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Upstream sediment transport of the gate across a channel

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ABSTRACT

The results of an experimental investigation of the time variation of scour width, upstream scour length and scour depth and the flow characteristics of the quasi-equilibrium state of scour a non-cohesive bed upstream of gate openings due to hydraulic differences and gate opening sizes are presented. Experiments were carried out with non-cohesive sediments for various gate openings, sediment diameter, and hydraulic differences including upstream depth. Attempts have been made to explain the main parameters affecting upstream sediment transport. The scour profiles at different times follow a particular geometrical similarity and can be expressed by a polynomial using relevant parameters. The characteristic parameters affecting the time variation of scour width, upstream scour length and scour depth are identified based on physical reasoning and a dimensional analysis. Equations for time variation of maximum scour width, upstream scour length, and scour depth are obtained empirically. A regression analysis between the measured value in a hydraulic laboratory and the predicted value in a prediction model of upstream sediment transport matched well with the determinant coefficients (r^2) which were 0.84 for scour width, 0.89 for upstream scour length, and 0.70 for scour depth.

Keywords: Non-cohesive sediment; Scour (width, upstream scour length, and scour depth); Upstream sediment transport; Open channel flow; Regression analysis

1. Introduction

The installation of artificial structures including cross-arms and gates that span across rivers is increasing to enhance river usage and increase the capacity of water resources recently. These artificial structures might affect the sedimentation and transportation of upstream sediments. Especially considering the water body and bottom sediment quality in a river, there is a need for more detailed research on the discharge of upstream sediments.

The velocity field in the upstream of gates and orifice has been studied because of their use in channels as flow control structures. Rajaratnam and Humphries [1] measured velocities and pressure distributions upstream of sluice gates and showed that the pressure reduction just upstream of the gate was approximately 40% of the hydrostatic pressure and was negligible after a distance of five times the gate opening. Montes [2] studied flow and pressure variations under gates and showed that a pressure deficit upstream of the gate opening extends upstream to nearly twice the gate opening height. Chanson et al. [3] studied unsteady flow in large orifices and showed that a

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hemi-elliptical shape was that of half of a 3-D ellipse, similar to an egg against a wall. Shammaa et al. [4] studied the flow field upstream of sluice gates and orifices and showed that velocity contours are hemi-elliptical up to 1.5 times an orifice's diameter and the velocity profile of a sluice gate reached approximately 2% of the uniform velocity at a location of 1.5 times the water depth upstream.

One of the situations that have attracted considerable attention to the researchers is the downstream scour [5]. Local erosion on a large scale caused by the action of flowing fluid near hydraulic structures is of immense concern because their foundations can be undermined which is detrimental to the structure and can lead to a failure. Scour downstream of an apron was experimentally studied by Breusers [6], Chatterjee and Ghosh [7], Hassan and Narayanan [8], Balachandar and Kells [9,10], Sarkar and Dey [11], Dey and Westrich [12]. Dey and Sarkar [5] investigated the scouring of non-cohesive sediment beds downstream of an apron due to a submerged horizontal jet issuing from a sluice opening.

However, no attempt has so far been made to study the scouring of a non-cohesive bed upstream of a cross-arm and gate.

Powell [13] investigated sediment transport upstream of orifices and it was found that while the initial stage of sediment motion appeared to be governed by high-shear stress, the equilibrium size of the scour hole was governed by a vortex system which developed beneath the orifice and also these vortices were responsible for entraining and lifting the sediment out of the scour hole and through an orifice. In this paper, results of an experimental investigation of the time variation of scour and the flow characteristics of quasi-equilibrium scour of non-cohesive bed upstream of a gate due to upstream vortices are presented. First attempts were made to explain characteristic parameters affecting the time variation of scour based on dimensional analysis to obtain an equation of scour depth, scour width, and upstream scour length. Second, using a regression analysis, determinant coefficients were derived between the measured value in a hydraulic laboratory and the predicted value in a prediction model of upstream sediment transport.

2. Materials and methods

2.1. Experiments

Experiments were conducted in a Hydraulic Laboratory at Hanbat National University, Korea. Altogether, 48 tests were performed in a glass walled flume 0.4 m wide, 0.5 m deep, and 13 m long, as shown in Fig. 1.

A sediment of 6 cm thick and 3 m long was constructed to the upstream of the gate. Three types of the non-cohesive sediments which have d_{50} (median size) of 0.110 mm, 0.149 mm and 0.297 mm were added to the upstream of the gate. The gate was made of a perspex sheet that spans across the channel and has different openings (5 × 5 cm, 5 × 10 cm, 10 × 2.5 cm, and 10 × 5 cm). The upstream water level was between a max of 25 and a min of 10 cm, whereas the downstream water level, considering the effect of water depth, was between a Max of 5 cm and a Min of 0 cm. The shape of the gate has the combination of width and height. As this study is mainly focusing on upstream sediment transport by gate opening, the upstream water level was constantly controlled.

The downstream flow depth was adjusted by a tail water gate. The flow depths were measured by a gage with an accuracy of ±0.10 mm. The water discharge at the inlet which was controlled by an inlet valve was measured by an electromagnetic flow meter. In order to avoid the undesirable scouring of the sediment bed, the flume was slowly filled with water at a low rate by carefully opening the inlet valve. Once the desirable flow depth was reached, the experimental run was initiated by adjusting the discharge to a desired value.

Fig. 1. Experimental setup.

To set up upstream sediment transport by the gate opening, it was necessary to have a scour time to reach a quasi-steady state which had almost no or very slow upstream sediment transport. The scour time was set to 150 min for the high-water level and 120 min for the low-water level in order to achieve a quasi-steady state.

As was observed by Powell [6], initially the sediments appear to lift from the bed and become suspended in the flow before being carried out of the gate and it appears that the primary mechanism of sediment transport during this initial stage was due to excessive bed shear stress. After this initial motion, two counter-rotating vortices began to form below the gate and vortices at the gate helped to lift the sediments near the gate. After this short transition period, the vortices became the dominant mechanism for removing sediments from the scour hole.

3. Results and discussion

Experimental flow conditions and the maximum scour width, upstream scour length, and scour depths at different median sizes (d_{50}) are shown below in Table 1.

3.1. Dimensional analysis

Dimensional analysis is a method to examine the relationship between physical quantities by comparing their fundamental dimensions such as length [L], mass [M], time [T], temperature [K], and the method is useful to explore the relationship between range of scouring and their influence parameters.

The parameters influencing the equilibrium scour depth (D_{se}), scour width (W_{se}), upstream scour length (L_{se}) can be given in a functional form as follows:

$$D_{se}, W_{se} \text{ and } L_{se} = f_1(\rho, \rho_s, v, d_{50}, g, h_1, h_1 - h_2, U, B_{sg}, H_{sg}) \quad (1)$$

where ρ = mass density of water, ρ_s = mass density of sediments, v = kinematic viscosity of water (=10^{-6} m^2/s), d_{50} = median particle diameter, g = gravitational acceleration. In sediment–water interaction, it is appropriate to represent the independent parameters g, ρ, and ρ_s as a combined parameter Δg ; where $\Delta = s - 1$; and s = relative density of sediments, that is ρ_s/ρ.

In addition, the influence of kinematic viscosity v is considered negligible under a fully turbulent flow over a rough bed (Yalin 1977); h_1 = upstream water depth, $h_1 - h_2$ = hydraulic difference between upstream and downstream, U = average flow velocity, B_{sg} = width of the gate, H_{sg} = height of the gate.

With the arrangement, Eq. (1) can be given as follows

$$D_{se}, W_{se} \text{ and } L_{se} = f_2(d_{50}, \Delta g, h_1, h_1 - h_2, U, B_{sg}, H_{sg}) \quad (2)$$

Applying the Buckingham π theory with repeating variable U [LT^{-1}] and B_{sg} [L], rearranging the non-dimensional parameters logically yields.yields.

$$\bar{D}_{se}, \bar{W}_{se} \text{ and } \bar{L}_{se} = f_3(F_J, \bar{d}_{50}, \overline{h_1 - h_2}, \bar{h}_1, \bar{H}_{sg}) \quad (3)$$

where $\bar{D}_{se} = D_{se}/B_{sg}$, $\bar{W}_{se} = W_{se}/B_{sg}$, $\bar{L}_{se} = \bar{L}_{se}/B_{sg}$, $F_J = U/\sqrt{\Delta g\ B_{sg}}$, that is jet Froude number, $\bar{d}_{50} = d_{50}/B_{sg}$, $\overline{h_1 - h_2} = h_1 - h_2/B_{sg}, \bar{h}_1 = h_1/B_{sg}, \bar{H}_{sg} = H_{se}/B_{sg}$ that is shape factor of gate.

The justification of the effects of the non-dimensional parameters on scour depth, scour width, and upstream scour length is as follows:

(1) The term F_J indicates the influences of the mobility of submerged sediment particles
(2) The term, $\bar{d}_{50}$ represents the effect of the sediment size
(3) The term $\overline{h_1 - h_2}$ indicates the role of hydraulic differences between the upstream and downstream
(4) The term $\bar{h}_1$ refers to the effect of upstream depth
(5) The term $\bar{H}_{sg}$ corresponds to the influence of the gate opening

Consequently, $\bar{D}_{se}$, $\bar{W}_{se}$ and $\bar{L}_{se}$ can be estimated by using a form

$$\bar{D}_{se}, \bar{W}_{se} \text{ and } \bar{L}_{se} = C\left[\frac{U}{\sqrt{\Delta g B_{sg}}}\right]^a \left[\frac{d_{50}}{B_{sg}}\right]^b \left[\frac{h_1 - h_2}{B_{sg}}\right]^c \left[\frac{h_1}{B_{sg}}\right]^d \left[\frac{H_{sg}}{B_{sg}}\right]^e \quad (4)$$

3.2. Statistical analysis for exploring sediment scour boundary prediction model

For examining the coefficient of Eq. (4) and relationship between sediment discharge and influence parameters quantitatively, significance test and regression analysis were conducted using results from lab-scale experiment. In this study, the Statistical Package for the Social Science was used for statistical analysis.

A significance test was used to verify the correlation between independent and dependent parameters. The equation, which was developed by non-dimensional analysis, was transferred into linear algebra and analyzed each correlation and significance in Table 2.

Table 1
Experimental data

					d_{50} = 0.110 mm					d_{50} = 0.149 mm					d_{50} = 0.297 mm				
B_{sg} (cm)	H_{sg} (cm)	h_1 (cm)	h_2 (cm)	Δh (cm)	Run	U (m/s)	W_{se} (cm)	L_{se} (cm)	D_{se} (cm)	Run	U (m/s)	W_{se} (cm)	L_{se} (cm)	D_{se} (cm)	Run	U (m/s)	W_{se} (cm)	L_{se} (cm)	D_{se} (cm)
5	5	25	0	25	1R1	1.99	20.5	8.6	4.5	2R1	1.11	23.0	7.0	3.9	3R1	3.13	18.8	7.0	3.5
5	5	10	0	10	1R2	2.34	16.0	7.5	3.5	2R2	1.25	14.3	6.9	2.8	3R2	2.12	13.3	3.0	1.4
5	5	25	5	20	1R3	1.82	20.5	8.5	4.6	2R3	1.50	18.2	7.5	3.8	3R3	1.70	18.0	7.4	3.5
5	5	10	5	5	1R4	1.19	14.0	5.5	3.3	2R4	0.87	12.4	4.7	3.2	3R4	1.11	10.2	3.6	2.7
5	10	25	0	25	1R5	2.11	25.3	11.3	5.2	2R5	2.13	24.0	11.2	4.4	3R5	2.41	22.8	10.0	4.0
5	10	10	0	10	1R6	1.31	17.6	6.4	3.3	2R6	1.30	17.5	7.5	3.0	3R6	2.68	15.4	6.1	2.9
5	10	25	5	20	1R7	1.69	26.8	11.3	5.2	2R7	1.06	24.4	10.5	4.0	3R7	1.62	22.0	9.6	3.7
5	10	10	5	5	1R8	1.39	17.0	7.2	3.5	2R8	0.88	15.1	6.4	2.8	3R8	1.11	13.0	6.1	2.5
10	5	25	0	25	1R9	1.61	30.5	13.0	6.0	2R9	4.73	31.8	12.2	5.3	3R9	3.45	28.7	11.0	5.2
10	5	10	0	10	1R10	1.87	27.3	9.5	4.6	2R10	2.35	25.0	10.0	1.8	3R10	1.94	22.1	6.8	3.5
10	5	25	5	20	1R11	1.95	34.0	12.5	6.0	2R11	1.41	31.6	17.2	4.7	3R11	1.81	22.4	11.0	4.4
10	5	10	5	5	1R12	1.66	23.9	7.2	3.7	2R12	1.58	25.8	8.3	3.2	3R12	1.38	22.5	6.7	3.1
10	2.5	25	0	25	1R13	1.24	27.0	9.7	5.1	2R13	2.89	24.9	9.1	4.4	3R13	1.88	18.0	7.9	8.4
10	2.5	10	0	10	1R14	1.89	23.0	6.2	2.8	2R14	2.33	18.8	6.4	3.9	3R14	1.64	21.3	4.6	3.2
10	2.5	25	5	20	1R15	1.74	26.6	9.5	4.8	2R15	1.55	25.9	9.2	3.8	3R15	2.00	22.6	7.4	4.3
10	2.5	10	5	5	1R16	1.78	19.8	6.1	3.7	2R16	1.63	10.3	7.0	3.4	3R16	1.47	17.3	5.2	3.5

Table 2
Significance test for independent and dependent parameters

		Independent parameters					Dependent parameters		
		X_1	X_2	X_3	X_4	X_5	Y_1	Y_2	Y_3
Independent parameters	X_1	–	0.048	0.201	0.053	0.084	0.159	0.162	−0.172
	X_2	0.048	–	0.297*	0.386**	0.573**	0.235	0.209	0.291*
	X_3	0.201	0.297*	–	0.924**	0.423**	0.772**	0.750**	0.729**
	X_4	0.053	0.386**	0.924**	–	0.540**	0.792**	0.813**	0.826**
	X_5	0.084	0.573**	0.423**	0.540**	–	0.729**	0.745**	0.628**
Dependent parameters	Y_1	0.159	0.235	0.772**	0.792**	0.729**	–	0.872**	0.718**
	Y_2	0.162	0.209	0.750**	0.813**	0.745**	0.872**	–	0.796**
	Y_3	−0.172	0.291*	0.729**	0.826**	0.628**	0.718**	0.796**	–

*Coefficient of correlation is meaningful between 0.05 level.
**Coefficient of correlation is meaningful between 0.01 level.

where $X_1 = \ln[U/\sqrt{\Delta g B_{sg}}], X_2 = \ln[d_{50}/B_{sg}], X_3 = \ln[(h_1 - h_2)/B_{sg}], X_4 = \ln[h_1/B_{sg}], X_5 = \ln[H_{sg}/B_{sg}]; Y_1 = \ln[W_{se}/B_{sg}], Y_2 = \ln[L_{se}/B_{sg}], Y_3 = [D_{se}/B_{sg}]$.

Independent parameters comparatively show low correlations with the other independent parameters and shows high correlation with dependent parameters. It is appropriate that each of the dependent parameters, scour width, upstream scour length, and scour depth for a transportation model is combined with comparatively meaningful independent parameters.

In sequence, coefficient of sediment scour boundary prediction model was estimated by regression analysis. Regression Analysis is a statistical tool used to predict specific dependent parameters from independent parameter through relationships between more than two parameters.

For regression analysis, the multiple regression model was used as Eq. (5).

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_k x_{ki} + \epsilon_i \quad (5)$$

where y_i is dependent parameter (i.e. $Y_1 = \ln[W_{se}/B_{sg}], Y_2 = \ln[Lse/B_{sg}], Y_3 = [D_{se}/B_{sg}]$), x_{ki} is independent parameter (i.e. $X_1 = \ln[U/\sqrt{\Delta g B_{sg}}]$, $X_2 = \ln[d_{50}/B_{sg}], X_3 = \ln[(h_1 - h_2)/B_{sg}], X_4 = \ln[h_1/B_{sg}]$, $X_5 = \ln[H_{sg}/B_{sg}]$), ϵ_i is error of i-th measured value, and β_k is unknown regression coefficient. $\beta_k s$ can be estimated by method of least squares, minimizing the sum of the squares of the errors, ϵ_i.

Thus, it is available to derive a sediment scour boundary prediction model for affecting parameters for upstream sediment transport.

Based on the hydraulic laboratory experiment, the regression result for scour width can be given as follows:

$$y_1 = -0.137 + (-0.190)X_2 + 0.264X_3 + 0.276X_5$$

As on the basis of independent parameters, the affection of X_3 and X_5 to dependent parameter y_1 is comparatively large. The main parameters for scour width with a gate opening are water level difference between the upstream and downstream and the size of a gate opening. It is reasonable that the more median particle diameter, the less scour width and the more level difference and area of gate opening, the more scour width. Sediment scour boundary prediction model for scour width finally can be stated as follows:

$$W_{se} = B_{sg}\left\{e^{-0.137}\left[\frac{d_{50}}{B_{sg}}\right]^{-0.190}\left[\frac{h_1 - h_2}{B_{sg}}\right]^{0.264}\left[\frac{H_{sg}}{B_{sg}}\right]^{0.276}\right\}$$

Second, regression result for upstream scour length can be given as follows:

$$y_2 = -2.032 + 0.067X_1 + (-0.301)X_2 + 0.447X_4 + 0.334X_5$$

As on the basis of independent parameters, the affection of X_4 and X_5 to dependent parameter y_2 is comparatively large. The main parameters for upstream scour length are water upstream depth and the size of a gate opening. Sediment scour boundary prediction model for upstream scour length finally can be stated as follows:

$$L_{se} = B_{sg}\left\{e^{-2.032}\left[\frac{U}{\sqrt{\Delta g B_{sg}}}\right]^{-0.067}\left[\frac{d_{50}}{B_{sg}}\right]^{-0.301}\left[\frac{h_1}{B_{sg}}\right]^{0.447}\left[\frac{H_{sg}}{B_{sg}}\right]^{0.334}\right\}$$

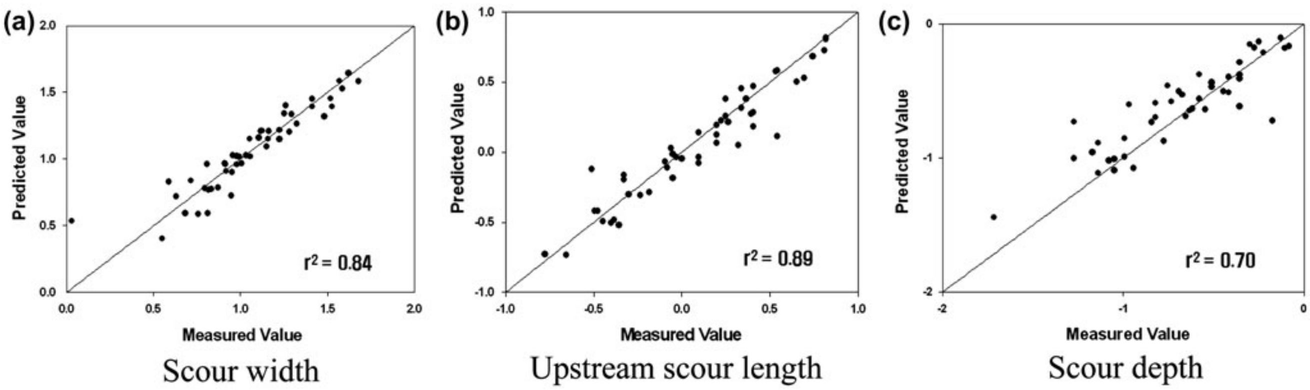

Fig. 2. Regression analysis between measured value and predicted value.

Third, regression result for scour depth can be given as follows:

$$y_3 = -1.586 + (-0.153)X_1 + (-0.132)X_2 + 0.447X_4 + 0.184X_5$$

As on the basis of independent parameters, the affection of X_4 and X_5 to dependent parameter y_3 is comparatively large. The main parameters for scour depth are water upstream depth and the size of a gate opening. Sediment scour boundary prediction model for scour depth finally can be stated as follows:

$$D_{se} = B_{sg}\left\{ e^{-1.586}\left[\frac{U}{\sqrt{\Delta g B_{sg}}}\right]^{-0.153}\left[\frac{d_{50}}{B_{sg}}\right]^{-0.132}\left[\frac{h_1}{B_{sg}}\right]^{0.447}\left[\frac{H_{sg}}{B_{sg}}\right]^{0.184}\right\}$$

Regression analysis between the measured value in a hydraulic laboratory and the predicted value in a prediction model of upstream sediment transport, as shown in Fig. 2, match well and the determinant coefficients (r^2) were 0.84 for scour width, 0.89 for upstream scour length, and 0.70 for scour depth.

4. Conclusions

The findings of the investigation on local scours, including scour width, upstream scour length, and scour depth for uniform sediment of upstream sediment transport under clear-water scour are summarized as follows:

(1) Scour width increases as water level differences between the upstream and downstream increases and the size of a gate opening, reversely decreases with increases in the diameter of sediments.
(2) Upstream scour length increases as upstream water depth increases and the size of a gate opening, reversely decreases with increases in the diameter of sediments.
(3) Scour depth increases as upstream water depth increases and the size of a gate opening, reversely decreases with increases in the diameter of sediments.
(4) Regression analysis between the measured value in a hydraulic laboratory and the predicted value in a prediction model of upstream sediment transport matches well and the determinant coefficients (r^2) were 0.84 for scour width, 0.89 for upstream scour length, and 0.70 for scour depth.
(5) Main parameters for upstream sediment transport are upstream water depth, differences between upstream and downstream water depth, gate openings, and diameter of sediments.
(6) Non-uniform sediments might reduce sediment scouring due to the formation of the armour layer within the scour hole.

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