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Multiple floods impact on scour at engineering structures

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ABSTRACT: *The scour development in time during multiple floods and equilibrium stage and the assessment of flood damage risk for bridge abutments have been investigated. A method for computing scour development in time at hydraulic structures during multiple floods was used. The test confirmation of the method allows us to perform computer modelling of scour processes and estimate the influence of floods with different probability, duration, frequency, and sequence on the depth of scour. 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. The results obtained are presented.*

Key words

Multiple floods, scour development in time, hydrograph

I INTRODUCTION

During the past decade, several high floods that occurred in Europe were the reason for failures of engineering structures, environmental damages, and economic losses.

The equilibrium, or temporal, stage of scour near hydraulic structures was studied by many authors, and new approaches have been elaborated by Cardoso & Bettess (1999), Kothyari & Ranga Raju (2001), Balio & Orsi (2001), Radice et al. (2002), Hager et al. (2002), Armitage & McGahey (2004), Yanmaz & Celebi (2004), Grimaldi et al. (2006), Gjunsburgs et al. (2001, 2004, 2007, 2008), Tregnaghi & Marion (2008), and Yanmaz & Kose (2009).

For computing the equilibrium or temporal depth of scour, the discharge on the peak of the flood was used; it is not restricted in time for the whole maintenance period of bridge crossings, but is time-restricted for temporal scour estimation. In field conditions, the scour is formed by multiple floods of different probability, duration, frequency, and sequence.

A method for calculating the general scour development in time during the floods at bridge crossings under conditions of clear water and bed sediment movement was first presented by Rotenburg (1969).

However, no formulae are available for computing the depth of scour formed in time near bridge abutments during multiple floods, predicting the development of scour depth before, during, or after the floods, proving the safety of the abutments, and taking necessary protection measures.

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 foundations of engineering structures and to know whether it will or will not be destroyed after a current or forth-coming 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. There are no answers to these and other questions.

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 (Gjunsburgs & Neilands, 2004) 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.

II 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 (Gjunsburgs & Neilands 2004).

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 (1969) 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 (1969) 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 (Gjunsburgs & Neilands 2004).

Now we have

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

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 (1964) 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 $b = A_i m V_l^4$

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 $N_i = 1/6x_i^6 - 1/5x_i^5$, $N_{i-1} = 1/6x_{i-1}^6 - 1/5x_{i-1}^5$, $x = 1 + h_s/2h_s$ 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:

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

We assume that the scour depth depends on the slope of the side wall (Yaroslavcev, 1956) described by the coefficient k_m and on the angle of flow crossing (Richardson & Davis, 1995). In our study, the angle of flow crossing was 90° and $k_\alpha = 1$.

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

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

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 (1965) method [a comparison of the values of Δh obtained in the tests with those calculated by Rotenburgh (1965) was illustrated earlier (Gjunsburgs & Neilands, 2004) 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 [Gjunsburgs & Neilands, 2004]. Comparison results between the experimental and calculated scour depth at the abutments was in good agreement.

III MODELLING

Based on the method described, a computer modeling of the time-dependent scour during multiple floods with different probability, duration, frequency, and sequence was performed. In the frame of this study, the impact of the floods with different shapes of hydrograph on the scour process was investigated as well.

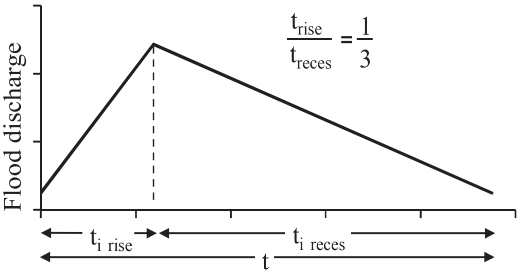

Figure 1: Ratio between the time periods of the rising and recession parts of hydrograph is equal to 1/3

The total duration of floods includes the time t_{rise}, when the flood discharge reaches its peak value, and the time t_{reces}, when the flood discharge decreases down to the low-water level, and $t = t_{rise} + t_{reces}$. The form of the hydrograph is also characterized by the ratio between the time periods of the rising and recession parts (Fig. 1):

$$G = \frac{t_{rise}}{t_{reces}} \tag{25}$$

The steepness of the rising part of the hydrograph depends on many factors, namely rainfall intensity, relief, soil type, etc. The steeper the raising limb of hydrograph, the less the time when the flood maximum discharge is reached. In our investigation the shape of the hydrograph was changed with time of the rising and recession parts of the flood (Fig. 2). The duration of floods was the same. The time of the rising and recession parts of the flood had different ratios, for example, 1:2, 1:3, 1:4, 1:6, and 1:8, where the first and second numbers are the rising and recession time periods of the flood.

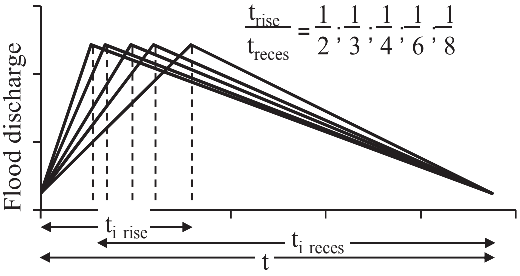

Figure 2: Hydrographs with different ratios between the rising and recession parts; the peak discharge and duration are the same

The multiple floods with different duration, probability, frequency and sequence were modelled. 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-dependant scour development. The peak discharge was changed for the series of multiple floods.

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. 3). Two, three and four floods were modelled during equal multiple floods period.

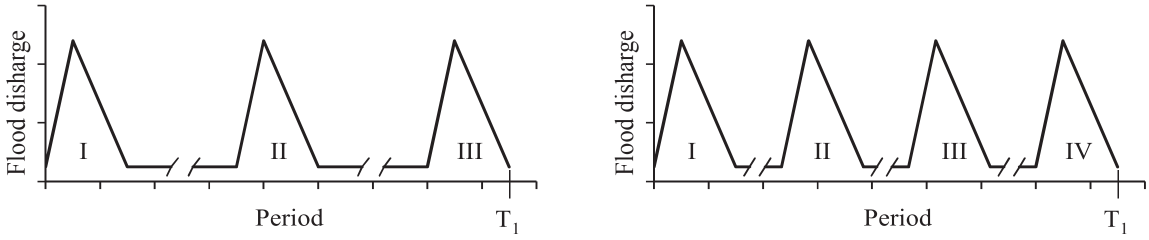

Figure 3: Multiple floods with different frequency; example of three and four floods are presented on left and right parts respectively during similar multiple floods period T_1

The influence of the sequence of floods with a different probability on the time-dependant scour development was examined according to three scenarios (Fig. 4). Left part of Figure 4 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 4.

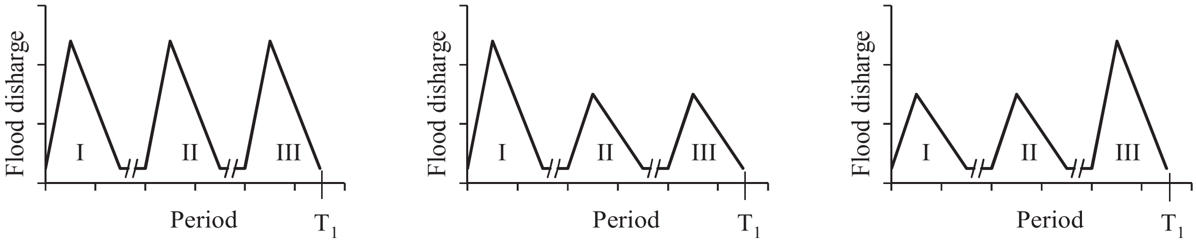

Figure 4: Multiple floods with different sequence

IV RESULTS

The influence of the hydrograph steepness on the scour depth $h_{s\ max}$ was found insignificant, but the scour process was different at the initial stage (Fig. 5). After an equal period of time t_i at the beginning of the flood, the depth of scour was not the same for different hydrograph shapes. The shorter the time of the rising part of the floods, the greater the depth of scour. According to calculation results, the maximum scour depth develops more intensively during the floods with a higher slope of the rising limb of hydrograph.

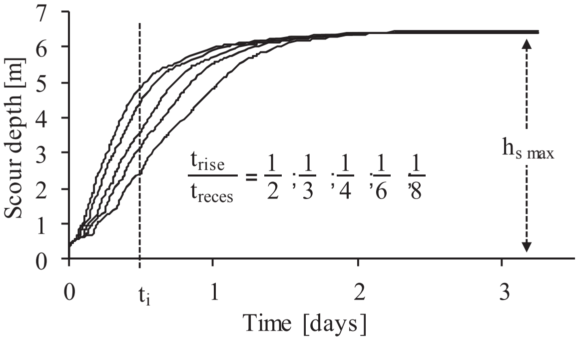

Figure 5: Scour development for floods with an equal duration and a different ratio between the rising and recession parts of hydrograph

The scour development in time for the floods of different duration is illustrated in Figure 6. It is seen that the scour depth increases with the flood duration, i.e., the greater duration, the deeper the scour depth.

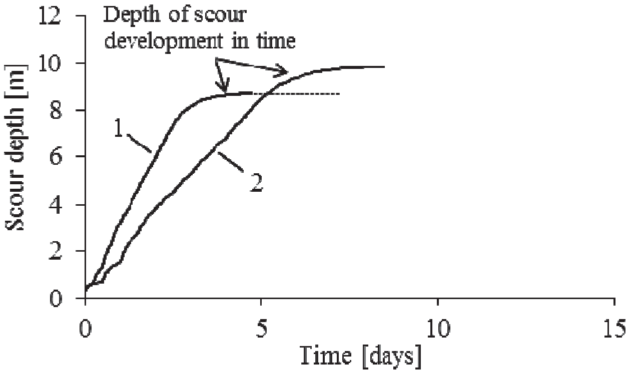

Figure 6: Scour development in time: 7-day duration (1) and 14-day duration (2).

Figure 7 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.

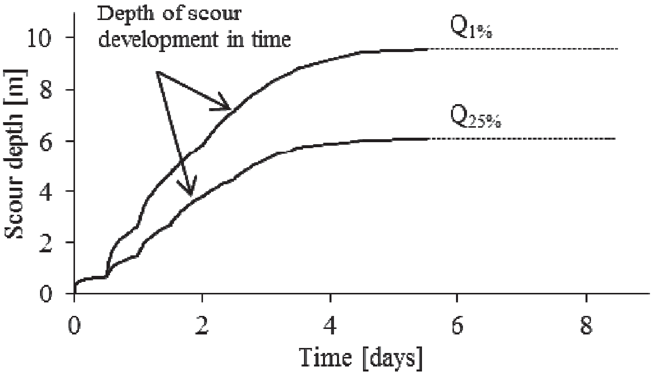

Figure 7: Time-dependant scour development with discharges of different probabilities.

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 8 that the scour depth after two floods at an accepted period of time h_{s1} is less than that after four floods occurred during the same period h_{s2}. After every flood, the depths of scour are summed up, and finally the equilibrium stage can be reached.

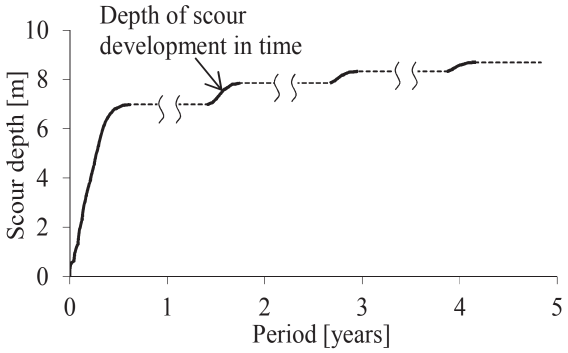

Figure 8: Scour development in time for floods with different frequencies.

The influence of the sequence of floods with a different probability on the scour development in time was examined according to three scenarios (Fig. 4). The left scheme of Figure 4 shows three floods of the same probability. The scour starts when the flood-plain 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. 9, curve 1).

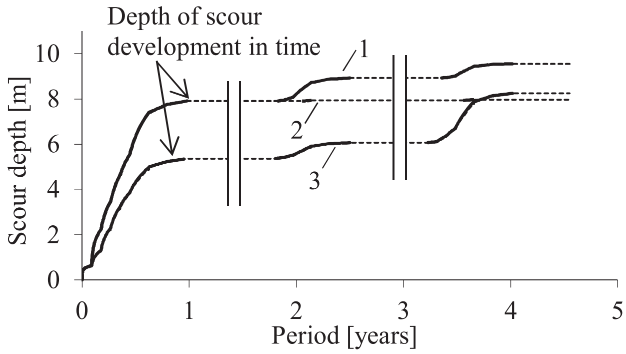

Figure 9: Scour development in time for floods of different sequences

The middle scheme of Figure 4 shows the sequence of multiple floods where the high flood was followed by two lower floods. As seen from Fig. 9 (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. (3)] but the critical velocity V_{0t} increases [Eq. (5)] 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.

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. 9, curve 3).

V CONCLUSIONS

During the last decade, a lot of engineering structures were destroyed or damaged because of scour, and this means that the designed equilibrium depth of scour was exceeded by unexpected floods. The reason was high floods which come more frequently and have different sequence and duration. In some cases, the designed equilibrium depth of scour was exceeded, and bridge crossings were destroyed.

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. In the frame of this study, the impact of the floods with different shapes of hydrograph on the scour process was investigated as well.

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. Since the scour process stops just after the peak of the flood, the time when the maximum depth is reached is usually smaller than the flood duration.

The influence of the hydrograph shape on the scour depth was low, but the scour process was different at the initial stage. After an equal period of time at the beginning of the flood, the scour depth was different for different shapes of hydrograph. The shorter time of the rising part of the floods, the greater the scour depth. According to our calculations, the maximum scour depth is developed more intensely during the flush floods with a higher slope of the rising limb of hydrograph. The value of the ratio between the rising and recession cycles of the flood impacts the scour development with time.

It was found that, with a less probability, increased duration and frequency of the floods, and certain sequences of different probability, the scour depth at the abutments increases.

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