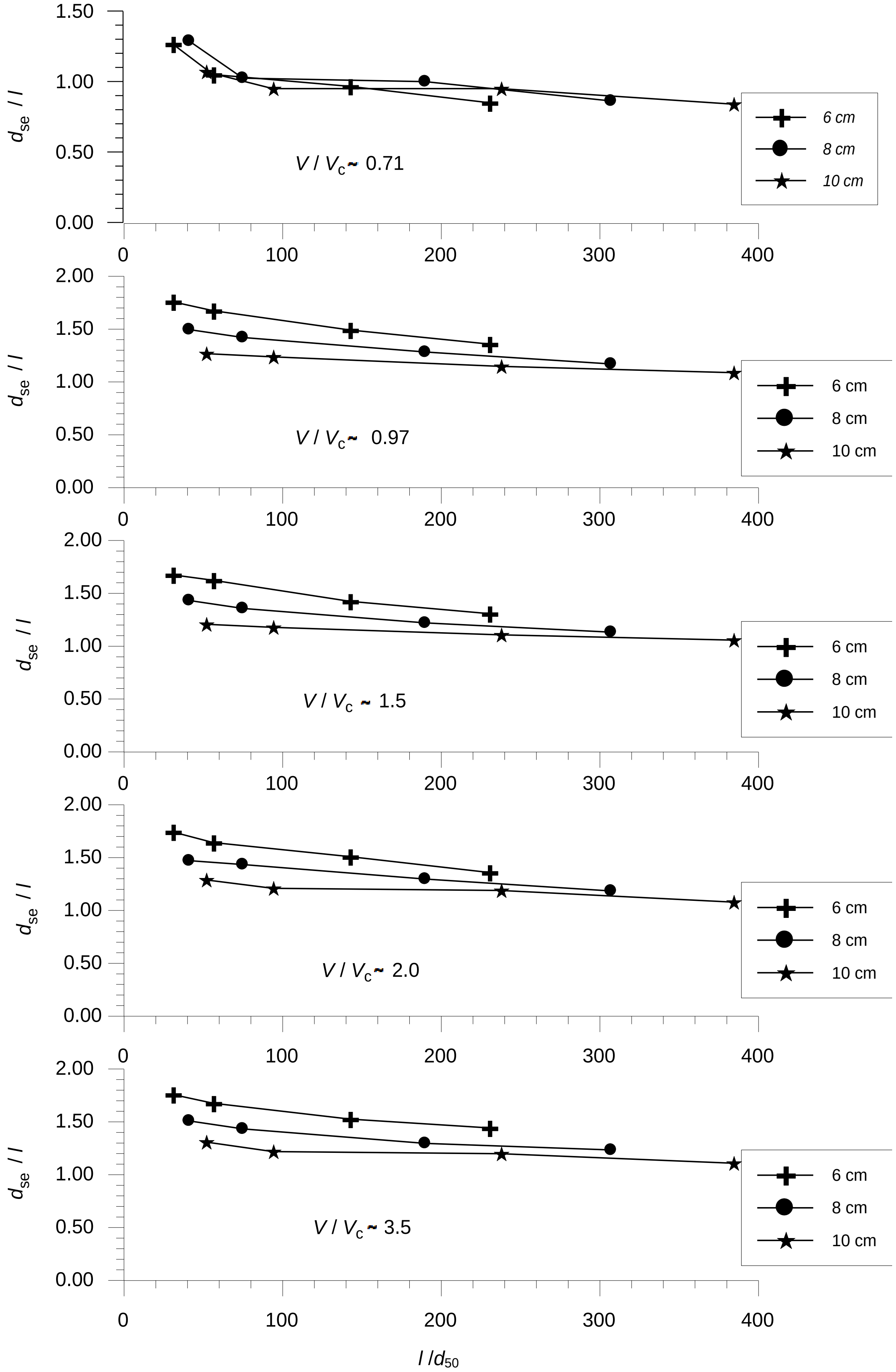


Fig 5: Normalized scour depth (d_{se} / l) versus flow intensity (l / d_{50})

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 wing-wall abutment placed perpendicular to the flow in a rectangular channel is

$$d_{se} = K_{hl} K_I K_d K_s \tag{2}$$

Where, $K_{hl} = 2l$ if $l/h \le 1$, $K_{hl} = 2(hl)^{0.5}$ if $1 < l/h < 25$, $K_{hl} = 10h$ if $l/h \ge 25$

$K_I = V/V_c$ if $V/V_c < 1$, $K_I = 1$ if $V/V_c > 1$

$K_d = 0.57 \log(2.24 l/d)$ if $l/d \le 25$, $K_d = 1$ if $l/d > 25$

$K_s = 1$ for vertical-wall abutments and 0.75 for wing-wall abutments.

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

$$\left(1 + \frac{d_{se}}{2h}\right)^{4/3} = \frac{1 + 1.2\sqrt{l/h}}{\sqrt{\frac{u_{*c}^2}{u_*^2} + \left(\frac{l \tan\phi_b}{d_{se}} + 1\right)^{2/3}\left(1 - \frac{u_{*c}^2}{u_*^2}\right)}} \tag{3}$$

where ϕ_b = side slope angle of scour hole.

Eqs. (1)-(3) are used to predict the equilibrium scour depths under the conditions of experiments. The computed results along with flow velocity intensity and measured values are given in Table-x (). From the table, it is seen that Froehlich's equations over predicts the scour depths for all sizes of abutment length and sediments. This may be due to the addition of 1 in 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 little over predicts when the abutment length is large and Lim and Cheng's equation gives the maximum scour depths at flow intensity V/V_c =1.5, the scour depth decreases with the further increase of flow intensity.

Test No	V/V_c	Measured (m)	Froehlich (1989) (m)	Melville (1997) (m)	Lim and Cheng (1998) (m)
3	1.5	0.078	0.247	0.09	0.134
4	2.0	0.081	0.266	0.09	0.126
5	3.5	0.086	0.230	0.09	0.088
6	4.98	0.086	0.221	0.11	0.073
9	1.5	0.09	0.260	0.12	0.153
10	2.0	0.094	0.281	0.12	0.143
11	3.5	0.098	0.248	0.12	0.100
12	4.98	0.098	0.241	0.127	0.082
15	1.5	0.105	0.299	0.15	0.127
16	2.0	0.107	0.353	0.15	0.103
17	3.5	0.11	0.264	0.15	0.107
18	4.98	0.11	0.258	0.142	0.090
21	1.5	0.105	0.249	0.09	0.130
22	2.0	0.107	0.264	0.09	0.121
23	3.5	0.11	0.227	0.09	0.086
24	4.96	0.11	0.219	0.108	0.071
27	1.5	0.097	0.262	0.12	0.149
28	2.0	0.103	0.279	0.12	0.138
29	3.5	0.103	0.245	0.12	0.097

30	5.0	0.102	0.239	0.125	0.079
33	1.5	0.11	0.275	0.15	0.162
34	2.0	0.118	0.328	0.15	0.116
35	3.5	0.119	0.261	0.15	0.104
36	5.0	0.12	0.199	0.14	0.127
39	1.5	0.097	0.257	0.09	0.118
40	2.0	0.098	0.237	0.09	0.097
41	3.5	0.1	0.220	0.108	0.070
44	1.5	0.108	0.267	0.12	0.142
45	2.0	0.114	0.239	0.12	0.126
46	3.5	0.114	0.208	0.125	0.099
49	1.5	0.117	0.271	0.15	0.094
50	2.0	0.12	0.224	0.15	0.102
51	3.5	0.121	0.184	0.134	0.127
54	1.5	0.100	0.219	0.09	0.119
55	2.0	0.104	0.211	0.09	0.093
56	2.93	0.105	0.199	0.104	0.081
59	1.5	0.114	0.254	0.12	0.112
60	2.0	0.117	0.244	0.12	0.093
61	2.93	0.120	0.241	0.12	0.076
64	1.50	0.120	0.269	0.15	0.118
65	2.01	0.128	0.261	0.15	0.101
66	2.93	0.130	0.259	0.134	0.084

Table 2. Comparison of Measured and Computed Equilibrium Scour Depth.

5. Conclusions

The results of laboratory experiments on local scour at 45^o wing-wall abutments in uniform sediments under a live-bed scour condition have been used to analyze effect of flow intensity, and sediment sizes for different abutment lengths. The equilibrium scour depth and the normalized equilibrium scour depth (dividing scour depth by abutment length) have been related to the flow intensity. The equilibrium scour depth increases with increase in flow intensity upto threshold value ($V/V_c = 1$) and reaches the clear water peak and then decreases and again increases and reaches the second peak known as live-bed peak scour at flow intensity $V/V_c = 3$ to 5. It is found that the live-bed peak scour is little more than the clear water peak for sediment sizes 0.26 mm and 0.42 mm, but live-bed peak and clear water peak are almost same for sediment sizes 1.06 mm and 1.92 mm. The presentation of scour depth with sediment size shows that the scour depth increases with the increase of sediment size under clear water scour conditions whereas, under live-bed condition, scour depth is almost independent of sediment sizes. Normalized plotting of data show that d_{se}/l decreases with the increase of l/d_{50} at smaller value of normalized sediment size ($l/d_{50} < 100$). At larger values of normalized sediment size ($l/d_{50} > 100$), d_{se}/l decreases, but the decrease is not very significant.

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