Experimental Study on Riprap Extension around Wing-wall Abutments

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Abstract

Various equations are proposed for stable design of riprap stones in different abutment shapes. However, extension of the riprap layer at wing-wall abutments and its launching action is not properly studied. In the present paper, the necessary dimensions of the riprap layer around bridge wing-wall abutments placed in flood plain was studied experimentally. To reduce the volume of required stones, the launching action of the riprap layer was also investigated with accepting 10% loss of the riprap area due to some scouring downstream of the riprap layer. It was postulated that limited scouring downstream of the riprap if does not develop at its sides is acceptable. An empirical equation was also developed for the depth and location of the maximum scour hole downstream of the riprap layer. Experimental results indicated that flow intensity and the riprap extension's length and width caused the most pronounced effects on the pattern of scouring downstream of the riprap layer. Moreover, the results showed that changing riprap thickness from $3D_{50}$ to $5D_{50}$ where D_{50} is average size of riprap stones had no significant effect on the scour depth in the range of variables tested.

1. Introduction

Reports indicate that most of bridge failures are due to scouring at their piers and abutments [1,2, 3,4,5,6]. The flow field around a bridge abutment involves a complex 3D structure, including flow separation and downstream vortex shedding [7]. The main features of this complex structure are downward flow, horseshoe vortices, and wake vortices [8,9]. While the downward flow impinges the streambed and dislodges sediments, the horseshoe vortex intensifies scouring. On the other hand, wake vortices act as tornados and transport sediment downstream and enlarge the scour hole. Together, these vortices deepen the scour hole around the abutments [10].

Local scouring undermines the abutments and endangers the bridge stability [11,12,13,14]. In a survey it was found that 80,000 bridges were classified as scour-sensitive in the U.S.[15]. In Iran, damages resulting from bridge failures in flood events between 2002 to 2012 raised to $562.5 million, with a significant portion of these losses attributed to scouring [16]. The impact of flooding events on bridge infrastructure is further underscored by the experience in the UK in 2009, where 20 road bridges suffered partial or complete failure [17].

Prevention and control of this phenomenon is, therefore, one of the missions of hydraulic and river engineers. Various materials can be used to stabilize the river bed and to protect the piers and abutments against scouring, including vanes, riprap, collars, and geobags [18,19,20,21,22,23]. Using riprap layer around bridge abutments is one of the most common stabilization methods [24,25,26,27]. If the required stone is available, using riprap as a protection measure is a cost-effective method Weight of the riprap stones increases the streambed strength against high velocities and turbulence caused by the presence of the abutment in the flow. With a riprap layer protection, scouring removes away from the abutment to the rim of the riprap layer. In addition, in excessive scouring condition riprap layer around an abutment acts as a launching apron and by fall in to the sides of a developing scour hole, prevents the scour hole development and protects the abutment foundation from undermining [28].

Abutments are constructed in different shapes mainly including vertical wall, spill-through and wing-wall abutment, each leading to various stress distributions at the river bed [29,30,31]. Therefore, different equations are needed for design of stable riprap size in each abutment type. Riprap design in the vicinity of the abutment includes determination of three parameters which are i-stable stones size, ii-extension shape and dimensions, and iii- the adequate thickness. There has been a significant research effort focused on the design of riprap aprons to protect abutments. Equations to determine the stable riprap size for vertical wall and spill-through abutments are presented in Pagán-Ortiz [32], Lagasse et al. [33] ,Brown and Clyde [34], Atayee et al. [35], Constantinescu and Wu [36], and for wing-wall abutment in Melville et al. [28] and Wu et al. [24]. Dey et al. [37] studied local scour and riprap stability at a 45° wing-wall abutment in a degrading river bed. Melville et al. [28] studied extent and type of riprap protection on spill-through abutments located in the flood plain of a compound channel. Cardoso and Fael [38] addressed the design of riprap layer near vertical-wall bridge abutments. An equation for minimum necessary extent of the riprap layer for both spill-through and vertical-wall abutments was also given by Cardoso et al. [39].

Though there are equations for design of riprap size around very common wingwall abutments, there is no data on the riprap extension, and engineering practice is still based on limited evidence. No information is also available on how launching action protects further development of scouring towards an abutment. Stable riprap size for this type of abutment was studied in a previous work [23]. In this work an empirical equation is developed for the stable size of riprap stones corresponding to the upstream Froude number and characteristics of the wing-wall abutment. In the present research, the necessary extension of the riprap layer around a 45° wing-wall abutments is studied. In addition, equations expressing the depth and location of the downstream scour hole corresponding to riprap layer dimensions are also proposed. Some additional experiments were also performed to assess the effect of riprap thickness on scouring pattern.

2. Design of the riprap extension

To prevent scouring around an abutment a very large riprap extension would be necessary. However, an abutment will be safe if the scour hole is removed from the vicinity of the abutment to a distance away from it. Furthermore, the scour hole should be kept downstream of the bridge crossing. This is because scour hole development at the bridge section may overlap and intensifies the piers' scour hole [40]. It should also be noticed that scouring at the riprap layer edges cause a launching action. In this way some riprap stones drop in to the scour hole and protect it from further development.

To design riprap extension in the present work two assumptions were made. 1-scour hole should be kept downstream of the riprap layer and bridge crossing and 2- edge failure and launching action does not reduce the original riprap area more than about 10%. The first assumption was made because the extension of the scour hole at the side of the protective layer may overlaps the piers' scour. The second assumption was made arbitrary not to lose much of the protective layer and in the same time use the launching action to reduce the longitudinal dimension of the protective layer. To prevent any scouring downstream of the riprap layer, the longitudinal dimension of the layer becomes too long [41].

Parameters effective on the scour hole depth around bridge abutments are presented by Melville [42] and Raudkivi [43]. Adding additional terms related to riprap layer and considering a rectangular form for the riprap extension as shown in Figure 1 one can write the following effective parameters on the scour hole depth downstream of the riprap layer:

$$f(D_{s\max}, U, U_c, d_{50}, W_a, h, \rho, \rho_s, W_{u0}, L_{d0}, L_{u0}, \sigma, K_s) = 0 \tag{1}$$

where D_{smax} is the maximum depth of the scour hole, U is the upstream undisturbed average velocity, U_c is the threshold velocity of the bed material, d_{50} is median size of bed particles, h is upstream flow depth, ρ_s is the stones density, ρ is water density W_a is the abutment length in transverse flow direction, , W_{u0} is length of the riprap extension in transverse flow direction, L_{d0} is the length of riprap extension in longitudinal flow direction downstream of the abutment , L_{u0} is the length of riprap extension upstream of the abutment in longitudinal flow direction, σ is the geometric standard deviation of particle size distribution, and K_s is the abutment shape coefficient (Figure 1).

Figure 1. Characteristics of the abutment and the riprap extension.

The scour depth may be normalized by h or W_a or $\sqrt{hW_a}$ [44]. In the present study, the scour depth is normalized by $\sqrt{hW_a}$ due to better correlations obtained during the regression analysis. According to Melville [42], scour hole depth is correlated to the abutment length in short abutments, to both abutment length and flow depth in average abutments, and to flow depth in long abutments. In this study, both short and average length abutments have been studied. Some parameters including ρ/ρ_s, σ, and K_s were omitted from the equation since they were constant during the experiments. $\frac{d_{50}}{W_a}$ is much less than 1/50 and therefore its effect on scour depth is negligible [42]. In addition, it was found during the experiments that L_{u0} has no effect on scouring downstream of the riprap layer and was removed from the equation too. Eq. (1) can therefore be simplified in the following form:

$$\frac{D_{s\max}}{\sqrt{hW_a}} = f\left(\frac{U}{U_c}, \frac{W_{u0}}{W_a}, \frac{L_{d0}}{W_a}, \frac{h}{W_a}\right) \tag{2}$$

In Eq. (2) U/U_c which indicates the flow intensity is a significant parameter used by many researchers. W_{u0}/W_a and L_{d0}/W_a are parameters that represent the area protected by riprap and h/W_a represents the effect of relative flow depth. It can also be inferred that the location of the maximum scour hole would also be a function of the above parameters.

3. Experimental setup

Experiments were conducted in a horizontal flume, 10 m long 0.74 m wide. The discharge up to 0.075m^3/s was supplied by two centrifugal pumps. A rectangular sharp-crested weir with a manometer was used to measure the flow discharge at the flume end. Tail water elevation was controlled by a gate at the downstream end of the flume, and flow depth was measured by a point gage. The flume had a working section in the form of a recess below its bed which was filled with sediment and located 5 m downstream from the flume entrance where the abutment was installed (Figure 2). The bed was covered by sand with median size of 0.72 mm and a relative density of 2.65. A 45° wing-wall abutment as shown in Figure 1 was utilized in three 10 cm, 15 cm, and 20 cm lengths in transverse flume direction (W_a). Narrower and wider lengths of the abutment (L_{a1} and L_{a2} in Figure 1) are 15 cm and 35 cm respectively. The abutment was made of transparent Perspex and was anchored to the flume's bed and sides in order to resist the forces imposed by the flow. Experiments were conducted with different transverse and longitudinal extensions of the riprap layer. In each experiment depth and location of the scour hole as well as the launching area of the riprap layer was recorded.

Figure 2. Laboratory flume plan.

The length of the abutment in transverse direction in the present work was between 14% and 27% of the flume width. Since the abutment was protected by riprap layer, scouring occurred only downstream of the riprap protection layer that is downstream of the contraction section. It is therefore expected that the effect of the contraction ratio be negligible on scour depth. On the other hand, Morales and Ettema [45] in their study on flow contraction around spill-through abutments in compound channels showed that for L/B_f<0.3 and B_f/B > 0.7 less than 10% of floodplain flow enters the main channel, where B_f is the floodplain width, B the channel half-width and L the abutment length. Therefore, in the present work the abutment was considered in a wide flood plain at which the effect of the main channel is negligible.

Various researchers have proposed different values from 1.5 to 3 times the riprap median size for the riprap thickness [46,33]. The thickness of the riprap layer was set to 3 times the median stones size *($3D_{50}$)* in the present work. In addition, to study the effect of the riprap thickness on the launching action, the scour hole geometry and riprap extension, a number of experiments were repeated with the riprap thickness equal to $5D_{50}$. To prevent the potential winnowing failure, a granular filter was also used underneath the riprap layer [47].

Melville and Chiew [48], in their study on bridge piers assumed that the time to achieve equilibrium scour is the time at which the rate of scouring reduces to 5% of the pier diameter in the succeeding 24-hour period. Coleman et al. [49], defined the time to achieve equilibrium scour as the time at which the rate of scour reduces to 5% of the smallest of the abutment length or the flow depth in the succeeding 24-hour period. To determine the scouring time of equilibrium in the present studies, the maximum and minimum flow intensities were tested with the 10 cm long abutment in the presence of riprap layer. The scour hole depth at the riprap layer edge was then measured over time and the longest time at which changing in scour hole depth was less than 5% of abutment length or flow depth in 24 hours was achieved in the higher flow intensity after 48 hours. Based on these experiments the time at which the scouring reached 90% of its equilibrium value in the worst case of these two tests was about 24 hours. Therefore, all tests were carried out in 24 hours. Figure 3 shows time development of scouring for two of experiments with low and high flow intensity (Table 1). As can be seen Series 10-3-3 satisfies the definition for equilibrium scour time after 48 hours and in Series 10-1-3 with lower flow intensity change in the scour depth is negligible after 24 hours.

Figure 3. Time development of scouring for experiment with code 10-1-3 and 10-3-3 (see Table 1).

Studies were performed with various U/U_c for each length of the abutment. U_c is calculated by equations of Oliveto and Hager [50]. Flow intensity was limited between $0.5 \leq U/U_c \leq 0.87$ since in flow intensities exceeding 0.87, the scour hole depth in unprotected abutment reached the flume bed and in flow intensities lower than 0.5, scouring around the riprap layer was negligible. A summary of the parameters value in various experiments is given in Table 1. In this table, X is the longitudinal distance of the maximum scour location from the abutment axis and the last column shows the percent of the launched riprap area.

The stable size of riprap with a relative density of 2.65 was determined based on the equation presented by Movahedi et al. [23] for wing wall abutments as follows:

$$\frac{D_{50}}{h} = 0.28 \times S_f \times Fr^{1.5} \times \left(\frac{W_a}{h}\right)^{0.52} \times \left(\frac{L_{a1}}{h}\right)^{-0.57}$$
$$S_f = 2.0 \rightarrow if : \frac{D_{50}}{h} < 0.02 \qquad (3)$$
$$S_f = 1.35 \rightarrow if : \frac{D_{50}}{h} \geq 0.02$$

In this equation D_{50} is median stone size of stable riprap, Fr the Froude number is defined based on approach flow condition, and S_f is factor of safety. By using this equation stable size of 2.87 mm to 5.56 mm were calculated for flow intensities between 0.518 and 0.87 (Table 1). Observations proved that calculated riprap stones were stable in all experiments.

Table 1. Summary of the experimental conditions.

A rectangular riprap extension as illustrated in Figure 1 was utilized. Since the scour hole was expected to move toward downstream at the presence of the riprap layer, the extension length of riprap layer (L_{d0}) was regarded as the most important effective parameter and assigned 4 different values for each flow condition. Experiments showed that as the flow intensity increases W_{u0} should also increase to prevent development of the scour hole toward upstream along the side of the riprap layer. On the other hand, experiments showed that L_{u0} has no significant effect on scour hole characteristics at side and downstream of the abutment and was therefore selected a minimum value to prevent scouring at the upstream of the riprap layer, equal to half of W_a. Tests were also performed without riprap for each flow condition and abutment length to study the scour depth and dimensions without riprap protection.

4. Results and Discussion

4.1 Extension of the riprap layer

Since it was intended to limit the scouring at downstream of the riprap layer, the required extension of the riprap layer in various U/U_c. was found by trial and error. At the beginning of each test, scouring started from downstream of the riprap layer corner (point A in Figure 4). However, when flow intensity was larger than 0.7, the scour depth increased considerably with flow intensity and it was necessary to increase L_{d0} to reduce the scour depth and prevent it from developing towards upstream. In another word to control and reduce the scour hole depth larger riprap extension was necessary for U/Uc>0.7. The required L_{d0} can be decided based on acceptable scour hole depth downstream of the riprap layer as will be explained in the following section.

Figure 4 shows development of the scour hole at the riprap layer in 2 of the experiment codes 15-1-2 and 15-2-3 (Table 1). In Figure 4(b), L_{d0} as well as W_{u0} are the same as in Figure 4(a) with higher U/Uc. According to the observations in this study, W_{u0} had also an important role regarding development of the scour hole towards upstream at the side of the riprap layer. Lower W_{u0} caused extensive loss of original riprap area due to the deeper scour hole and therefore the launching action. It was observed that for flow intensities less than 0.8, a riprap width W_{u0} equal to W_a was large enough to hold the scour hole downstream of the riprap layer extending only slightly towards upstream. For larger flow intensities, due to excessive riprap launching action W_{u0} was selected equal to 1.5 times the abutment length W_a. The reduction of the riprap area due to launching action was minor (less than 10%, see Table 1) in most of these tests (see Figure 4).

Figure 4. The growth of scour hole.

4.2 Extension of the riprap layer

Variation of $\frac{D_{smax}}{\sqrt{hW_a}}$ with $\frac{L_{d0}}{W_a}$ and U/U_c is shown in Figure 5. Experiments show that in flow intensities more than 0.7 scouring increases considerably with increasing flow intensity or reducing L_{d0}.

Figure 5. Dimensionless scour hole depth versus flow intensity and riprap layer length (data from Table 1).

Based on Eq. (2), regression analysis led to the following equations regarding the maximum scour depth downstream of the riprap layer. In deriving this equation tests with riprap layer reduction more than about 10% were not considered. Including the term W_{u0}/W_a was found to be ineffective in increasing the accuracy of the equation. It should be noticed that W_{u0} was selected based on U/U_c.

$$\frac{D_{s\max}}{\sqrt{hW_a}} = 2.037(1+\frac{L_{d0}}{W_a})^{-0.165} \times (\frac{U}{U_c})^{3.369} \times (\frac{h}{W_a})^{-0.922}$$

$$0.518 \le \frac{U}{U_c} \le 0.618 \quad ,0.6 \le \frac{h}{W_a} \le 1.2 \quad ,0 \le \frac{L_{d0}}{W_a} \le 3.75 \qquad (4)$$

$$\frac{D_{s\max}}{\sqrt{hW_a}} = 2.77(1+\frac{L_{d0}}{W_a})^{-0.404} \times (\frac{U}{U_c})^{4.187} \times (\frac{h}{W_a})^{-0.227}$$

$$0.72 \le \frac{U}{U_c} \le 0.87 \quad ,0.67 \le \frac{h}{W_a} \le 1.5 \quad ,0 \le \frac{L_{d0}}{W_a} \le 3.75$$

The correlation coefficient of Eq. (4) regarding the available laboratory data is the acceptable value of R^2=0.9 **,**RSME=0.031 and mean relative error=6.5% for $0.518 \le U/U_c \le 0.618$ and R^2=0.962 and RSME=0.051 mean relative error=10% for $0.72 \le U/U_c \le 0.87$ (Figure.6). The power of the U/U_c term in this equation shows the significance effect of the flow intensity on scour depth in the range of parameters tested in the present work. The negative power of the L_{d0}/W_a term also demonstrates the inverse correlation between the scour depth and the longitudinal length of the riprap layer which is more effective in $U/U_c>0.7$. In any flow intensity, abutment length and riprap longitudinal length, Eq. (4) can be used to calculate the depth of the scour hole. Location of the scour hole can then be estimated from the equation given in the following section.
Figure 6 shows the predictions of Eq. (4)for the scour hole in all experiments given in Table 1 versus measured values with a good agreement.

Figure 6. Comparison of experimental data with predicted by Eq. (4)

4.3 Location of the Maximum Scour depth

Predicting the location of the maximum scour is another important problem regarding the geometry of the scour hole. According to the observations made through experiments in the present work, the bottom of the scour hole was a flat area. The center of this area corresponding to the abutment axis of symmetry (Figure 1) was recorded in each test and is plotted in Figure 7 versus L_{d0}/W_a. According to this figure it is evident that an increase in the riprap extension length leads to an increase in longitudinal distance of the maximum scour location.

Figure 7. The x-coordinate of the maximum souring point versus riprap length variations.

The transverse distance (Y-coordinate) of the maximum scour point, however, was at the side edge of the riprap layer (Figure 8). A separate equation for calculating the Y-coordinate of the maximum scouring point is therefore not necessary.
The x-coordinate of the maximum scour depth location collected through the tests was best fitted to the following regression equation with a R^2 value of 0.957 and RSME= 0.173 and mean relative error=4%. Note that in this equation W_{u0} varies with flow intensity as mentioned before.

$$\frac{X}{\sqrt{hW_a}} = 2.066(\frac{L_{d0}}{W_a})^{0.567} \times (\frac{W_{u0}}{W_a})^{0.93} \times (\frac{h}{W_a})^{-0.387} \quad (5)$$

Figure 8. Definition of parameters for the geometry of the scour hole.

4.4 The Effect of Riprap Thickness

In addition to the tests performed for the $3D_{50}$ riprap thickness, 10 more experiments (Table 1) were performed with $5D_{50}$ thickness for flow intensities larger than 0.6. In thicker riprap layer, less original riprap layer area was reduced due to the launching action and therefore less riprap stones dropped into the scour hole. Such an action in some cases lead to even a deeper scour hole though such an increase was not considerable (see Table 1). Since increase in riprap thickness was not effective in decreasing the scour depth, the thickness of $3D_{50}$ seems to be adequate and is recommended**.**

5. Conclusions

In the present work, the extension of the riprap layer around 45° wing-wall abutments in clear water condition was experimentally studied. The aim of these studies was to design the riprap layer with minimum extension so that the scour hole at the riprap edge is kept downstream of the riprap layer and away from the bridge crossing. Experiments were conducted in the range of $0.5 \le h/W_a \le 1.6$ and $0.52 \le U/U_c \le 0.87$ where h is the flow depth, W_a the abutment length in transverse flow direction, U the average flow velocity upstream of the abutment and U_c is critical average flow velocity for beginning of bed particles motion.

- It was observed that scouring started from downstream of the riprap layer. A reduction in the riprap layer width gave rise to the scour hole development toward upstream along the riprap edge and excessive launching of the riprap layer. Reduction of the original riprap area more than 10% under the launching action was not accepted in the present work.
- Experimental results showed that for flow intensities less than 0.8, a riprap width equal to the abutment length was large enough to cause the hole to form only downstream of the riprap layer and prevent extensive edge failure. The riprap layer width equal to 1.5 times the abutment length was necessary at higher flow intensities.
- The longitudinal extension of the riprap layer can be determined based on the acceptable scour hole depth downstream of the riprap layer. Based on experimental data and regression analysis, equations were derived for maximum scour depth and its location with an acceptable correlation factor.
- Experiments showed that increasing riprap thickness from $3D_{50}$ to $5D_{50}$ was not effective in reducing the scour hole depth.

More experiments are recommended to study the effect of flow depth independent to the flow intensity on scour hole depth.

Nomenclature

A_{Launch} =launched area of the riprap layer

A_0 =Area of the riprap layer

B_f =floodplain width

B =channel half-width

d_{50} =median size of bed particles, h is upstream flow depth

D_{smax} = maximum depth of the scour hole

D_{50} =median stone size

Fr =approach Froude number

h = upstream flow depth

K_s =abutment shape coefficient

L =abutment length

L_{d0} =length of riprap extension in longitudinal flow direction downstream of the abutment

L_{u0} =length of riprap extension upstream of the abutment in longitudinal flow direction

S_f =factor of safety

t =riprap thickness

U =upstream undisturbed average velocity

U_c =threshold velocity of the bed material,

W_a =abutment length in transverse flow direction

W_{u0} =length of the riprap extension in transverse flow direction

X =location of the Maximum Scour depth

ρ_s = stones density, ρ is water density

σ =geometric standard deviation of particle size distribution

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List of tables' captions

Figure 1

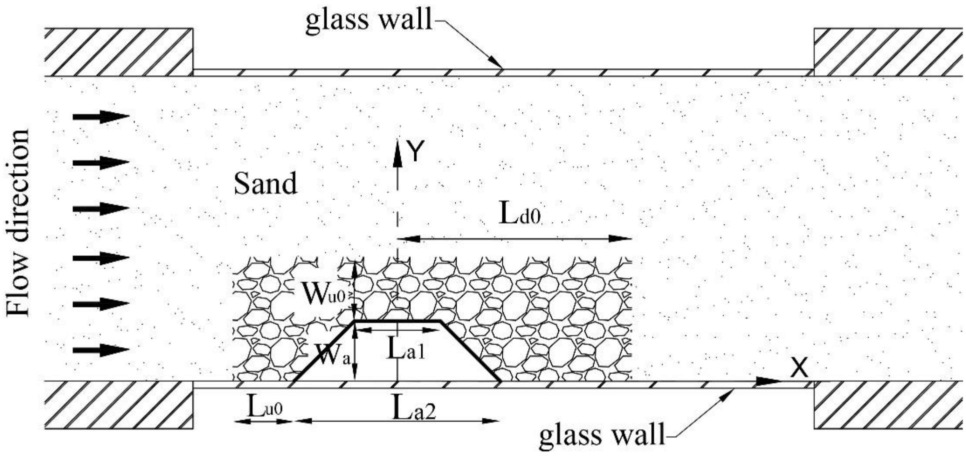

glass wall
Flow direction
Sand
Y
Ld0
Wu0
Wa
La1
X
Lu0
La2
glass wall

Figure 2

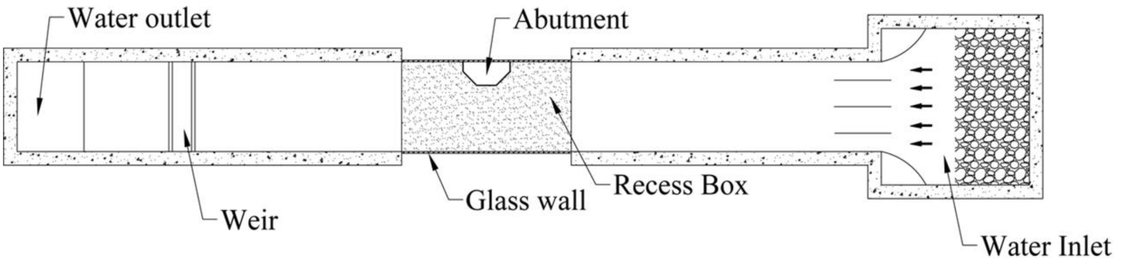

Water outlet
Abutment
Weir
Glass wall
Recess Box
Water Inlet

Figure 3

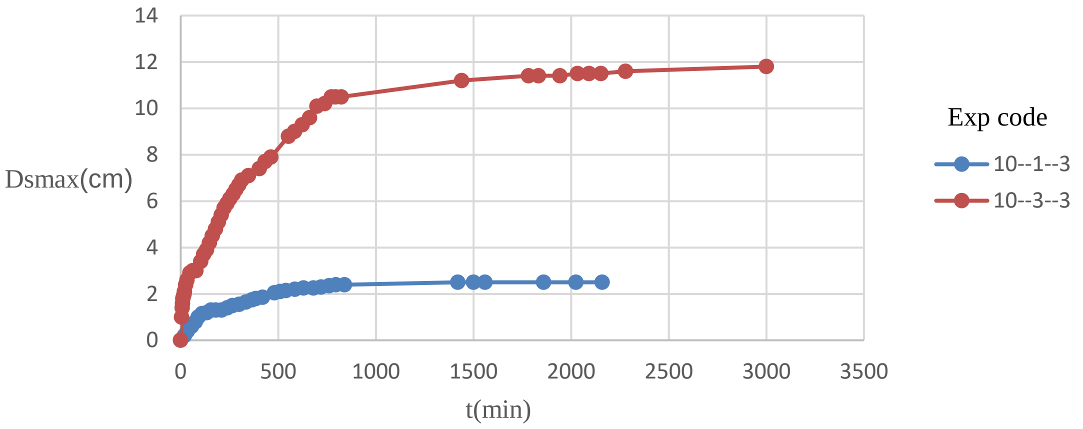
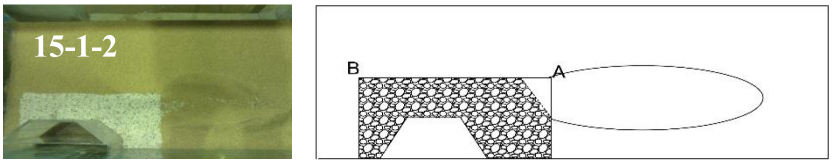

14
12
10
8
6
4
2
0
Dsmax(cm)
0
500
1000
1500
2000
2500
3000
3500
t(min)
Exp code
10--1--3
10--3--3

Figure 4

(a)



(b)

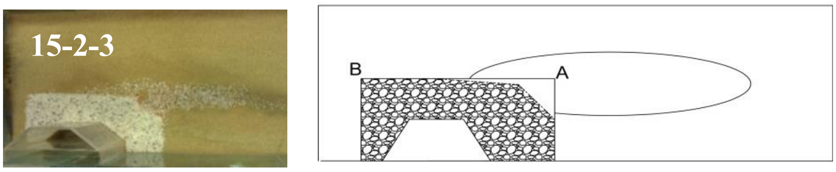


Figure 5

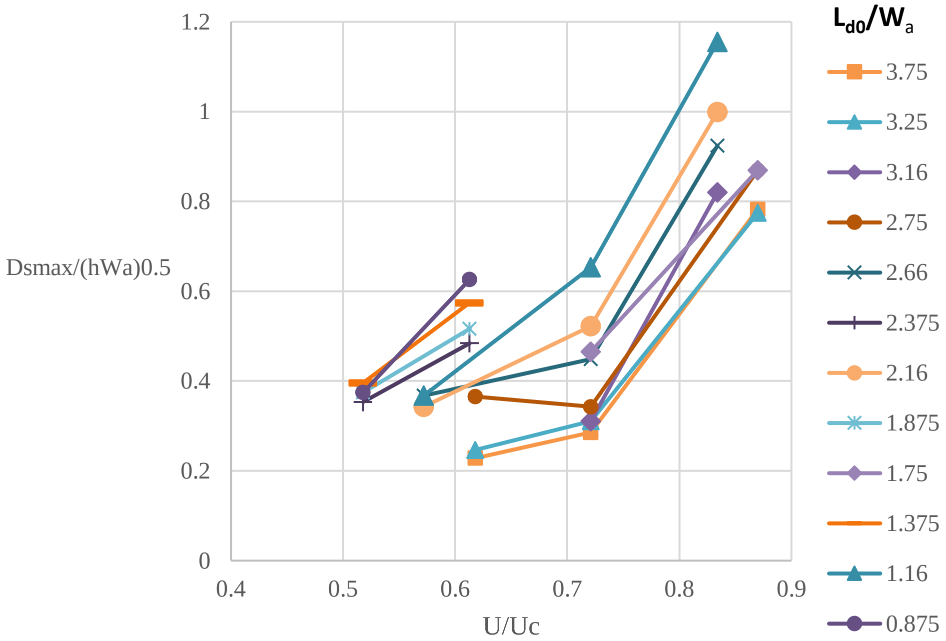

1.2
1
0.8
0.6
0.4
0.2
0
Dsmax/(hWa)0.5
0.4
0.5
0.6
0.7
0.8
0.9
U/Uc
Ld0/Wa
3.75
3.25
3.16
2.75
2.66
2.375
2.16
1.875
1.75
1.375
1.16
0.875

Figure 6

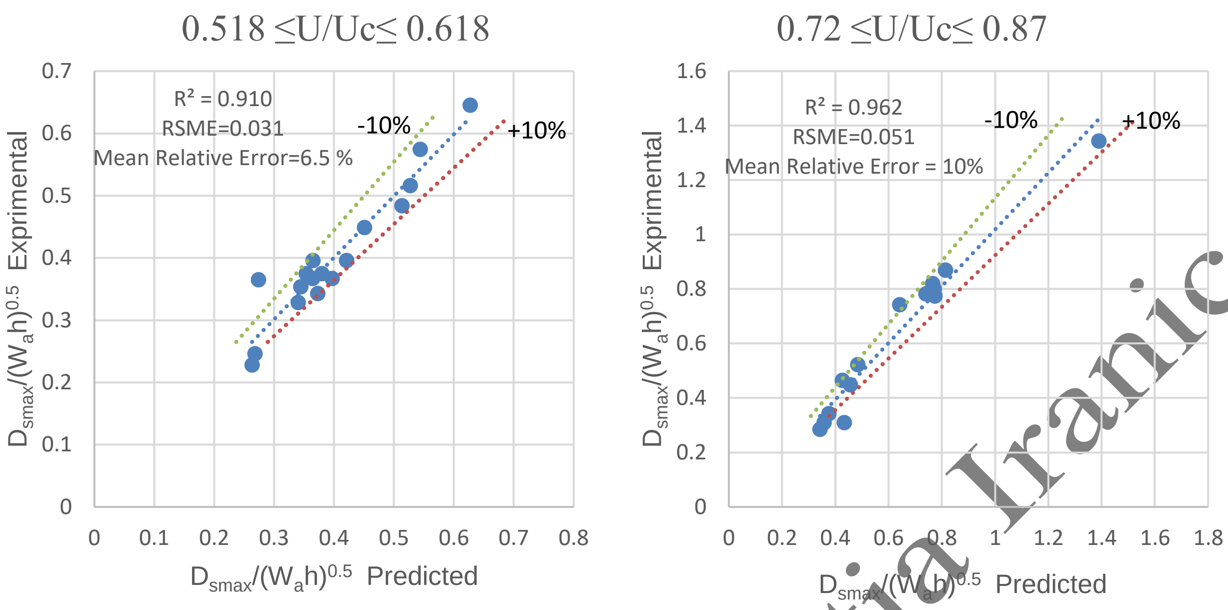

0.518 ≤U/Uc≤ 0.618
R² = 0.910
RSME=0.031
Mean Relative Error=6.5 %
-10%
+10%
Dsmax/(Wah)0.5 Exprimental
Dsmax/(Wah)0.5 Predicted
0.72 ≤U/Uc≤ 0.87
R² = 0.962
RSME=0.051
Mean Relative Error = 10%
-10%
+10%
Dsmax/(Wah)0.5 Exprimental
Dsmax/(Wah)0.5 Predicted

Figure 7

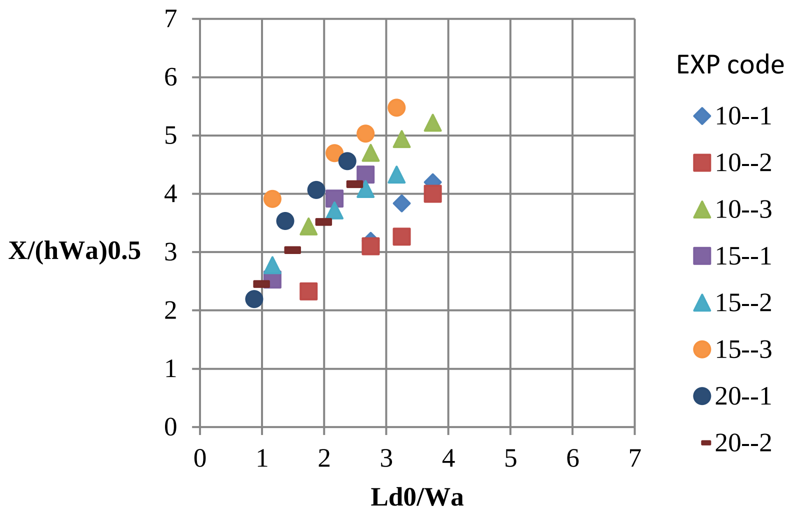

7
6
5
4
3
2
1
0
X/(hWa)0.5
0
1
2
3
4
5
6
7
Ld0/Wa
EXP code
10--1
10--2
10--3
15--1
15--2
15--3
20--1
20--2

Figure 8

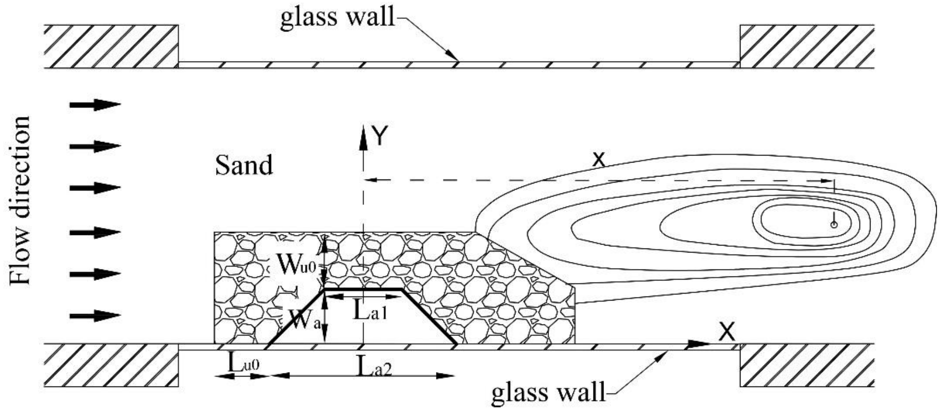

glass wall
Flow direction
Sand
Y
x
Wu0
Wa
La1
X
Lu0
La2
glass wall

Table 1

W_a	Exp Code	Exp. No.	U/U_c	D_{50} (mm)	h (cm)	t (mm)	L_{u0} (cm)	W_{u0} (cm)	L_{d0} *(cm)*	D_{smax} (cm)	X *(cm)*	$(A_{lunch}/A_0)\%$
W_a=10	10-1	10-1-1	0.618	2.87	12	$3D_{50}$	5	10	*37.5*	2.5	46	1.2
		10-1-2				$3D_{50}$	5	10	*32.5*	2.7	42	1.1
		10-1-3				$3D_{50}$	5	10	*27.5*	4	35	2.9
		10-1-4				0	0	0	*0*	3.6	0	0
	10-2	10-2-1	0.721	4.06	15	$3D_{50}$	5	10	*37.5*	3.5	49	5.3
		10-2-2				$3D_{50}$	5	10	*32.5*	3.8	40	8.8
		10-2-3				$3D_{50}$	5	10	*27.5*	4.2	38	10
		10-2-4				$3D_{50}$	5	10	*17.5*	5.7	28.5	9.5
		10-2-5				0	0	0	*0*	9.1	0	0
		10-2-6				$5D_{50}$	5	10	*27.5*	4.8	38	6.83
		10-2-7				$5D_{50}$	5	10	*17.5*	6.8	35.7	7.16
	10-3	10-3-1	0.87	5.56	16	$3D_{50}$	5	15	*37.5*	9.9	66	8
		10-3-2				$3D_{50}$	5	15	*32.5*	9.8	62.5	10.5
		10-3-3				$3D_{50}$	5	15	*27.5*	11	59.5	10.7
		10-3-4				$3D_{50}$	5	15	*17.5*	11	43.5	28.3
		10-3-5				0	0	0	*0*	17	0	0
		10-3-6				$5D_{50}$	5	15	*27.5*	8.7	51	8.4
		10-3-7				$5D_{50}$	5	15	*17.5*	12	44	14.13
W_a =15	15-1	15-1-1	0.572	2.87	10	$3D_{50}$	7.5	15	*40*	4.5	53	0
		15-1-2				$3D_{50}$	7.5	15	*32.5*	4.2	48	0.6
		15-1-3				$3D_{50}$	7.5	15	*17.5*	4.5	31	3.8
		15-1-4				0	0	0	*0*	5.5	0	0
	15-2	15-2-1	0.721	4.06	10	$3D_{50}$	7.5	15	*47.5*	3.8	53	3.6
		15-2-2				$3D_{50}$	7.5	15	*40*	5.5	50	5.9
		15-2-3				$3D_{50}$	7.5	15	*32.5*	6.4	46	6.6
		15-2-4				$3D_{50}$	7.5	15	*17.5*	8	34	17.3
		15-2-5				0	0	0	*0*	9.8	0	0
		15-1-6				$5D_{50}$	7.5	15	*32.5*	6.8	45.5	5
		15-1-7				$5D_{50}$	7.5	15	*17.5*	8.9	36	11.13
	15-3	15-3-1	0.834	5.56	12	$3D_{50}$	7.5	20	*47.5*	11	73.5	9.6
		15-3-2				$3D_{50}$	7.5	20	*40*	12.4	67.5	11.4
		15-3-3				$3D_{50}$	7.5	20	*32.5*	13.4	63	12.9
		15-3-4				$3D_{50}$	7.5	20	*17.5*	15.5	52.5	24.6
		15-3-5				$5D_{50}$	7.5	20	*32.5*	12.8	59	8.7
		15-3-6				$5D_{50}$	7.5	20	*17.5*	15	49	14.11
W_a =20	20-1	20-1-1	0.518	2.87	10	$3D_{50}$	10	20	*47.5*	5	64.5	0
		20-1-2				$3D_{50}$	10	20	*37.5*	5.3	57.5	0
		20-1-3				$3D_{50}$	10	20	*27.5*	5.6	50	2.8
		20-1-4				$3D_{50}$	10	20	*17.5*	5.3	31	6.7
		20-1-5				0	0	0	*0*	5.6	0	0
	20-2	20-2-1	0.613	4.06	12	$3D_{50}$	10	20	*47.5*	7.5	64.5	7.6
		20-2-2				$3D_{50}$	10	20	*37.5*	8	54.5	7.4
		20-2-3				$3D_{50}$	10	20	*27.5*	8.9	47	6.5
		20-2-4				$3D_{50}$	10	20	*17.5*	9.7	38	17.2
		20-2-5				0	0	0	*0*	10	0	0
		20-2-6				$5D_{50}$	10	20	*27.5*	6.6	52	5.3
		20-2-7				$5D_{50}$	10	20	*17.5*	6.7	39	8.33

Biographies

Mohammad Hossein Sayyad received his M.Sc. degree in Hydraulic Structures from Amirkabir University of Technology in 2013 and is currently working as a project manager in civil engineering projects.

Amir Reza Zarrati is a professor of Hydraulic Engineering at the Department of Civil and Environmental Engineering, Amirkabir University of technology (Tehran, Polytechnic). His main area of research is numerical and physical modeling of flow behavior such as in hydraulic structures and rivers. He is also interested in scouring phenomenon and methods of its control. Dr Zarrati has also a long collaboration with industry in a number of large dams. Dr Zarrati is a member of Iranian Hydraulic Association (IHA) and International Association of Hydraulic Research (IAHR).