INTERNATIONAL SCIENTIFIC CONFERENCE
PEOPLE BUILDINGS AND ENVIRONMENT 2012
7.-9. 11. 2012, LEDNICE, CZECH REPUBLIC

MULTIPLE FLOOD AS THE CAUSE OF FAILURE OF ENGINEERING STRUCTURES IN RIVER FLOWS

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Abstract

The scour development with time during multiple floods, equilibrium stage and the assessment of flood damage risk for engineering structures have been investigated. A method for computing scour development with time at engineering structures during multiple floods was used. The test confirmation of the method allows as to perform computer modelling of scour processes and to estimate the influence of floods with different probability, duration, sequence and frequency on the depth of scour. It was found that the scour parameters increase with decrease in probability and with increasing duration and frequency of the floods. The sequence of floods can increase or reduce the scour development with time, depending on their probability. The successive floods of the same probability considerably increase the value of the scour depth.

Key words

Hydrograph, scour, modelling, multiple floods.

To cite this paper: *G. Jaudzems, B. Gjunsburgs, J. Govsha. Multiple Flood as The Cause of Failure of Engineering Structures in River Flows, In Proceedings of International Scientific Conference People, Buildings and Environment 2012, Vol .2, pp. 548-557, ISSN: 1805-6784.*

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1 INTRODUCTION

Transport system infrastructures, such as roads, bridges, dams, and water intakes in rivers, are under permanent impacts of multiple floods. To estimate their safety and stability during scour development at hydraulic structure foundations, a multidisciplinary approach, involving the principles of hydraulics, hydrology, morphology, geology, and so on, is required.

During the past few decades equilibrium and temporal depth of scour at engineering structures has been studied by many authors, and new approaches have been elaborated by Cardoso & Bettess [1], Kothyari & Ranga Raju [2], Balio & Orsi [3], Radice et al. [4], Hager et al. [5], Armitage & McGahey [6], Yanmaz & Celebi [7], Grimaldi et al. [8], Gjunsburgs et al. [9, 10, 11], Tregnaghi & Marion [12], and Yanmaz & Kose [13]. For computing the equilibrium depth of scour flow parameters at the peak of the flood with unrestricted or restricted duration (some hours or days) was used. However, in the nature the flow load on engineering structures are in the form of a hydrograph and multiple floods form scour holes.

The scour hole parameters (depth, width, and volume) during floods under clear-water conditions in the floodplain are summed up and increase from flood to flood. Hence, it is impossible to predict how multiple floods will affect the scour depth at the abutment and to know whether it will or will not be destroyed after a current or forthcoming event, whether the scour depth will exceed or not the designed equilibrium depth if the floods are higher than the calculated ones, and how long the structure will stay undamaged and safe enough after unexpected multiple flash floods.

Using the differential equation of equilibrium of the bed sediment movement in clear water, a method for calculating the scour development in time at engineering structures during floods has been elaborated. The agreement between the experimental and calculated results [9] allows us to use this method for computer modelling of the scour process in nature during floods with different probability, duration, frequency, and sequence. This method enables us to compute the scour depth at any stage of the flood during the maintenance period or at the stage of designing the bridge crossings.

It was found that the scour parameters increase with decreasing probability and with increasing duration and frequency of the floods. The sequence of floods can increase or reduce the scour development in time, depending on their probability. The successive floods of the same probability considerably increase the value of scour depth.

2 SCOUR DEVELOPMENT IN TIME DURING MULTIPLE FLOODS

The differential equation of equilibrium for the bed sediment movement in clear-water conditions has the form:

$$\frac{dw}{dt} = Q_s \tag{1}$$

where w is the volume of the scour hole, which, according to the test results, is equal to $1/6\pi m^2 h_s^3$, t is a time, and Q_s is the sediment discharge out of the scour hole. The volume and shape of the scour hole are independent of the contraction rate of the flow [9].

The left-hand part of Eq. (1) can be written as

$$\frac{dw}{dt} = \frac{1}{2}\pi m^2 h_s^2 \frac{dh_s}{dt} = a h_s^2 \frac{dh_s}{dt} \tag{2}$$

where h_s is the scour depth, m is the steepness of the scour hole, and $a=1/2\pi m^2$.

The sediment discharge was determined by the Levi [14] formula:

$$Q_S = AB \cdot V_l^4 \tag{3}$$

where $B = mh_s$ describes width of the scour hole, V_l is the local velocity at the abutments with a plain bed, and A is a parameter in the Levi [14] formula.

The discharge across the width of a scour hole before and after the scour is determined as follows:

$$Q_f = Q_{sc} \cdot k \tag{4}$$

where Q_f is a discharge across the width of the scour hole with a plain bed, Q_{sc} is the discharge across the scour hole with a scour depth h_s, and k is a coefficient of changes in discharge because of scour, which depends on the flow contraction [9].

Now we have

$$m h_s h_f V_l = k\left(m h_s h_f + \frac{m h_s}{2} h_s \right) \cdot V_{lt} \tag{5}$$

where mh_s is the width of the scour hole, h_f is a water depth in the floodplain, h_s is the scour depth, and V_{lt} is the local flow velocity at a scour depth h_s. From Eq. (5) the local velocity for any depth of scour is

$$V_{lt} = \frac{V_l}{k\left(1 + \frac{h_s}{2h_f}\right)} \tag{6}$$

The critical velocity at the plain bed V_0 can be determined by the Studenitcnikov [15] formula $V_0=3.6d_i^{0.25}h_f^{0.25}$, where d_i is a grain size of the bed materials. The critical velocity V_{0t} for any depth of scour h_s and for the flow bended by the bridge crossing embankment is

$$V_{0t} = \beta \cdot 3.6 \cdot d_i^{0.25} \cdot h_f^{0.25} \left(1 + \frac{h_s}{2h_f}\right)^{0.25} \tag{7}$$

At a plain river bed, the formula for $A = A_1$ reads

$$A = \frac{5.62}{\gamma}\left(1 - \frac{\beta V_0}{V_l}\right)\frac{1}{d_i^{0.25} \cdot h_f^{0.25}} \tag{8}$$

where γ is a specific weight of sediments.

The parameter A depends on the scour, local velocity V_l, critical velocity V_0, and grain size of the bed material during the floods:

$$A_i = \frac{5.62}{\gamma}\left[1-\frac{k\beta V_0}{V_l}\left(1+\frac{h_s}{2h_f}\right)^{1.25}\right]\cdot\frac{1}{d_i^{0.25}\cdot h_f^{0.25}\left(1+\frac{h_s}{2h_f}\right)^{0.25}} \tag{9}$$

Then, we replace V_l in Eq. (3) with the local velocity at any depth of scour V_{lt} from Eq. (6). The parameter A in Eq. (3) is replaced with the parameter A_i from Eq. (9). The sediment discharge upon development of the scour is

$$Q_s = A_i\cdot mh_s\cdot V_{lt}^4 = b\frac{h_s}{k^4\left(1+\frac{h_s}{2h_f}\right)^4} \tag{10}$$

where $b = A_i mV_l^{\,4}$.

The hydraulic characteristics, such as contraction rate of the flow, the velocities V_0 and V_l, the grain size in different bed layers, the sediment discharge, and the depth, width, and volume of the scour hole, varied during the floods.

Taking into account formulas (2) and (10), the differential equation (1) can be written in the form

$$ah_s^2\frac{dh_s}{dt} = b\frac{h_s}{k^4\left(1+\frac{h_s}{2h_f}\right)^4} \tag{11}$$

After separating the variables and integration of Eq. (11), we have:

$$t = D_i\int_{x_1}^{x_2} h_s\left(1+\frac{h_s}{2h_f}\right)^4 dh_s \tag{12}$$

where $x_1 = 1+h_{s1}/2h_f$ and $x_2 = 1+h_{s2}/2h_f$ are relative depths of scour and $D_i = \frac{k^4 a}{b} = \frac{\pi\cdot m\cdot k^4}{2A_i\cdot V_l^4}$.

According to the method, the hydrograph was divided into time steps, and each step in turn was divided into time intervals. It was assumed that D_i was constant inside the time interval.

After integration with new variables, $x = 1+h_s/2h_f$, $h_s = 2h_f(x-1)$, and $dh_s = 2h_f dx$, we obtain

$$t = 4D_i h_f^2 \left(N_i - N_{i-1}\right) \tag{13}$$

Where $N_i = 1/6x_i^6 - 1/5x_i^5$, $N_{i-1} = 1/6x_{i-1}^6 - 1/5_{xi-1}^5$, $x = 1 + h_s / 2h_s$ are the relative depths of scour.

From Eq. (13), the value of N_i can be found

$$N_i = \frac{t_i}{4D_i h_f^2} + N_{i-1} \tag{14}$$

where t_i is a time interval.

Using the graph $N = f(x)$ for the calculated value of N_i, we find x_i and the depth of scour at the end of time interval:

$$h_s = 2h_f \left(x - 1\right) \tag{15}$$

We assume that the scour depth depends on the slope of the side wall [16] described by the coefficient k_m and on the angle of flow crossing [17] described by the coefficient k_α. In our study, the angle of flow crossing was 90° and $k_\alpha = 1$.

Then, Eq. (15) can be given in the form

$$h_s = 2h_f \left(x - 1\right) \cdot k_m \cdot k_\alpha \tag{16}$$

To determine the scour depth development during the flood or multiple floods, the hydrograph was divided into time steps with duration of 1 or 2 days, and each time step was divided into time intervals up to several hours. For each time step, the following parameters must be determined: the water depth in the floodplain h_f; contraction flow rate Q/Q_b, where Q is the discharge of flow and Q_b is the discharge in the bridge opening under open-flow conditions; the maximum backwater Δh determined by the Rotenburg [18] method (a comparison of the values of Δh obtained in the tests with those calculated by Rotenburgh [18] was illustrated earlier [9] and gave good results); grain size d_i; thickness H of the bed layer with d_i; the specific weight γ of the bed material. As a result, we have V_l, V_{lt}, V_0, V_{0t}, A, A_i, D_i, N_i, N_{i-1}, x, 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 parameters were changed because of the flood and because of the scour developed during the previous time step. The experimental data for open flow conditions, as well as comparisons between the values of local velocities and scour depth at the abutment obtained in tests and calculations have been presented previously [9]. Comparison results between the experimental and calculated scour depth at the abutments was in good agreement.

3 MODELLING OF MULTIPLE FLOODS

Based on the method described, a computer modelling of the time-dependent scour during multiple floods with different probability, duration, frequency, and sequence was performed.

The duration was changed for each separate flood in the series of multiple floods. Investigation was made on the influence of the flood probability on the time-dependent scour development. The peak discharge was changed for the series of multiple floods.

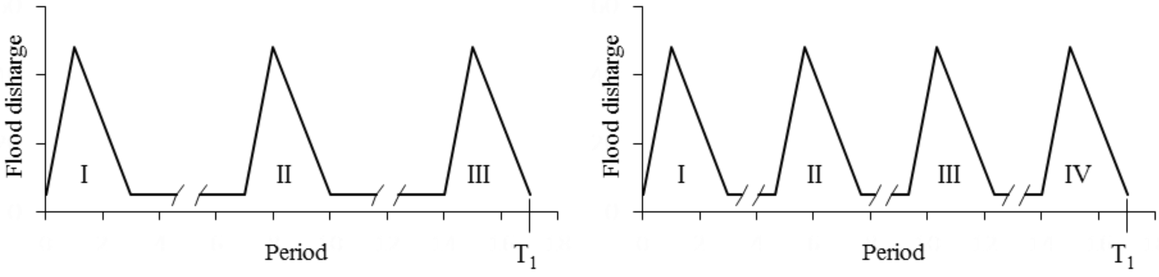

Fig. 1) Multiple floods with different frequency

The multiple floods with different frequency were modelled. The period of multiple floods was assumed similar however flood number was changed during this time (Fig.1). Two, three and four floods were modelled during equal multiple floods period.

The influence of the sequence of floods with a different probability on the time-dependent scour development was examined according to three scenarios (Fig.2). Left part of Figure 2 shows a scheme of three floods of the same probability. The high flood follows by two lower floods in the middle scheme and two floods with higher probability are followed by the flood with less probability right scheme of Figure 2.

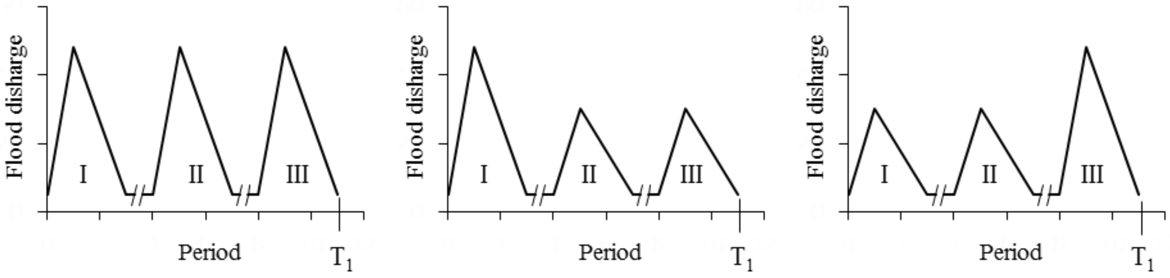

Fig. 2) Multiple floods with different sequence

4 RESULTS

The contraction of the river flow by engineering structures leads to considerable changes in flow pattern, local increase in velocities, and origin of turbulence, eddy and vortex structures. The patterns of the scour development in time have the rapid development at the start of the scour process and gradual reduction with time.

The scour development in time for the floods of different duration is illustrated in Figure 3. It is seen that the scour depth increases with the flood duration, i.e., the greater duration, the deeper the scour depth.

Figure 4 shows the scour development in time for the discharge with a return period of 1 and 4 times over 100 years. The scour hole at the abutments is deeper for the flood of a lower probability.

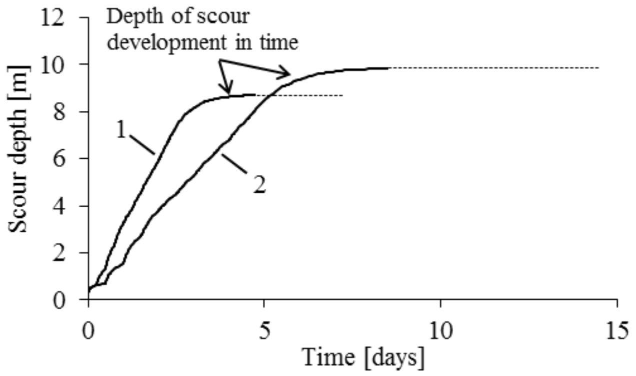

Fig. 3) Scour development with time: 7-day duration (1) and 14-day duration (2).

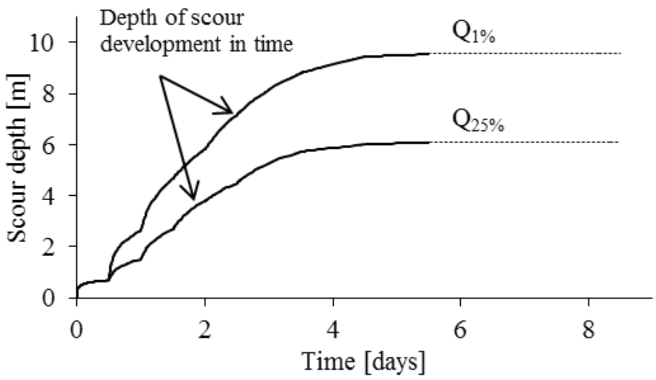

Fig. 4) Time-dependant scour development with discharges of different probabilities.

To investigate the influence of the flood frequency on the scour development in time, we choose a period of, for example, 5 years and suppose that, during this period, we have three or four floods of the same probability.

It is obvious that an increase in the frequency of the floods is accompanied by an increase in the scour depth, and it follows from Figure 5 that the scour depth after two floods at an accepted period of time hs1 is less than that after four floods occurred during the same period hs_2. After every flood, the depths of scour are summed up, and finally the equilibrium stage can be reached.

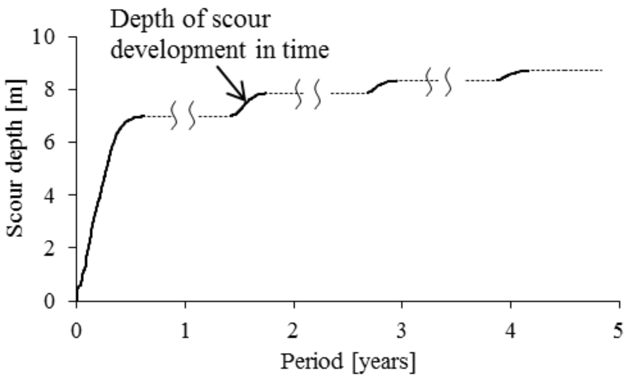

Fig. 5) Scour development with time for floods with different frequencies.

The influence of the sequence of floods with a different probability on the scour development in time was examined according to three scenarios (Fig.2). The left scheme of Figure 2 shows three floods of the same probability. The scour starts when the floodplain is flooded and increases rapidly. Because of the scour hole developed, in the second flood, the scour process starts at the step of hydrograph when $V_{lt\ II} \geq \beta V_{0t\ II}$ and has less duration, while for the third flood the velocities change due to the scour developed after the two previous floods, and it begins at $V_{lt\ III} \geq \beta V_{0t\ III}$ (Fig.6, curve 1).

The middle scheme of Figure 2 shows the sequence of multiple floods where the high flood was followed by two lower floods. As seen from Fig.6 (curve 2), during the first flood, the scour depth develops and remains the same till the next flood. The local velocity V_{lt} reduces [Eq.(6)] but the critical velocity V_{0t} increases [Eq.(7)] because of the scour depth developed during the previous flood. In the next flood, the capacity of the flow is not sufficient to remove sediments out of the scour hole, and V_{lt} is less than βV_{0t}. In the second and third floods, the scour depth remains the same, as after the first flood.

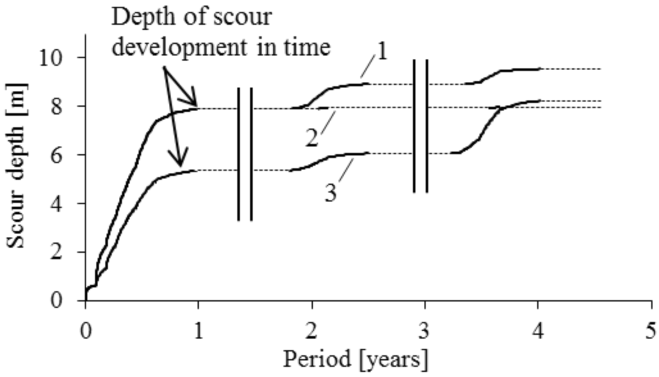

Fig. 6) Scour development with time for floods of different sequences

The third scheme of multiple floods sequence presented scenario when two floods with a return period of 25 years are followed by the flood with a return period of 100 years. The scour depth develops during the first and the second floods; in the third flood, the scour starts at the step of hydrograph when $V_{lt} \geq \beta V_{0t}$ and develops rapidly due to the increased discharge of the flow (Fig.6, curve 3).

5 CONCLUSIONS

Water flow in rivers during floods strongly impact transport system infrastructure- roads, bridges, dams, etc. Frequency and intensity of flood events with high water levels and considerable discharges becomes more frequent and increases the loads on engineering structures in rivers and at the same time the possibility to be damaged. The stability of intakes, piers, abutments, guide banks and spur dikes in floods depends on the depth and dimensions of the scour hole at foundations.

A computer modelling of the scour process was performed, and the influence of multiple floods with different probability, duration, frequency, and sequence on the scour depth at the abutments was determined. The time-dependant scour development was found similar for all calculations, namely the rapid development at the start of the scour process was followed by its gradual reduction with time. It was found that, the scour development depends on the flow hydraulics, the river-bed parameters, the multiple floods probability, 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 another time step, closer to the flood peak. This happens because of the scour hole developed in the previous flood, which reduces local flow velocity and flow capacity to remove 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.

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ACKNOWLEDGEMENT

The travel costs and participation fee to conference was supported by the European Regional Development Fund project «Development of international cooperation projects and capacity in science and technology Riga Technical University», Nr. 2DP/2.1.1.2.0/10/APIA/VIAA/003.