

# Assessment of flood damage risk for engineering structures in river floodplains

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## Abstract

The water flow in rivers during floods has a strong impact on the transport system infrastructure – roads, bridges, dams, etc. The frequency and intensity of flood events increase with high water levels and considerable discharges, thus raising the loads on engineering structures in rivers and, at the same time, the possibility of damage. The stability of piers, abutments, guide banks, and spur dikes in floods depends on the dimensions of scour holes at foundations. By preliminary computing the scour development in time during floods, we can estimate a possible scour-depth value induced by expected floods. According to the calculated scour value, protection measures can be taken if necessary, which will reduce the economical and environmental losses.

A method for predicting the damage risk of bridge structures during multiple floods is presented. The risk of flood damage is studied from the viewpoint of scouring. 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.

Under critical conditions, when the scour depth calculated in floods is close to the designed equilibrium stage of scour for bridge foundations, emergency protection measures should be taken to avoid the failure of bridge structures.

## Introduction

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 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 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.

During the past decades, the equilibrium and temporal stage of scour at bridge piers, abutments, guide banks, and spur dikes were studied, and fundamental books were published by Rotenburg (1969), Breuser & Raudkivi (1991), Hoffmans & Verheij (1997), Melville & Coleman (2000), and Annandale (2006).

However, in nature, the action on engineering structures has the form of a hydrograph, and the multiple floods form a scour hole at the bridge structures.

The existing formulas and methods do not take into account the fact that the scour is developing during multiple floods and depends on the probability, frequency, sequence, and duration of floods.

In investigating this problem, the differential equation of equilibrium for the bed sediment movement in clear water was used, and a calculation method for the scour development at the abutment and guide banks during multiple floods was elaborated (Gjunsburgs et al. 2001, 2004, 2005, and 2007).

According to the tests and the method suggested in the above studies, the scour originates when the floodplain is flooded and usually stops at the flood peak. The scour development depends on the flow hydraulics, the river-bed parameters, the probability of multiple floods, and their frequency, sequence, 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, which reduces the local flow velocity and the flow capacity to remove the sediments. 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 increase from flood to flood.

A new 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 velocity at which the sediment movement starts.

The parameters of the scour hole computed during multiple floods can be compared with its equilibrium parameters calculated by the equations suggested, and the flood damage risk factor for the abutments can be determined as a ratio of  $h_s/h_{equil}$ , where  $h_s$  is the scour depth calculated after multiple floods and  $h_{equil}$  is the equilibrium depth of scour.

Under critical conditions, when the scour hole developed after multiple floods is close to the equilibrium conditions, emergency protection measures (riprap, rock riprap, sand/cement-filled bags, etc.) should be taken.

The risk factors should be primarily estimated both for the most important (according to bridge classification) bridges, associated with the main roads of national economic importance, emergency evacuation roads to hospitals and rescue units, and so on, and also for the critical bridges that can be damaged by upcoming floods.

## **Experimental setup**

The tests were carried out at the Transport Research Institute (Russia) in a flume 3.5 m wide and 21 m long.

Experimental data for the open-flow conditions are presented in Table 1.

The tests were carried out under open flow conditions for 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 abutment, along it, and near the model abutment.

The aim of the sand bed tests was to study the scour process, the changes in the velocity in floods, the effect of different hydraulic parameters, the flow contraction rate, the grain size of the bed material, and the scour development in floods.

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 bridge opening under open-flow conditions) varied respectively from 1.56 to 5.69 for the floodplain depth of 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.

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	0.103	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

### Equilibrium depth of scour

At the stage of designing the bridge foundation, engineers calculate the equilibrium depth of scour with flood parameters of a 100-year probability, using a safety factor of 2 to 3, but they must also check the foundation safety and stability for extreme flood events, e.g., for a 0.2% flood probability (Richardson & Davis, 2001).

Therefore, the equilibrium depth of scour is an important parameter to be determined at the design stage to ensure the lifetime guaranty of safe maintenance of the 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.

Approaching the bridge contraction, the extreme streamlines become curved and then go parallel to the embankment. The flow velocity along the extreme streamline drops down almost to a zero and then gradually increases and reaches its maximum at the corner of the abutment.

The local velocity can be found in the form:

$$V_l = \varphi \sqrt{2g\Delta h} \quad (1)$$

where  $\varphi$  is the velocity coefficient for abutments (Fig. 1) and  $\Delta h$  is the maximum backwater at bridge crossing determined by the Rotenburg (1969) formula.

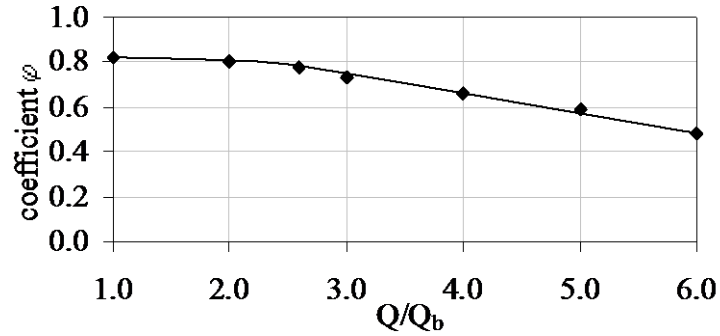


Figure 1. Coefficient  $\varphi$  vs. the flow contraction rate

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 (Fig.2); and  $Q_{sc}$  is the discharge across the width of a scour hole with a scour depth  $h_s$ .

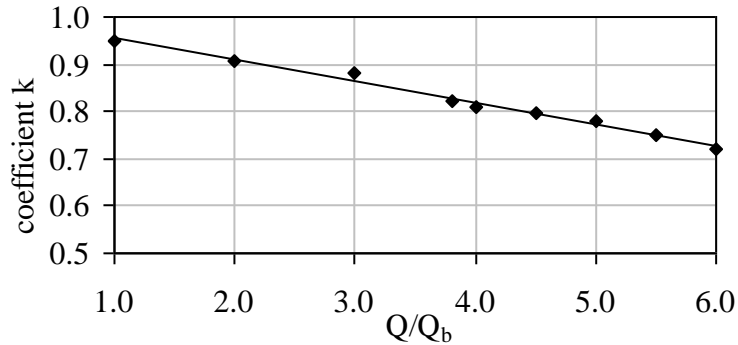


Figure 2. Coefficient  $k$  vs. the flow contraction rate

This equation can be written as:

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

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:

$$V_{lt} = \frac{V_l}{k \left( 1 + \frac{h_s}{2h_f} \right)} = \frac{\varphi \sqrt{2g\Delta h}}{k \left( 1 + \frac{h_s}{2h_f} \right)} \quad (3)$$

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

$$V_{ot} = \beta \cdot V_0 \left( 1 + \frac{h_s}{2h_f} \right)^{0.25} \quad (4)$$

where  $\beta$  is a coefficient of reduction in  $V_0$  because of the flow vortex structures.

The scour reaches its equilibrium and stops when the local flow velocity  $V_{lt}$  becomes equal to the velocity  $V_{0t}$ :

$$\frac{V_1}{k \left( 1 + \frac{h_{\text{equil.}}}{2h_f} \right)} = \beta V_0 \cdot \left( 1 + \frac{h_{\text{equil.}}}{2h_f} \right)^{0.25} \quad (5)$$

The equilibrium depth of scour at the abutments can be found from Eq. (5):

$$h_{\text{equil.}} = 2h_f \left[ \left( \frac{V_1}{k\beta V_0} \right)^{0.8} - 1 \right] \cdot k_m \cdot k_s \cdot k_\alpha \quad (6)$$

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

A comparison between the equilibrium scour depth calculated by Eq. (6) and the experimental equilibrium scour depth obtained by the method of scour development in time (Gjunsburgs et al., 2004), based on the prolonged, 7-hour duration of the laboratory tests, is presented in Table 2.

Table 2. Comparison of the calculated and experimental equilibrium scour depths

Tests	Q (l/s)	Q/ Q <sub>b</sub>	d <sub>i</sub> (mm)	h <sub>equil.EXP</sub> (cm)	h <sub>equil.CALC</sub> (cm)	h <sub>equil.CALC</sub> / h <sub>equil.EXP</sub>	ε <sub>equil</sub> (%)
SL1	16.6	5.27	0.24	15.67	16.19	1.033	3.34
SL4	16.6	3.66	0.24	11.38	11.82	1.038	3.82
SL7	16.6	2.60	0.24	6.33	6.70	1.059	5.89
SL10	16.6	1.56	0.24	2.86	3.22	1.124	12.39
SL2	22.7	5.69	0.24	20.67	21.25	1.028	2.84
SL5	22.7	3.87	0.24	15.78	16.30	1.033	3.30
SL8	22.7	2.69	0.24	10.63	11.05	1.040	4.00
SL11	22.7	1.66	0.24	4.10	4.46	1.087	8.74
SL3	23.6	5.55	0.24	22.45	23.12	1.030	3.02
SL6	23.6	3.78	0.24	19.27	19.83	1.029	2.91
SL9	23.6	2.65	0.24	13.41	13.88	1.035	3.52
SL12	23.6	1.67	0.24	5.34	5.71	1.068	6.84

## 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 methods that take into account the scour development in time.

The methods suggested for computing the scour development in time at abutments and guide banks are based on the differential equation of equilibrium of the bed sediment movement under clear-water conditions. The methods are confirmed by experimental data (Gjunsburgs et al. 2001, 2004, 2005, and 2007).

The depth of scour was calculated by using the multiple flood hydrographs of different probability, frequency, sequence, and duration, divided into several time steps, with each time step divided into time intervals (Fig. 3). For each time step, the following initial parameters must be determined: water depth in the floodplain, contraction rate of the flow, maximum backwater, grain size of the bed material, thickness of the bed layers, and specific weight of the bed material. As a result, we can determine the scour depth, width, and volume at the end of each time step of the hydrograph or after one, two, or multiple floods. The scour usually stops at the peak of the flood. 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. The depth, width, and volume of the scour hole are summed up from flood to flood (Figs. 4, 5, and 6).

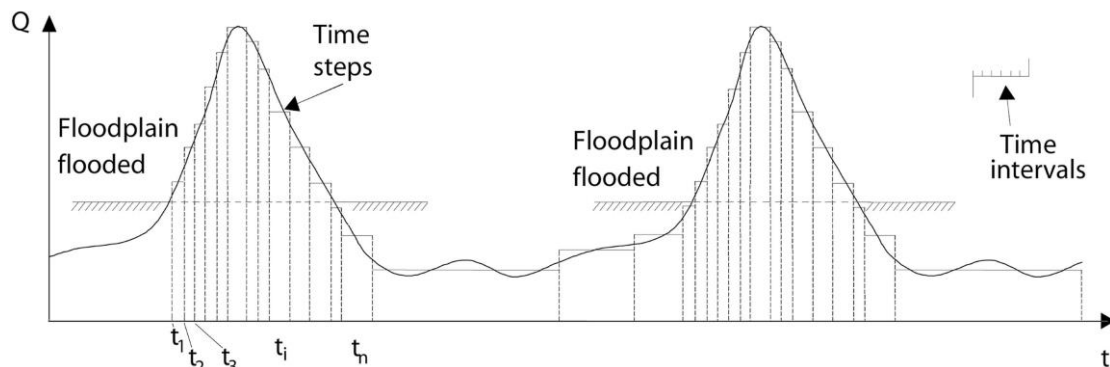


Figure 3. Hydrograph divided into time steps and time intervals

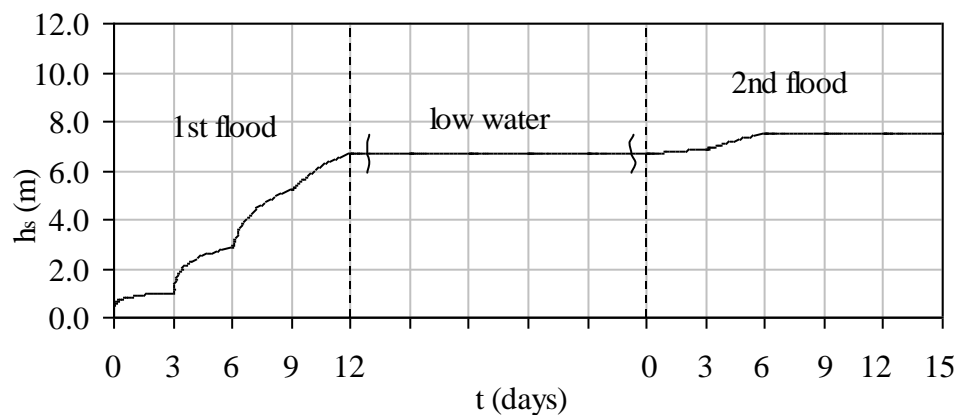


Figure 4. Example of scour depth development at abutments for two floods of the same probability

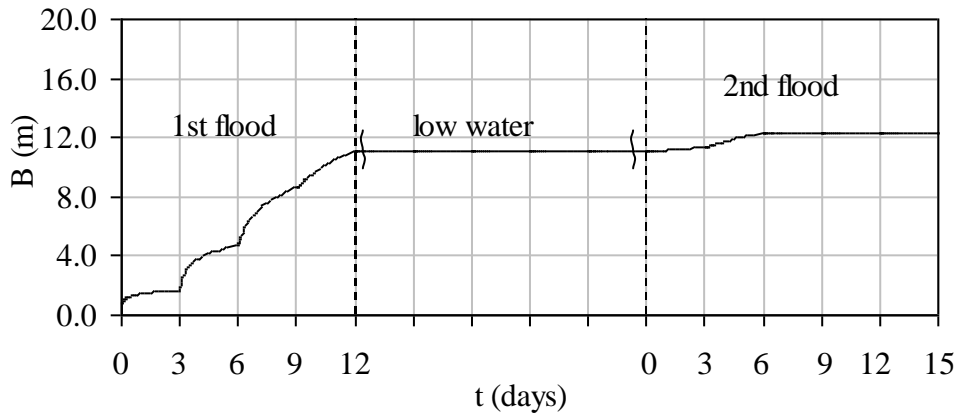


Figure 5. Example of scour hole width development at abutments for two floods of the same probability

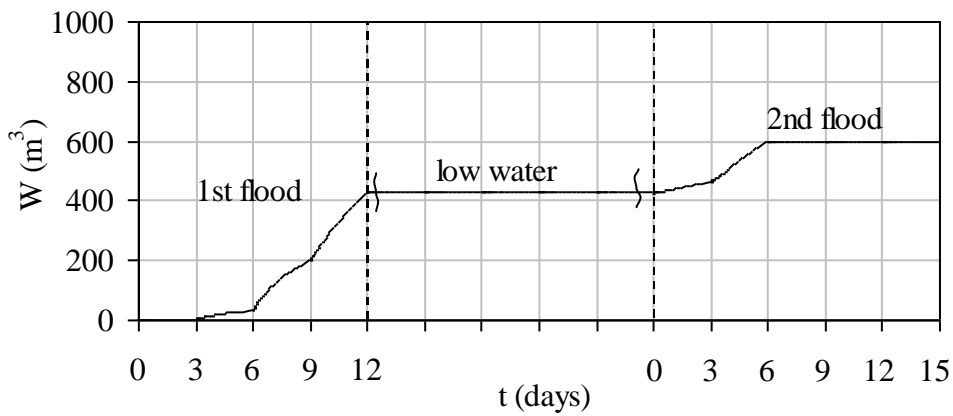


Figure 6. Example of scour hole volume development at abutments for two floods of the same probability

According to the method suggested, the hydrograph was divided into time steps, and each step was divided into time intervals. The calculations were performed for each time 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.

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

$$N_i = \frac{t_i}{4D_i h_f^2} + N_{i-1} , \quad (7)$$

where  $N_i = 1/6x_i^6 - 1/5x_i^5$  (according to Table 3);  $t_i$  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 3. 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 3 for the calculated  $N_i$ , we find:

$$h_s = 2h_f(x-1) \cdot k_m \cdot k_s \cdot k_\alpha \quad (8)$$

where  $h_s$  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  $k_\alpha$  is a coefficient depending on the angle of flow crossing (from Richardson et al., 1990, as presented in Richardson and Davis, 1995).

### **Stability of the engineering structures during multiple floods**

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. (6) and the method of computing the scour development during multiple floods of different probability, frequency, sequence, and duration according to Eq. (8).

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  $h_{\text{equil}}$ , the equilibrium scour depth at the abutments in the flood of the same probability:

$$R = \frac{h_s}{h_{\text{equil}}} \cdot 100\% \quad (9)$$

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 rippap, sand/cement-filled bags, etc.) should be taken.

### **Conclusions**

According to the classification of bridges, they should have different degrees of flood-protection measures.

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 are confirmed by experimental data.

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.

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