River bed deformation at water intakes

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Abstract

The damage of engineering structures in rivers, because of scour (near intakes, pumping stations, bridge structures – abutments, guide banks, dams, etc.) leads to considerable environmental and economical losses. During multiple floods the scour hole parameters, under clear-water conditions, are summed up and increases in time. The differential equation of equilibrium of the bed sediment movement in clear water was used, and a method for calculating the scour development with time at the intakes (abutments, guide banks) during the multiple floods was elaborated and confirmed with experimental data (Gjunsburgs et al., 2001, 2004). Method for computing equilibrium depth of scour and it's analysis is presented in this paper.The method based on the conditions that at equilibrium stage of scour the local velocity V_{lt} *becomes equal to critical one* $k\beta V_{0t}$. *According to theoretical analysis, the relative equilibrium depth of scour is depending on flow contraction rate; kinetic parameter of the flow; ratio of the Froude number to the river slope; relative flow depth; dimensionless grain size; stratified riverbed conditions; ratio of the local and critical velocities; side-wall slope, and angle of flow crossing.*

Keywords: *flood, flow, intakes, scour, depth*

Introduction

Contraction of the flow by engineering structures (intakes, abutments, piers, guide banks) leads to changes in the flow pattern, to local increase in velocities, sharp drop in water level and to local scours. This structures can be damaged by the next reasons: multiple floods, flow hydraulics, river bed geology, contraction rate of the flow, type and shape of the structure and that the scour hole parameters, under clear-water conditions, are summing up and increases from flood to flood. If structures are not damaged even after several floods, dimensions of scour hole increases, and every next flood can be the reason for damage or failure because scour.

During the past few decades the equilibrium and temporal scour development at bridge piers, abutments and spur dikes were studied by Laursen and Toch (1956), Liu et al. (1961), Froehlich (1989), Richardson and Davis (1995), Lim (1997), Cardoso and Bettess (1999), Melville and Coleman (2000), Kothyari and Ranga Raju (2001), Oliveto and Hager (2002), Yanmaz and Celebi (2004), Joko and Lim (2006), and others. However, in nature, the action of flow loads on engineering structures has the form of hydrograph, and multiple floods form scour holes. Because of the difference between laboratory tests and physical process of scour in nature, the existing formulae overestimates the scour depth value (Kwak et al. 2004) and considerably increase cost of the foundations.

The differential equation of equilibrium for bed sediment movement in clear water was used, and a calculation methods for the scour development during multiple floods at abutments and guide banks were elaborated (Gjunsburgs et al. 2001, 2004, 2006, and 2010). According to the tests and the methods suggested, the scour starts when the floodplain is flooded and usually stops at the flood peak. The scour development depends on the flow hydraulics, the river-bed parameters and the floods probability, sequence, frequency and duration. At the flood peak, a scour hole is usually formed. Although the scour process can be continued further, it stops, because the flood is time-restricted. The scour time is always less than the flood duration. At the next flood of the same probability, the scour process does not start when the floodplain is flooded, but at a later time step, closer to the flood peak. This happens because of the scour hole developed in the previous flood. The duration of the scour process at the second and forthcoming floods is less than at the previous floods. The scour hole depth, width, and volume increases from flood to flood.

The method for calculating the equilibrium depth of scour is presented in this paper. The equilibrium depth, width, and volume of the scour hole are achieved when the local velocity calculated at the flood peak becomes equal to the critical one.

According to the theoretical analysis, the relative equilibrium depth of scour depended on flow contraction rate; kinetic parameter of the flow under the bridge; ratio of the Froude number to the river slope; relative flow depth; dimensionless grain size; stratified riverbed conditions; ratio of the local and critical velocities; side-wall slope, and angle of flow crossing.

Experimental setup

The tests were carried out in a flume 3.5 m wide and 21 m long. The tests were carried out under open flow conditions studying the flow distribution between the channel and the floodplain.

The rigid bed tests were performed for different flow contractions and Froude numbers in order to investigate the velocity and the water level changes in the vicinity of the structure.

The aim of the sand bed tests was to study the scour process, the changes in the local velocity, because of flow contraction, the grain sizes, and stratification the river bed influence on the scour.

The openings of the bridge model were 50, 80, 120, and 200 cm. The flow contraction rate Q/Q_b (where Q is the flow discharge and Q_b is the discharge in the opening under open-flow conditions) varied respectively from 1.56 to 5.69, floodplain depth was 7 and 13 cm, and the Froude numbers varied from 0.078 to 0.134; the slope of the flume was 0.0012.

The sand bed tests were carried out under clear-water conditions. The sand was placed 1 m up and down the contraction of the flume. The mean grain size was 0.24 and 0.67 mm. The condition that $Fr_R = Fr_f$ was fulfilled, where Fr_R and Fr_f are the Froude numbers for the plain river and for the flume, respectively. The tests in the flume lasted for 7 hours, the length scale was 50 and the time scale was 7. With respect to the real conditions, the test time was equal to 2 days. This was the mean duration of time steps into which the flood hydrograph was divided. The development of a scour was examined with different flow parameters in time intervals within one 7-hour step and within two steps of the hydrograph, 7 hours each.

The tests were carried out with one floodplain model and one side contraction of the flow and with two identical or different floodplain models and two side contractions. The position of the main channel was varied for different tests. Experimental data for the open-flow conditions are presented in Table 1.

Table 1. Experimental data for open-flow conditions in flume

Test	L (cm)	h_f (cm)	V (cm/s)	Q (l/s)	Fr	Re_c	Re_f
L1	350	7	6.47	16.60	0.0780	7500	4390
L2	350	7	8.58	22.70	0.0103	10010	6060
L3	350	7	10.30	23.60	0.1243	12280	7190
L4	350	7	8.16	20.81	0.0984	10270	5590/5660
L5	350	7	9.07	23.48	0.1094	11280	6140/6410
L6	350	7	11.10	28.13	0.1339	13800	7550/7840
L7	350	13	7.51	35.48	0.0665	13700	9740
L8	350	13	8.74	41.38	0.0756	16010	11395
L9	350	13	9.90	47.10	0.0876	14300	14300

Scour development in multiple floods

The differential equation of equilibrium of the bed sediment movement in clear water was used, and a method for calculating the scour development with time at the intakes=abutments, and guide banks during the multiple floods was elaborated and confirmed with experimental data(Gjunsburgs et al., 2001, 2004, 2006, 2010).

The depth of scour was calculated by using the flood hydrograph of certain probability divided into several time steps, with each time step divided into time intervals. For each time step, the following initial parameters must be determined: depth of water in the floodplain; contraction rate of the flow; maximum backwater; grain size of the bed material; thickness of the bed layer; specific weight of the bed material. As a result, we can determine the scour depth, the width, and volume at the end of each time step or after one, two, or multiple floods. The scour depth can be calculated during/after multiple floods of the same or higher probability. In floods of less probability, the scour depth does not change and remains at the level of previous floods. The scour stops at the peak of the flood or just after it, since the duration of the flood is restricted and the local velocity is reduced by the scour hole developed during the previous steps. The time of scour is always less than the time of flood. At the next flood of the same probability, the scour process does not start when the floodplain is flooded, but at a later time step, closer to the flood peak. It happens because of the scour hole developed in the previous flood. The duration of the scour process at the second and forthcoming floods is less than at the previous floods.

According to the method, the hydrograph was divided in time steps, and each step was divided into time intervals. Calculations were performed for each step of the hydrograph, so that to estimate the influence of the flow unsteadiness during the flood, but in each time step, the flow was assumed to be steady.

Using the graph $N = f(x)$ for calculated N_i

$$N_i = \frac{t_i}{4D_i h_f^2} + N_{i-1} \ , \tag{1}$$

where $N_i = 1/6x_i^6 - 1/5x_i^5$, t_i is the time interval, D_i is a constant parameter in steady flow time step, and h_f is the flow depth in floodplain, we find x_i and the scour depth at the end of the time interval:

$$h_s = 2h_f(x-1)\cdot k_m \cdot k_s \cdot k_\alpha \, , \tag{2}$$

where k_m is a coefficient depending on the side-wall slope of the abutment (Yaroslavcev, 1956); k_s is a coefficient depending on the abutment shape and k_α is a coefficient depending on the angle of flow crossing (Richardson and Davis, 1995).

According to the method- scour development in time depends on the flow hydraulics, the river-bed parameters, side-wall slope, angle of flow crossing, as well as on the probability, sequence, frequency and duration of multiple floods (Gjunsburgs et al.2010).

Equilibrium depth of scour

According to experimental data, the concentration of streamlines, a sharp drop in water level, and an increase in velocity are observed at the head of the structure. As found from the tests, the local velocity forms the scour hole.

The local velocity V_{lt} is decreasing and the critical one V_{ot} is increasing with development of the scour depth. The scour stops when V_{lt} becomes equal to $k\beta V_{ot}$:

$$\frac{V_l}{k\left(1+\frac{h_{equil.}}{2h_f}\right)} = \beta V_o \cdot \left(1+\frac{h_{equil.}}{2h_f}\right)^{0.25} \ , \tag{3}$$

where β = reduction coefficient of the critical velocity at the bended flow determined by using the Rozovskyi (1957) approach; k is a coefficient depending on contraction rate of the flow (Gjunsburgs and Neilands, 2004), h_f is the water depth in the floodplain; and h_{equil} is the equilibrium depth of scour.

The equilibrium depth of scour can be determined from Equation (3) as follows:

$$h_{equil.} = 2h_f\left[\left(\frac{V_l}{k\beta V_o}\right)^{0.8} - 1\right]\cdot k_m \cdot k_s \cdot k_\alpha \, , \tag{4}$$

The local velocity V_l can be calculated by Gjunsburgs and Neilands formula (2004) and the critical one V_0 by Studenitcnikov (1964) formula.

Method analysis

Equation (4) is transformed to show dependence relative depth of scour from dimensionless parameters of the flow:

$$h_{equil.} = 2h_f\left[\left(\frac{\varphi\sqrt{2g\Delta h}}{3.6\cdot k\cdot \beta \cdot d^{0.25} h_f^{0.25}}\right)^{0.8} - 1\right]\cdot k_m \cdot k_s \cdot k_\alpha \, . \tag{6}$$

Rotenburg et al. (1965) has found that the relative maximum backwater is a function of the following parameters:

$$\frac{\Delta h}{h_f} = f\left(\frac{Q}{Q_b};P_K;P_{Kb};\frac{Fr}{i_0};\frac{h}{h_f}\right), \tag{7}$$

where *Q/Q$_b$* is the flow contraction rate; *P$_K$* is the kinetic parameter of the open flow; *P$_{Kb}$* is the kinetic parameter of the flow under the bridge; *Fr/i$_0$* is the ratio of the Froude number to the river slope; *h/h$_f$* is the relative flow depth; *h* is an average depth of the flow; and *h$_f$* is the water depth in the floodplain.

Equation (6) can be written, to open maximum backwater value Δ h, as

$$h_{equil.} = 2h_f \left[\left(\frac{\varphi \sqrt{2g \left\{ \frac{P_K}{2} \left[\left(\frac{Q}{Q_b} \right)^2 - 1 \right] + \frac{P_{Kb}}{2} \sqrt{\frac{1}{Fr / i_0}} \left[\left(\frac{Q}{Q_b} \right)^2 + 1 \right] + P_{Kb} \right\}}}{3.6 \cdot k \cdot \beta \cdot d^{0.25} h_f^{0.25}} \right)^{0.8} - 1 \right] \cdot k_m \cdot k_s \cdot k_\alpha \cdot \quad (8)$$

The relative equilibrium depth of scour is a function of the following parameters:

$$\frac{h_{equil}}{h_f} = f\left(\frac{Q}{Q_b}; P_K; P_{Kb}; \frac{Fr}{i_0}; \frac{h}{h_f}; \frac{d_i}{h_f}; H_{strat}; \frac{V_l}{k\beta V_o}; k_m; k_s; k_\alpha \right), \quad (9)$$

where Q/Qb is the flow contraction rate; PK is the kinetic parameter of the open flow; PKb is the kinetic parameter of the flow under the bridge; Fr/i0 is the ratio of the Froude number to the river slope; h/hf is the relative flow depth; di/hf is a dimensionless grain size; $H_{strat.}$ is stratified riverbed conditions; Vl/βV0 is the ratio of the local and critical velocities; β is a coefficient of reduction in the velocity due to vortex structures;.

Figure 1 shows the relative depth of scour versus the contraction rate of flow. With increase in the flow contraction rate of the flow, the relative depth of scour increases.

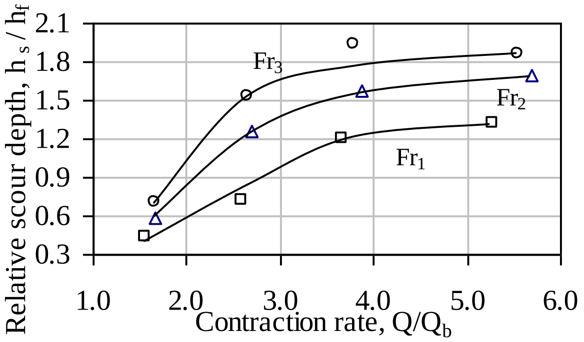

Figure 1. Relative depth of scour vs. contraction rate

The relative scour depth increases with increasing kinetic parameter of the flow (Figure 2).

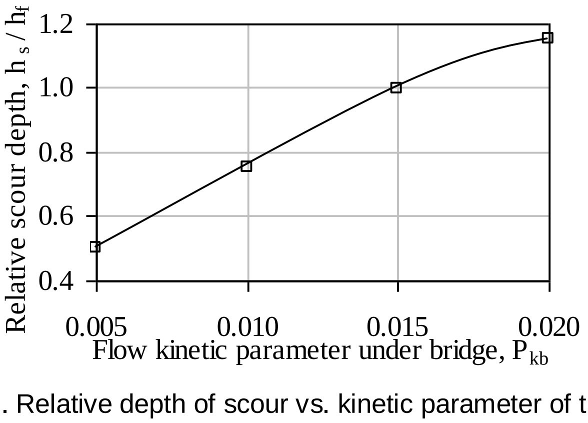

Figure2. Relative depth of scour vs. kinetic parameter of the flow

The relative depth of scour in relation to the relative grain size of bed material is presented in Figure 3.

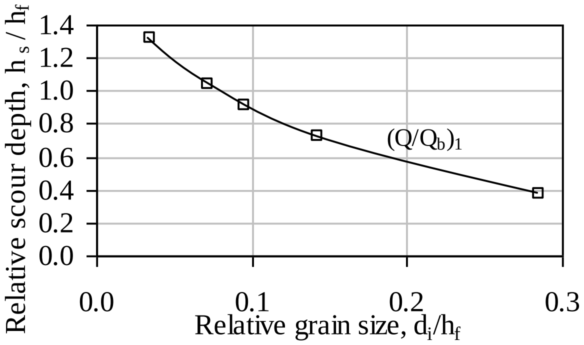

Figure 3. Relative depth of scour vs. relative grain size

With increase in the relative grain size of bed material, the relative depth of scour decreases. The influence of the Froude number *Fr* is shown in Figure 4.

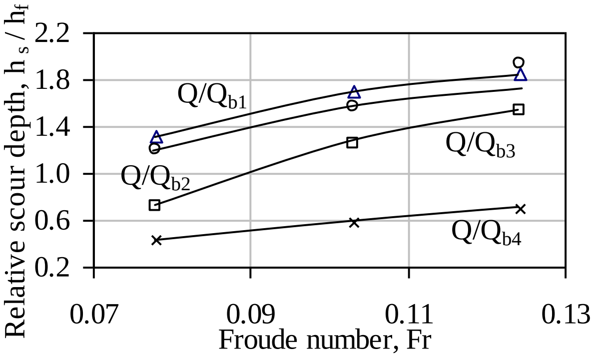

Figure 4. Relative depth of scour vs. Froude number

The smaller the value of *Fr* (the smaller the ratio between the inertia and frictional forces), the smaller the relative scour depth (Figure 4). With increasing ratio between the local velocity and th ecritical one $V_l/\beta V_0$, the relative scour depth is increases (see Figure 5.)

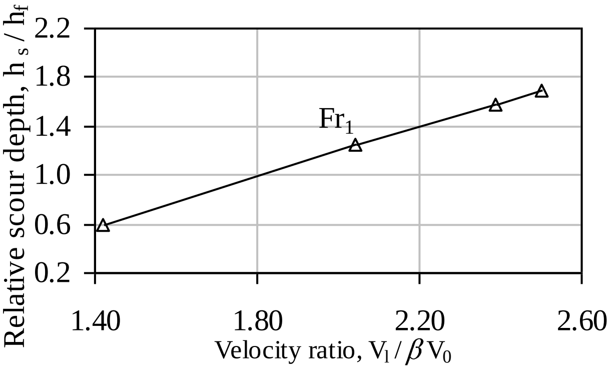

Figure 5. Relative depth of scour vs. velocity ratio

Scour development during multiple floods presented in Figure 6, from flood to flood, under clear water conditions, the depth of scour is increasing and is summing up.

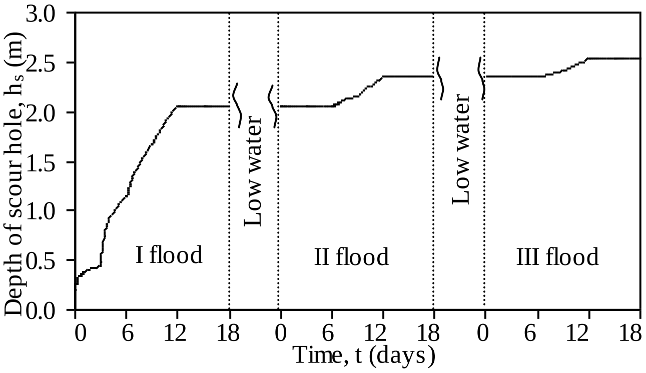

Figure 6. Scour development in time during multipje floods

In Figure 7 are presented depth of scour, local and critical velocities modeling in time in different sequence of the layers (test EUL4). The first layer was with d_1= 0.67 mm and the second layer with d_2= 0.24 mm. On the top of the second layer the critical velocity rapidly reduced, because of the grain size reduction (d_2= 0.24 mm).

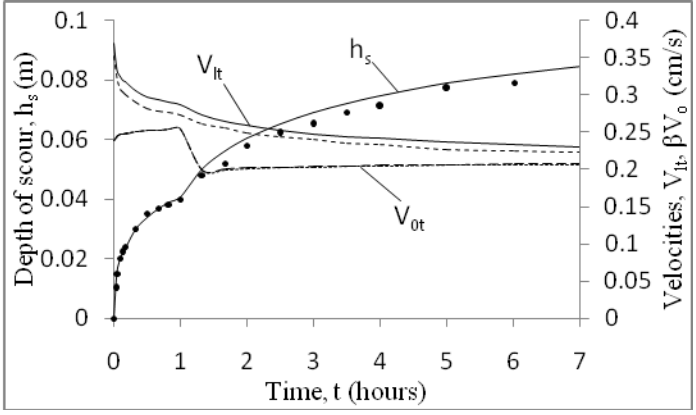

Figure 7. Changes in scour depth and in the local V_{lt} and critical βV_{0t} velocities, with d_1 = 0.67 mm in the first layer and d_2 = 0.24 mm in the second one; test EUL 4.

Depth of scour is always greater when the fine-sand layer is under the coarse sand layer, and smaller when the fine-sand layer is on the top of the coarse sand layer. According to the results obtained in tests and by the method elaborated the depth of scour is always greater when a fine-sand layer is under a coarse-sand layer(s). At stratified bed conditions ($H_{strat.}$) the sequence of the layers has the significant influence on the scour depth value.

Conclusions

The action of flow loads on engineering structures has the form of hydrograph, and multiple floods form scour holes at water intakes, piers, abutments, spur dikes, and guide banks.

Because of the difference between laboratory tests and physical process of scour in nature, the existing formulae overestimate the scour depth value and considerably increase the costs of engineering structures.

The differential equation of the bed sediment movement under clear water conditions was used, and a method for computing the scour development at the elliptical guide banks during multiple floods was elaborated and confirmed by experimental data. (Gjunsburgs et al., 2004, 2006, 2010)

Method for calculation equilibrium depth of scour is presented. As scour depth is developing, the local velocity is reducing and the critical one is increasing. The method proposed based on the fact that at equilibrium stage of scour local velocity Vlt becomes equil to critical on βV_{ot}.

According to the theoretical analysis, the relative equilibrium depth of scour is depending on flow contraction rate; kinetic parameter of the flow under the bridge; ratio of the Froude number to the river slope; relative flow depth; dimensionless grain size; stratified riverbed conditions; ratio of the local and critical velocities; side-wall slope, and angle of flow crossing.

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