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Hydrograph Shape Impact on the Scour Development with Time at Engineering Structures in River Flow

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Abstract. **Transport system infrastructures are under permanent impacts of multiple floods. To estimate their safety and stability during scour development at hydraulic structure foundations is required. In these studies, the flow parameters at the peak of the flood with unrestricted or restricted duration were used. The effects of probability, duration, sequence, and frequency of multiple floods on the safety and stability of engineering structures in river flow are studied. The impact of the floods with different shapes of hydrograph on the scour process is investigated. The method for estimating the scour development with time was used to perform computer modelling. It was found that the shape of the hydrograph affects the depth, width, and volume of the scour hole developed during the floods. The results obtained in this study and presented in figures and tables confirm our conclusions.**

Keywords: **scour, floods, sediments, hydrograph.**

I. 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.

The high floods in Europe during the last decade have destroyed a lot of engineering structures because of the scoured foundations; however, the EU Floods Directive 2007/60/EC does not take into account increased loads of floods, damage risk estimation, and management of structure foundations in river flow.

During the past few decades, the equilibrium and temporal depths of scour have been studied by different authors. In these studies, the flow parameters at the peak of the flood with unrestricted or restricted duration were used. However, in nature, the flow loads on engineering structures have the form of hydrograph, and multiple floods form scour holes.

In the present study, the effects of probability, duration, sequence, and frequency of multiple floods on the safety and stability of engineering structures in river flow are studied. In the frame of this study, the impact of the floods with different shapes of hydrograph on the scour process is investigated. The shape of the hydrograph depends on many factors, such as rainfall intensity, relief, soil type, and others. As a result, the hydrograph has specific steepness because of the time when the flood maximum discharge is reached and the time when the flood maximum discharge decreases down to the low-water level. The steepness of the hydrograph can be different for floods with an equal peak discharge, and this can be the reason for changes in the depth of scour. The impact of floods with different shapes of hydrograph on the scour process has not been studied at all.

The differential equation of equilibrium for the bed sediment movement in clear water conditions was used, and a method for computing the scour development with time was elaborated. According to the method, the relative scour depth at the hydraulic structures depends on the following dimensionless parameters: the contraction rate of the flow, kinetic flow parameter under the bridge, Froude number of open flow, Froude number/slope ratio, relative grain size of the bed material, relative depth of flow, relative local velocity, steady or unsteady flow conditions, relative depth of scour developed during the previous time, stratified bed conditions, as well as the time, probability, duration, frequency, and sequence of the multiple floods, sediment transport conditions, shape of the structures, slope of the wall side, the angle of the flow crossing, and the shape of hydrograph.

The method for estimating the scour development with time [1] was used to perform computer modelling; it allows us to determine the influence of the shape of the hydrograph on the scour process near engineering structures in river flow. The method was confirmed by test results.

II. METHOD

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

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

The sediment discharge was determined by the [13] formula:

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

where $B = mh_s$ = width of the scour hole, V_l = local velocity at the abutments with a plain bed, and A = parameter in the [13] formula which depends on specific weight of sediments, grain size of bed materials, local and critical velocities, and the depth of the floodplain.

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 = discharge across the width of the scour hole with a plain bed, Q_{sc} = discharge across the scour hole with a scour depth h_s, and k = coefficient of changes in discharge because of scour, which depends on the flow contraction [1].

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 m = the steepness of scour hole, mh_s = width of the scour hole, V_l = local velocity with a plain bed [1], h_f = water depth in the floodplain, h_s = scour depth, and V_{lt} = 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 can be determined by the [19] formula. The critical velocity V_{0t} for any depth of scour h_s and for the flow bended by the bridge crossing embankment is

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

where d_i = grain size of the bed materials, β = reduction coefficient of the critical velocity at the bended flow determined by using the [18] approach; $h_f\left(1 + h_s / 2h_f\right)$ = h_m = average depth of the flow at scour hole.

The parameter A depends on the scour, local velocity V_l, critical velocity V_0, and grain size composition of the bed material during the floods. The parameter A_i at any depth of scour can be found:

$$A_i = \frac{5.62}{\gamma}\left[1 - \frac{k\beta V_0}{V_l}\left(1 + \frac{h_s}{2h_f}\right)^{1.25}\right] \cdot \frac{1}{d_i^{0.25} \cdot h_f^{0.25}\left(1 + \frac{h_s}{2h_f}\right)^{0.25}} \tag{8}$$

where γ = specific weight of sediments and V_0 = critical velocity at the plain bed.

The sediment discharge also changes with the local velocity V_{lt}. 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) we replace with parameter A_i from Eq. (8). Thus the sediment discharge upon development of the scour is

$$Q_s = A_i \cdot mh_s \cdot V_{lt}^4 = b \frac{h_s}{k^4\left(1 + \frac{h_s}{2h_f}\right)^4} \tag{9}$$

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 and composition 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 (9), the differential equation (1) can be written in the form

$$a h_s^2 \frac{dh_s}{dt} = b \frac{h_s}{k^4\left(1 + \frac{h_s}{2h_f}\right)^4} \tag{10}$$

After separating the variables

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

or

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

where

$$D_i = \frac{k^4 a}{b} = \frac{\pi \cdot m \cdot k^4}{2A_i \cdot V_l^4}$$

After integration of Eq. (11), we have:

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

where $x_1=1+h_{s1}/2h_f$ and $x_2=1+h_{s2}/2h_f$ = relative depths of scour.

According to the method for computing scour depth, the hydrograph was divided into time steps, and each step in turn was divided into time intervals (Fig. 1). It was assumed that D_i was constant inside the time interval.

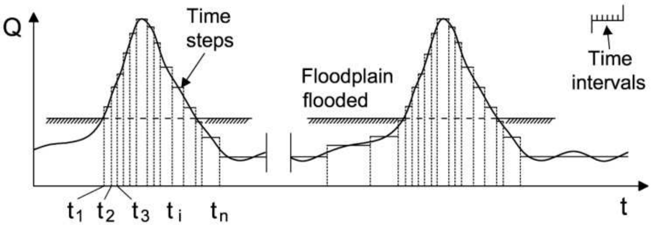

Fig. 1. Hydrographs divided into time steps and time intervals

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

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

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

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

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

where t_i = time interval.

TABLE 1

The value of N_i as a function of x_i

x_i	1.0	1.2	1.4	1.6	1.8
N_i	-0.033	0.0002	0.18	0.70	1.90
X_i	2.0	2.2	2.4	2.6	2.8
N_i	4.29	8.62	15.98	27.2	46.07

Using the graph $N = f(x)$ or the data of Table 1 for the calculated value of N_i, we find x_i and the depth of scour at the end of time interval:

$$h_s = 2h_f\left(x-1\right) \quad (15)$$

We assume that the scour depth depends on the slope of the side wall [23] described by the coefficient k_m (Table 2) and on the angle of flow crossing k_α [15]. In our study, the angle of flow crossing was 90° and $k_\alpha=1$.

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

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

TABLE 2

Dependence of the coefficient k_m on the side-wall slope of the abutment

Side-wall slope of the abutment	0	1.5	1.75	2.0	2.5	3.0
k_m	1	0.71	0.55	0.44	0.37	0.32

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. In laboratory tests, the time steps were divided into 20 time intervals. 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 = discharge of flow and Q_b = discharge in the bridge opening under open-flow conditions; the maximum backwater Δh determined by the [16] method, 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.

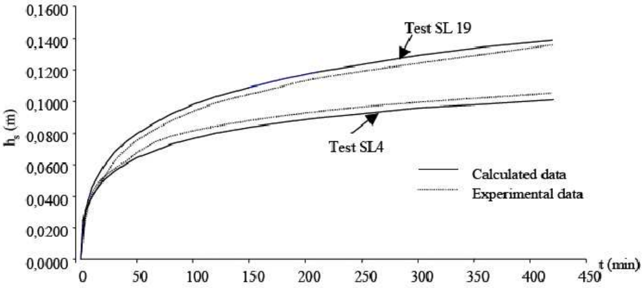

Fig. 2. Scour development in time under steady flow conditions

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 [1]. Comparison results between the experimental and calculated scour depth at the abutments was in good agreement (Fig. 3).

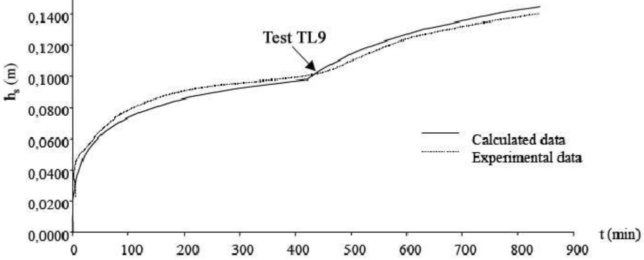

Fig. 3. Scour development in time under unsteady flow conditions

The patterns of the scour development in time, both determined in tests and computed by the suggested method, are similar, namely the rapid development at the start of the scour process and gradual reduction with time (Figs. 2 and 3) was observed.

III. MODELLING

The method elaborated for determining the scour depth development during floods was confirmed by test results [1]. Based on this method, a computer modeling of the time-dependent scour during floods with different shapes of hydrograph was performed.

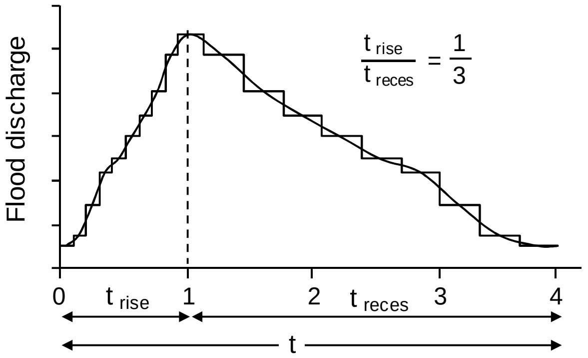

Fig. 4. Ratio between the time periods of the rising and recession parts of hydrograph is equal to 1/3

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. 4):

$$a = \frac{t_{rise}}{t_{reces}} \qquad (17)$$

The ratio between the rising and recession part of the hydrograph was varied in modeling the scour process.

TABLE 3

Initial data for hydrographs with different duration

h_f [m]	Δh [m]	Q/Q_b	Q [m^3/h]	t [days]
0.185	0,2172	1.047	510	varied
0.975	0.1926	1.542	760	varied
1.720	0.3156	1.865	1440	varied
2.300	0.4242	2.021	2200	varied
2.500	0.4646	2.052	2500	varied
2.700	0.5698	2.112	3000	varied
3.000	0.6636	2.206	3500	varied

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. According to the method described, the hydrograph was divided into time steps. Examples of the parameters used to form steps of hydrograph are shown in Table 3, where h_f = the depth of floodplain, Δh = maximum backwater value, Q/Q_b = flow contraction rate, Q = discharge of the floods, and t = time of one step of hydrograph. The time of the rising or recession parts of hydrograph was varied for different types of the hydrograph (Figs. 5 and 6).

The shape of the hydrograph was changed with time of the rising and recession parts of the flood. Two types of the hydrograph shape were studied.

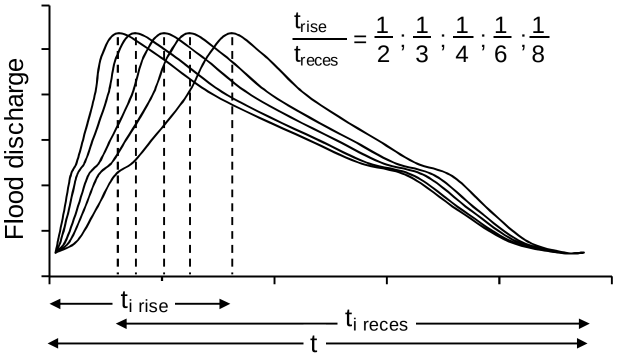

Fig. 5. Hydrographs with different ratios between the rising and recession parts; the peak discharge and duration are the same

For the first type (Fig. 5), the duration of the flood in both parts 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.

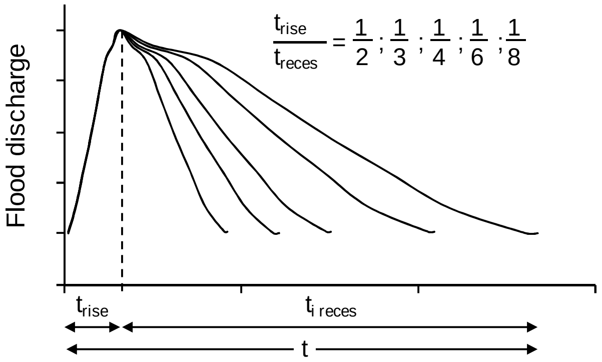

Fig. 6. Hydrographs with different ratios between the rising and recession parts. Duration of the floods depends on the ratio between the rising and recession parts

For the second type of the flood (Fig. 6), the duration of floods was different, but the time of the rising part of the flood was constant. The ratio between the time periods of the rising and recession parts was set different: 1:2, 1:3, 1:4, 1:6, and 1:8. The probability of the floods was the same for all the types of hydrograph shape.

IV. RESULTS

The behaviour of the scour hole development with time, determined in tests and calculated by the method used in this study, was similar: the rapid development at the start of the scour process was followed with a gradual reduction with time. The sour process usually stops just after the peak of the flood, therefore the time T_s, when the maximum depth is reached, is usually smaller then the duration of the flood (Fig. 7).

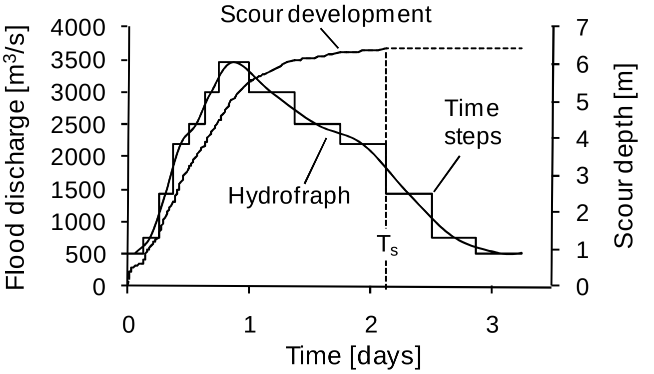

Fig. 7. Scour development with time; T_s is the time, when the maximum scour depth is reached

For the first type of hydrograph (Fig. 5), the influence of its shape on the scour depth $h_{s\ max}$ was small, but the scour process was different at the initial stage (Fig. 8). 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 (Table 4). 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.

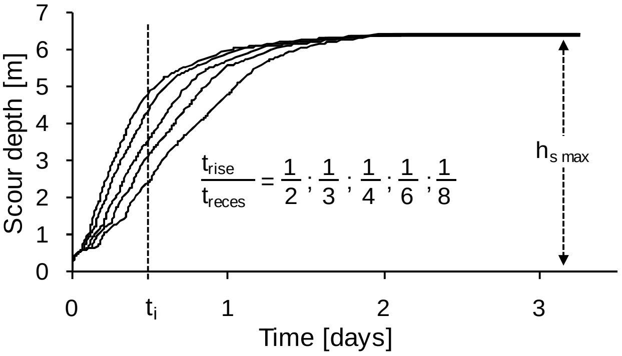

Fig. 8. Scour development for floods with an equal duration and a different ratio between the rising and recession parts of hydrograph

TABLE 4

Scour hole depth after $t_i = 0.5$ days for floods with an equal duration but a different ratio between the rising and recession parts of hydrograph (Fig. 8)

$\frac{t_{rise}}{t_{reces}}$	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{6}$	$\frac{1}{8}$
h_s *[m]*	2.44	3.19	3.60	4.47	4.87

The time T_s, when the maximum depth $h_{s\ max}$ is reached, varies for different shapes of the hydrograph. The shorter the time of the rising part of the floods, the faster the maximum scour depth is reached (Table 5).

TABLE 5

Dependence of the time T_s, when the maximum scour depth is reached, on the ratio between the rising and recession parts of hydrograph (Fig. 8)

$\frac{t_{rise}}{t_{reces}}$	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{6}$	$\frac{1}{8}$
T_s *[days]*	2.25	2.13	2.05	1.96	1.92

For the second type, the rising part of floods had the same duration, but the recession part was increased for each example (Fig. 6). The higher the recession time of floods, the greater their duration, and the greater the scour depth (Fig. 9).

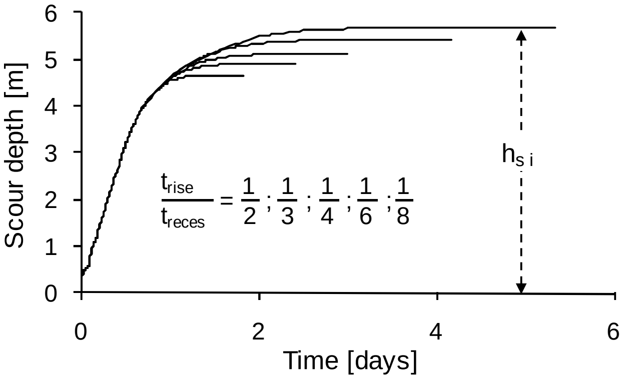

Fig. 9. Scour development for floods with the same duration of the rising part of hydrograph but different rising/recession time ratios

V. CONCLUSIONS

The effects of the probability, duration, sequence, and frequency of multiple floods on the safety and stability of engineering structures in river flow are studied. For this purpose, we studied the impact of the floods with different shapes of hydrograph on the scour process.

The hydrograph shape was changed with time of the rising and recession parts of the flood. The influence of two types of the hydrograph shape on the scour process near the structures in flow was investigated.

The scour development with time was found similar, both in tests and 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.

For the first type of hydrograph shape, its influence 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 rising part of floods had the same duration, but the recession part was increased for each example of the second type of hydrograph. The higher the recession time of the floods, the greater the depth of scour.

It was found that the shape of hydrograph affects the depth, width, and volume of the scour hole developed during floods. The value of the ratio between the rising and recession cycles of the flood impacts the scour development with time. The European flood forecasting system (De Roo, Bartholmes, Bates, et al., 2003) could be elaborated along with the method suggested by [1] for evaluating the scour depth development with time, thus making it possible to estimate the safety and stability of engineering structures in river flow during the maintenance period and avoid possible environmental damages and losses.

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Boriss Gjunsburgs, Gints Jaudzems, Elena Govša. Hidrogrāfa formas ietekme uz izskalojumu veidošanos laikā pie inženiertehniskām konstrukcijām upes plūsmā

Transporta sistēmas infrastruktūra, tajā skaitā ceļi, tilti, dambji, ūdens ņemšanas ietaises u.c. tiek pakļauti vairākkārtēju plūdu ietekmei. Lai noteiktu to drošību un noturību izskalojumu veidošanās laikā, tiek izmantotas aprēķinu metodes, kas ietver hidraulikas, hidroloģijas, morfoloģijas, ģeoloģijas un citus parametrus. Pēdējā desmitgadē dažādi autori izstrādājuši metodes izskalojumu noteikšanai pie hidrotehniskām konstrukcijām. Šajās aprēķinu metodēs tiek izmantoti nemainīgi caurplūdes parametri un ierobežoti vai neierobežoti laika parametri. Taču dabā plūdiem ir hidrogrāfa forma, un vairākkārtēju plūdu izskalojumu rezultātā veidojas izskalojumu piltuve. Pētījuma ietvaros par plūdu varbūtības, ilguma, biežuma un secības ietekmi uz izskalojumu dziļumu tika veikta arī hidrogrāfa formas ietekmes izpēte uz izskalojuma procesu. Izmantojot izskalojumu aprēķina metodi (Gjunsburgs et.al 2004), tika veikta izskalojumu procesa modelēšana un pētīta hidrogrāfa formas ietekme uz izskalojumu procesu pie hidrotehniskajām konstrukcijām upes plūsmā. Darbā aplūkoti divi hidrogrāfa formas izmaiņas varianti. Pirmajā gadījumā kopējais plūdu laiks nemainījās, taču mainījās attiecība starp laiku, kurā plūdi pieņemas spēkā, un laiku, kad plūdu maksimums sasniedz zemu ūdens līmeni. Otrajā gadījumā nemainīgs bija laiks, kurā plūdi pieņemas spēkā, bet caurplūdes samazināšanās laiks tika mainīts, tādā veidā mainījās arī plūdu kopējais ilgums. Tika noskaidrots, ka hidrogrāfa forma ietekmē plūdu laikā radītā izskalojuma dziļumu, platumu un tilpumu. Jo stāvāka hidrogrāfa pieaugošās līknes daļa, jo ātrāk tiek sasniegts plūdu radītais maksimālais izskalojuma dziļums. Jo lēzenāka hidrogrāfa līknes recesijas daļa jeb lielāks plūdu ilgums, jo lielāks izskalojuma dziļums. Attiecība starp hidrogrāfa augšupejošās līknes un lejupejošās līknes laiku ietekmē izskalojumu veidošanās laiku. Darbā iekļauti un aprakstīti šī pētījuma laikā iegūtie rezultāti un secinājumi.

Борис Гюнсбург, Гинтс Яудземс, Елена Говша. Влияние формы гидрографа на образование размыва во времени у фундаментов инженерно-технических сооружений

Транспортная система, а именно дороги, мосты, дамбы и водоприемные сооружения находятся под постоянным воздействием паводков. В течение последнего десятилетия многие авторы изучали предельные глубины размыва или развитие размыва во времени у гидротехнических сооружений, принимая параметры потока на пике паводка с ограниченным или неограниченным временем. Однако в природе нагрузка на гидротехнические сооружения со стороны потока имеет форму гидрографа, и многократные паводки формируют воронку размыва. В наших исследованиях изучается влияние вероятности, продолжительности, последовательности и частоты паводков на развитие глубины размыва у гидротехнических сооружений в речном потоке. В пределах этих исследований изучалось влияние формы гидрографа на процесс размыва. Метод, определяющий развитие размыва во времени (Gjunsburgs et.al 2004), использовался при моделировании и позволил нам оценить влияние формы гидрографа на величину размыва. Было рассмотрено два вида возможного изменения формы гидрографа и изучено влияние этих форм на величину размыва у сооружений. В первом случае продолжительность паводка не менялась, а менялось отношение между временем подьема и временем спада паводка. Во втором случае время подьема паводка было постоянным, но изменялась продолжительность спада расхода воды, тем самым общая продолжительность паводка увеличивалась. Установлено, что форма гидрографа влияет на глубину, ширину и обьем воронки размыва в период паводка. Чем круче гидрограф на подьеме паводка, тем быстрее достигается максимум размыва. Чем более пологий гидрограф на спаде, или чем больше продолжительность паводка, тем глубже размыв. Отношение времени подьема и спада паводка влияет на конечную величину размыва во времени. Результаты исследований представлены в статье и подтверждают наши выводы.