ASSESSMENT OF FLOOD DAMAGE RISK FOR ENGINEERING STRUCTURES IN RIVER FLOODPLAINS

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INTRODUCTION

The water flow in rivers during floods has a strong impact on such engineering structures as the transport system infrastructure – roads, bridges, dams, etc. Contraction of the flow by bridge structures leads to considerable changes in the flow pattern, a local increase in velocities, increase of turbulence, and the origin of eddy and vortex structures. All these changes in the flow system are the reasons for a local scour at the abutments, piers, guide banks, and spur dikes and the general scour at the alignment of the bridge crossing.

During multiple floods, the scour-hole parameters near the engineering structures under clear-water conditions are summed up and increase from flood to flood; each next flood can lead to failure of the structure and be the reason for environmental and economical losses.

A method for predicting the damage risk of engineering structures during multiple floods is presented. The risk of flood damage is studied from the viewpoint of scouring at structure foundations. The method is based on two approaches to scour calculation: (1) determination of the scour development in time during multiple floods and (2) determination of the designed equilibrium depth of scour. Using these two methods, we suggest estimating the factor of flood damage risk as a ratio between the scour depth calculated during/after multiple floods and the designed equilibrium scour depth.

SCOUR DEVELOPMENT DURING MULTIPLE FLOODS

In nature, the river engineering structures have to withstand the loads of multiple floods. We can calculate the scour depths developed at structure foundations in multiple floods of different probability, frequency, sequence, and duration by using the method that take into account the scour development in time (Gjunsburgs et al., 2001, 2004).

To determine the scour depth development during the flood, we divided the hydrograph into time steps with duration of 1 or 2 day, and each time step – into time intervals up to several hours (Fig. 1). At each time step the flow is steady, but is changing from step to step during the flood. In the laboratory tests, the time steps were divided into 20 time intervals. For each time step, the following parameters must be determined: h_f – water depth in the floodplain, Q/Q_b – flow contraction rate, Δh – maximum backwater, d – grain size, H – thickness of the bed layer with d, and γ – specific weight of the bed material. As a result, we have V_l, V_0, A_i, D_i, N_i, N_{i-1}, and h_s at the end of time intervals and finally at the end of the time step. For the next time step, the flow and bed parameters were changed because of the flood and the scour developed in the previous time step.

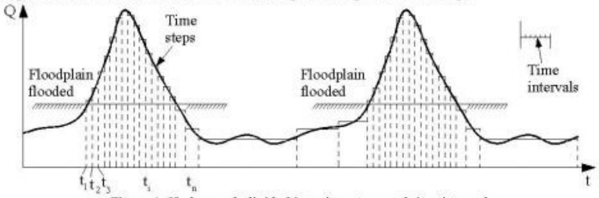

Figure 1. Hydrograph divided into time steps and time intervals

The scour depth depends on time and is calculated by the formula:

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

where $N_i = 1/6x_i^6 - 1/5x_i^5$ (according to Table 1); t_i is the time interval; D_i is a constant parameter in a steady-flow time step; and h_f is the flow depth in the floodplain.

Table 1. Relations between N_i and x_i

x_i	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8
N_i	-0.033	0.0002	0.18	0.70	1.90	4.29	8.62	15.98	27.2	46.07

Using the data from Table 1 for the calculated N_i, we find:

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

here h_s is the scour depth at the end of time interval; 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 (Richardson and Davis, 1995); and k_α is a coefficient depending on the angle of flow crossing (from Richardson et al., 1990, as presented in Richardson and Davis, 1995).

EQUILIBRIUM DEPTH OF SCOUR

The equilibrium depth of scour is an important parameter to be determined for the foundation of the structures at the design stage to ensure the lifetime guaranty of safe maintenance of the engineering structures in floods. This parameter is also important in determining the critical value of scour depth at which the emergency scour-protection measures should be taken.

In tests on the bridge abutment models, the streamline concentration, an additional flow action, flow separation, a sharp drop in water level, a local increase in velocities, the origin of eddy and vortex structures, and the development of a scour hole were observed at the corner of the abutment (Gjunsburgs et al. 2001, 2004).

The local velocity can be found in the form:

$$V_l = \varphi\sqrt{2g\Delta h} \tag{3}$$

where φ is the velocity coefficient for abutment which depends on the contraction rate of the flow; g is the gravitational acceleration; and Δh is the maximum backwater (Rotenburg, 1969).

During the scour process, the discharge across the width of a scour hole changes: $Q_f = kQ_{sc}$, where Q_f is the discharge across the width of a scour hole with a plain bed; k is a coefficient depending on the contraction of the flow; and Q_{sc} is the discharge across the width of a scour hole with a scour depth h_s.

This equation can be written as:

$$mh_s \cdot h_f V_l = k(mh_s h_f + \frac{mh_s}{2}\cdot h_s)\cdot V_{lt} \tag{4}$$

where h_s is the scour depth and m is the slope of a scour-hole wall.

The local flow velocity V_{lt} can be found at any depth of the scour hole:

$$V_{lt} = \frac{V_l}{k\left(1+\frac{h_s}{2h_f}\right)} = \frac{\varphi\sqrt{2g\Delta h}}{k\left(1+\frac{h_s}{2h_f}\right)} \tag{5}$$

The flow velocity at which the sediment movement starts is V_0, and it can be found at any depth of scour:

$$V_{0t} = \beta\cdot V_0\left(1+\frac{h_s}{2h_f}\right)^{0.25} = 3.6\cdot\beta\cdot d^{0.25}h_f^{0.25}\left(1+\frac{h_s}{2h_f}\right)^{0.25} \tag{6}$$

where β is a coefficient of reduction in V_0 because of the flow vortex structures; d is the grain size of bed material.

The scour reaches its equilibrium stage and stops when the local flow velocity V_{lt} becomes equal to the velocity V_{0t}. Using the Eqs. (5) and (6), we find equilibrium scour depth:

$$h_{equil} = 2h_f\left[\left(\frac{V_l}{k\beta V_0}\right)^{0.8} - 1\right]\cdot k_m \cdot k_s \cdot k_\alpha \tag{7}$$

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 (Richardson and Davis, 1995); and k_α is a coefficient depending on the angle of flow crossing (from Richardson et al., 1990, as presented in Richardson and Davis, 1995).

FLOOD DAMAGE RISK - ASSESSMENT OF STABILITY OF STRUCTURE

The stability of the engineering structures in floods from the aspect of scouring can be evaluated by combining two calculation methods, namely the method of computing the designed equilibrium depth of scour by Eq. (7) and the method of computing the scour development during multiple floods of different probability, frequency, sequence, and duration according to Eq. (2).

The scour-hole parameters calculated during or after multiple floods can be compared with the equilibrium parameters, and thus the stability of the engineering structure can be evaluated. The flood damage risk factor by abutment scour can be calculated as a ratio between h_s, the scour depth after the floods of certain probability, and h_{equil}, the equilibrium scour depth at the abutments in the flood of the same probability:

$$R = \frac{h_s}{h_{equil}} \tag{8}$$

The closer the current depth value of the scour hole to the equilibrium value of the latter, the greater the risk factor and the lower the stability of the construction. By using the risk factor, we can estimate the current stability of the structure or to predict/compute the time of safe maintenance at the stage of design. If the scour-hole depth developed is close to the equilibrium conditions, the critical conditions are reached and the emergency scour-protection measures (riprap, rock riprap, sand/cement-filled bags, etc.) for the structure should be taken .

CALCULATION EXAMPLE

An example of calculation of scour hole at the abutments near the bridge crossing on a plain river after two floods of a 1% probability is shown.

Initial data for calculation of equilibrium depth of scour: $h_f = 2.3$ m; $Q/Q_b = 1.42$; $d = 0.005$ m; $\Delta h = 0.406$ m (calculated from Rotenburg equation). Coefficient $\varphi = 0.8116$ according to graphical relation.

The local velocity at the abutments can be found according to Eq. (3):

$V_l = \varphi\cdot\sqrt{2g\Delta h} = 0.8116\cdot\sqrt{2\cdot 9.81\cdot 0.406} = 2.29$ m/s

The velocity at which the sediment movement starts is found:

$V_0 = 3.6\cdot d^{0.25}\cdot h_f^{0.25} = 3.6\cdot 0.005^{0.25}\cdot 2.3^{0.25} = 0.663$ m/s

We assumed that we have vertical wall abutment with 90° angle of flow crossing, respectively $k_m = 1.0$, $k_s = 1.0$, and $k_\alpha = 1.0$. According to graph, the coefficient $k = 0.9311$. The equilibrium scour depth according to Eq. (7) is:

$$h_{equil} = 2h_f\left[\left(\frac{V_l}{k\beta V_0}\right)^{0.8} - 1\right]\cdot k_m \cdot k_s \cdot k_\alpha = 2\cdot 2.3\cdot\left[\left(\frac{2.29}{0.9311\cdot 0.8\cdot 0.663}\right)^{0.8} - 1\right]\cdot 1.0\cdot 1.0\cdot 1.0 = 11.096 \text{ m}$$

The slope of the scour hole wall is $m = 1.65$, and we find equilibrium width of the scour hole:

$B_{equil} = m\cdot h_{equil} = 1.65\cdot 11.096 = 18.308$ m

The equilibrium volume of the scour hole is:

$W_{equil} = 1/6\cdot\pi\cdot m^2\cdot h_{equil}^3 = 1/6\cdot 3.14\cdot 1.65^2\cdot 11.096^3 = 1946.46$ m^3

By using the computer modelling and the method of scour development in time, we find the development of depth, width, and volume of scour hole during and after two floods with a 1% probability.

The developed scour depth is $h_s = 7.484$ m and the equilibrium depth of scour is $h_{equil} = 11.096$ m.

The flood damage risk factor of abutment scour is $R = h_s/h_{equil} = 7.484 / 11.096\cdot 100\% = 67.44\%$.

The calculated equilibrium stage and simulated development of depth, width, and volume of scour hole during two floods of 1% probability is presented in Figs. (2), (3), and (4), respectively.

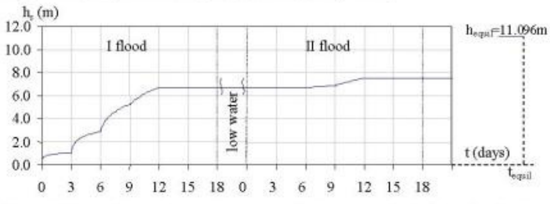

Figure 2. The equilibrium stage and development of scour hole depth during two floods

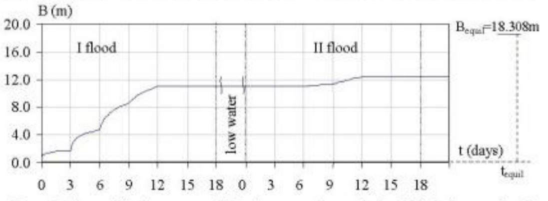

Figure 3. The equilibrium stage and development of scour hole width during two floods

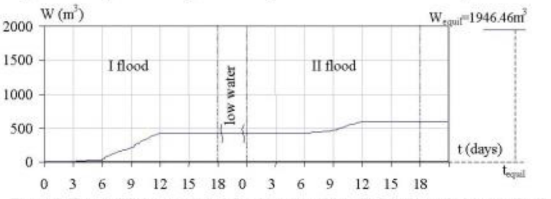

Figure 4. The equilibrium stage and development of scour hole volume during two floods

CONCLUSIONS

We suggest calculating the flood damage risk factor to estimate the stability of engineering structures on rivers. The flood damage risk factor can be computed by using two methods, which allows us to determine the scour-hole parameters during/after multiple floods of different probability, frequency, sequence, and duration and the scour-hole parameters at the equilibrium stage.

The methods suggested can be used for:

1. Computing the development of scour depth during the expected usual or extreme flood events, varying with the flood probability, frequency, sequence, and duration, at the stage of designing a river engineering structure. In such a way, the most dangerous sequence of expected floods for engineering structures can be found;

2. Computing the currently developed scour depth; by comparing it with the designed equilibrium scour depth, we can determine the flood-damage risk factor and estimate the safety and stability of the engineering structure at the stage of maintenance;

3. Computing the flood-damage risk factor. When the currently developed scour depth is close to the equilibrium scour depth and the flood-damage risk factor has reached the critical value, the flood-damage risk conditions for river engineering structures come into effect. Such critical river engineering structures should be marked as flood-hazard zones and included into flood risk maps. By using the flood-damage risk factor, we can evaluate the necessity of the emergency scour-protection measures for engineering structure.