EQUILIBRIUM DEPTH OF SCOUR AT THE BRIDGE ABUTMENTS

MAKSIMĀLAIS IZSKALOJUMA DZIĻUMS PIE TILTA BALSTIEM

B.Gjunsburgs, R.Neilands and E.Govsha

Keywords: flow, flood, hydrograph, velocity, scour, abutment

Introduction

The flow in plain rivers contracted by bridge crossings in floods leads to scour at piers, abutments, or guide banks and can cause considerable damage and losses.

An analysis of the literature showed that many authors: Laursen and Toch [8], Liu et al. [10], Froehlich [2], Richardson and Davis [14], Lim [9], Cardoso and Bettess [1], Melville [11], Oliveto and Hager [12], Radice et al. [13] do not take into account the flow and riverbed changes during the floods, the contraction rate of the flow, local increase in velocity near abutment, stratification of the riverbed, and cannot evaluate the stability of the constructions in the flow and the risk factor after several floods.

Differential equation of the bed sediment movement for clear water was used and a new method for calculating the scour development with time at the abutments during the floods was elaborated by Gjunsburgs and Neilands [3], [4], [5], [6]. Based on this method depth of scour can be computed during or after one, two or several floods of different probability, therefore it is possible to predict current riverbed changes at the abutment during the floods.

New method for calculation of equilibrium depth of scour at abutments is presented in this paper. The equilibrium depth, width and volume of scour hole are the maximum values that can be reached at certain flow and riverbed conditions. Comparison of current depth, width and volume of scour hole computed by taking into account scour development in time during the floods and equilibrium depth of scour allows to estimate stability of the abutments by risk factor. Risk factor can be determined as a ratio between the scour depth, width and volume after one, two or several floods and the equilibrium parameters of the scour hole. Using the risk factor we can estimate the stability of the abutment and predict/compute the time of safe maintenance at the stage of design of the construction.

An analysis of influence of the hydraulic and riverbed parameters on equilibrium depth of scour was made. The relative equilibrium depth of scour is depending on contraction of the flow, relative grain size and stratification of the bed materials, Froude number referred to the slope, relative local velocity, relative depth of the flow at the floodplain, kinetic parameter of the flow under the bridge, side-wall slope of the abutment, shape of the abutment and angle of the flow crossing.

Experimental Setup

Tests were carried out at the Transport Research Institute (Russia) in a flume 3.5 m wide and 21 m long and at the Budapest Technical University (Hungary) in a flume 1.35 m wide and 9 m long.

The tests with a rigid bed were performed for different flow contractions, in order to investigate the velocity and the water level changes in the vicinity of the embankment, along it, and near a modelled abutment. The aim of the tests with a sand bed was to study the scour processes, the changes in the velocity with time, the effect of hydraulic parameters and the contraction rate of the flow, grain size of the bed material, and the scour development in time. The openings of the bridge model were 50, 80, 120, and 200 cm in the first flume and 44.5, 57.5, 77.5, and 97.5 cm in the second one. The contraction rate of the flow Q/Q_b (Q was the discharge of the flow and Q_b was the discharge of the flow in a bridge opening in open-flow conditions) varied from 1.25 to 5.69 at a depth of floodplain of 5, 7, and 13 cm. The Froude numbers varied from 0.078 to 0.151. The slope in the first and second flumes was 0.0012 and 0.0015, respectively.

The tests with a sand bed were carried out in the conditions of clear water. The sand was placed 1 m up and down the contraction of the flumes. The mean size of grains was 0.24 and 0.67 mm in the first flume and 0.5 and 1.0 mm in the second one with a standard deviation. The scour development in time for the bed materials with different grain size was studied to estimate the identity of the processes. The tests in the flumes lasted for 7 hours, the vertical scale was 50, and the time scale was 7. With respect to the real conditions, the test time was equal to 2 days. That was the mean duration of time steps into which the flood hydrograph was divided. The development of 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.

Method

According to experimental data, the concentration of streamlines, a sharp drop in water level, and a drastic increase in velocity are observed at the corner of the abutments near the bridge crossings on plain rivers. As found from the tests, the local velocity with vortex structure forms scour holes. The local velocity V_l at the abutments is

$$V_l = \varphi\sqrt{2g\Delta h}\ , \tag{1}$$

where φ is the velocity coefficient (Fig. 1) and Δh is the maximum backwater determined by the Rotenburg formula [15].

The discharge across the width of a scour hole before and after the scour is $Q_f = k\cdot Q_{sc}$, where Q_f is the discharge across the width of the scour hole with a plain bed and Q_{sc} is that of the scour hole with a depth h_s.

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

where h_s is the depth of the scour hole, h_f is the depth of water on the floodplain, and m is the slope of the scour hole wall.

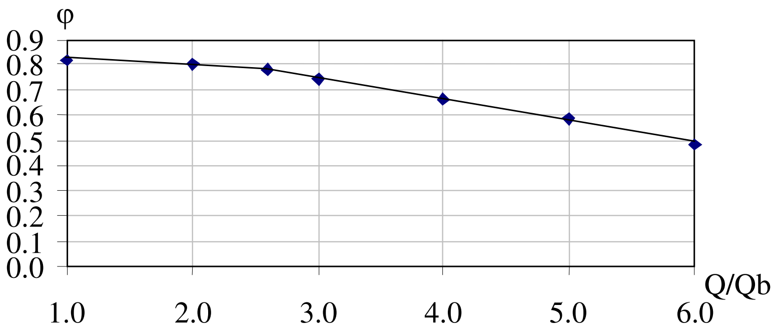

Fig.1. Coefficient φ *vs. the contraction of the flow*

The local velocity at any depth of the scour hole can be determined from Eq. (2):

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

According to the experimental data, the coefficient *k* depends on the contraction of the flow (Fig. 2).

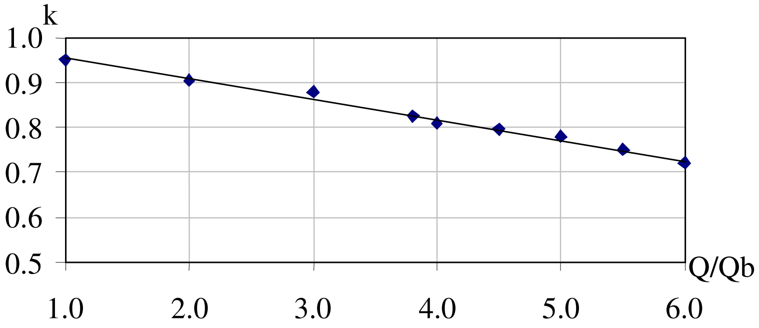

Fig.2. Coefficient k vs. the contraction of the flow

The velocity of the beginning of sediment movement V_0 can be found from the Studenitcnikov formula [16]:

$$V_0 = 3.6d^{0.25}h_f^{0.25}. \tag{4}$$

At a scour depth h_s, the velocity V_{0t} is given by

$$V_{ot} = \beta \cdot 3.6d^{0.25}h_f^{0.25}\left(1+\frac{h_s}{2h_f}\right)^{0.25}, \tag{5}$$

where β is the coefficient of reduction in the velocity because of vortex structures and *d* is the grain size of the bed material in the layer *H*.

The velocity V_{lt} is decreasing and V_{ot} is increasing with development of the scour hole. The scour ceases when V_{lt} becomes equal to βV_{ot}.

$$\frac{V_1}{k\left(1+\frac{h_{\text{equil.}}}{2h_f}\right)}=\beta V_o\cdot\left(1+\frac{h_{\text{equil.}}}{2h_f}\right)^{0.25}. \tag{6}$$

The equilibrium depth of scour can be determined from Eq. (6) as follows:

$$h_{\text{equil.}}=2h_f\left[\left(\frac{V_1}{k\beta V_o}\right)^{0.8}-1\right]\cdot k_m\cdot k_s\cdot k_\alpha, \tag{7}$$

where k_m is a coefficient depending on the side-wall slope of the abutment [7], k_s is a coefficient depending on the abutment shape, and k_α is a coefficient depending on the angle of flow crossing [14].

As a rule, in natural conditions riverbed is not homogeneous, but with stratified bed which is composed of layers with different grain sizes. Therefore if depth of scour is calculated by Eq. (7) and scour occurs deeper than h_1 layer with grain size d_1 (Figure 3), the changes of grain sizes and bed layers should be considered.

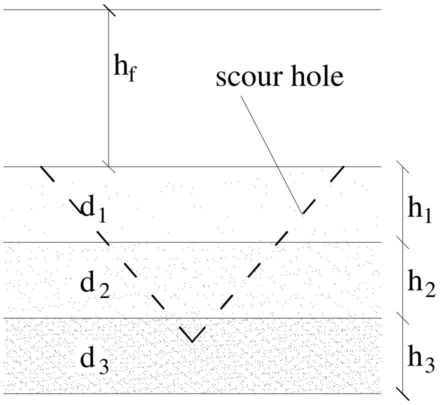

Fig.3. Scour at the stratified bed

According to the mentioned conditions the velocity of the beginning of sediment movement V_0^{II} should be calculated with flow depth h_f and grain size d_2:

$$V_0^{II}=3.6d_2^{0.25}h_f^{0.25} \tag{8}$$

and the velocity V_{0t}^{II} at the second bed layer with grain size d_2 can be determined:

$$V_{0t}^{\ II}=V_0^{II}\left(1+\frac{h_{1d_2}}{2h_f}\right)^{0.25}, \tag{9}$$

where h_{1d2} is the summary water depth on the floodplain till bed layer with grain size d_2.

The depth of scour calculation follows by Eq.(7)) in bed layer with grain size d_2. If calculated scour depth extends out of the bed layer h_2 with grain size d_2, that is, if $h_s > (h_f + h_1 + h_2)$, the calculation should be continued and the velocity of the beginning of sediment movement V_0^{III} with grain size d_3 and water depth on floodplain h_f is:

$$V_0^{\ III}=3.6d_3^{0.25}h_f^{0.25}. \tag{10}$$

Velocity at the bed layer with grain size d_3 can be found:

$$V_{0_t}{}^{III} = V_0^{III}\left(1+\frac{h_{2d_3}}{2h_f}\right)^{0.25}, \tag{11}$$

where h_{2d3} is the summary water depth on the floodplain till bed layer with grain size d_3. Further follows the calculation of the scour depth by Eq.(7) in bed layer with grain size d_3. The calculation mentioned above can be continued if necessary.

Using this method it has been found that scour value at the abutment with homogeneous bed is greater than scour value calculated with stratified bed with different grain sizes *d*.

For calculating the development of scour holes during the floods, a new method was developed by Gjunsburgs and Neilands [3], [4], [5], [6]. To determine the development of a scour hole during the flood, the hydrograph was divided into time steps of 1 or 2 days, and each time step was divided into time intervals. For each time step, the following initial parameters must be determined: depth of water in the floodplain; contraction rate of the flow; maximum backwater; grain size of the bed material; thickness of the bed layer; specific weight of the bed material. As a result, we can determine the scour depth, the width, and volume at the end of each time step or after one, two, or several floods.

The scour hole parameters calculated during or after one, two, or several floods can be compared with the equilibrium parameters found by Eq. (7), and thus the stability of the abutment can be evaluated. The risk factor of 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 depth of scour hole at the abutments of the same probability. By using the risk factor, we can estimate the current stability of the abutments or to predict/compute the time of safe maintenance at the stage of design.

Results

An analysis of Eq. (7) shows that the relative equilibrium depth of scour depends on the following hydraulic and riverbed parameters:

$$\frac{h_{equil.}}{h_f} = f\left(\frac{Q}{Q_b};\frac{d_i}{h_f};\frac{Fr}{i_o};\frac{V_l}{k\beta V_o};\frac{h}{h_f};P_K;P_{Kb};k_m;k_s;k_\alpha\right), \tag{12}$$

where Q/Q_b is the contraction rate of the flow; d_i/h_f is the relative grain size of the bed material; Fr/i_o is the Froude number in relation to the river slope; $V_l/k\beta V_{ot}$ is the velocity ratio; h/h_f is the relative depth of water; P_K is the kinetic parameter of the open flow; P_{Kb} is the kinetic parameter of the flow under the bridge; k_m, k_s, and k_α are coefficients described above. According to this study relative equilibrium depth of scour depends from stratification of the riverbed.

Dependence of the relative equilibrium depth of scour from different hydraulic and riverbed parameters is showed graphically.

Figure 4 shows the relative equilibrium depth of scour versus the contraction rate of flow. With increase in the contraction of the flow, the equilibrium depth of scour increases.

The relative equilibrium depth of scour in relation to the relative grain size of bed material is presented in Fig. 5. With increase in the relative grain size of bed material, the equilibrium depth of scour decreases.

The influence of the Froude number relative to the slope $Fr/i_o = V^2/gh_f i_o$ is shown in Fig.6. As seen from the figure, the smaller the value of Fr/i_o (the smaller the ratio between the inertia and frictional forces), the greater the relative equilibrium depth of scour.

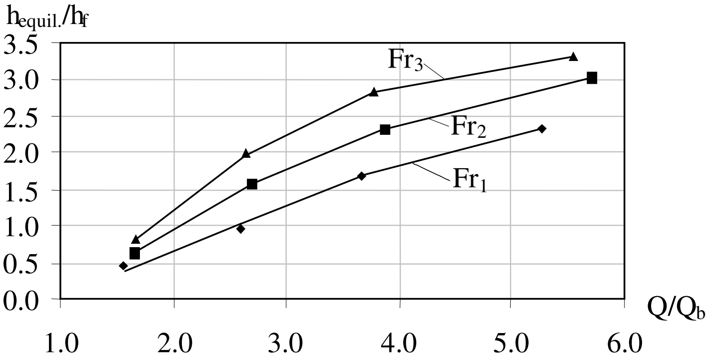

Fig.4. Relative equilibrium depth of scour vs. the contraction rate of the flow

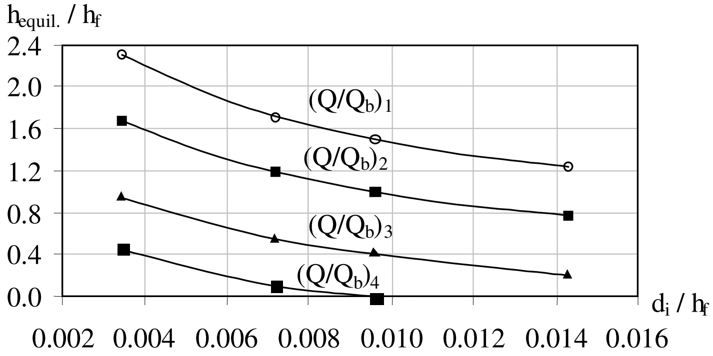

Fig.5. Relative equilibrium depth of scour vs. the relative grain size

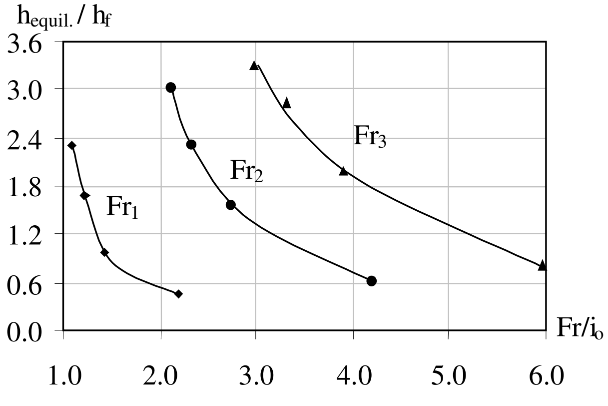

Fig.6. Relative equilibrium depth of scour vs. the Froude number referred to the slope

An increase in $V_l/k\beta V_0$ leads to an increase in the relative equilibrium depth of scour (Fig.7).

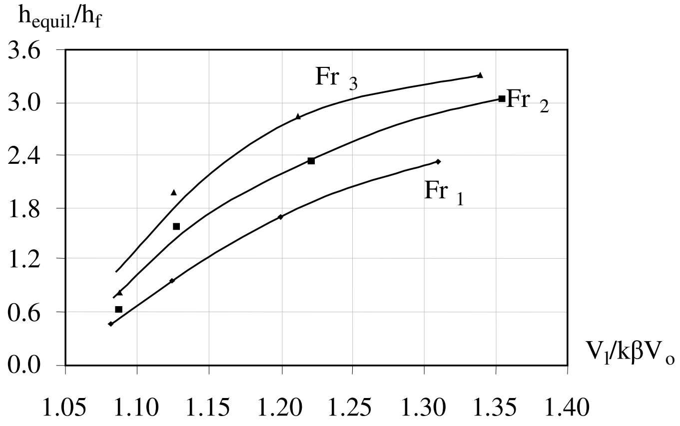

Fig.7. Equilibrium depth of scour vs. the velocity ratio $V_l/k\beta V_o$

An analysis of the literature showed that many authors like Laursen and Toch [8], Liu et al. [10], Froehlich [2], Richardson and Davis [14], Lim [9], Cardoso and Bettess [1], Melville [11], Oliveto and Hager [12], Radice et al. [13] do not take into account the flow and riverbed changes during the floods, the contraction rate of the flow, local increase in velocity near abutment, stratification of the riverbed, and cannot evaluate the stability of the constructions in the flow and the risk factor after several floods. The comparison of the depths of scour at the abutments computed by different author's equations showed considerable difference in the results (Table 1).

Table 1. Comparison of scour depth values computed by different author formulas

Test no.	L (m)	Q/Q_b	$h_{s.calc}$ t=7h (cm)	$h_{s.exp}$ t=7h (cm)	Our method h_{equil} (cm)	Laursen h_{equil} (cm)	Liu h_{equil} (cm)	Lim h_{equil} (cm)	Froeh-lich h_{equil} (cm)	Richardson h_{equil} (cm)
SL2	3.0	5.69	16.40	16.70	21.50	63.70	82.47	31.95	19.96	24.01
SL5	2.7	3.87	13.30	12.80	18.25	60.58	78.24	31.56	19.00	24.01
SL8	2.3	2.69	9.22	9.81	11.07	58.07	77.22	28.70	18.98	24.01
SL11	1.5	1.66	4.16	4.11	4.48	45.67	58.32	16.90	14.81	24.01

Calculation example

An example of calculating a scour hole at the abutments near the bridge crossing on a plain river after two floods of a 1% probability is made. The calculation results are presented graphically. The development of the depth, width, and volume of the local scour hole is shown in Figs. 8, 9, and 10, respectively.

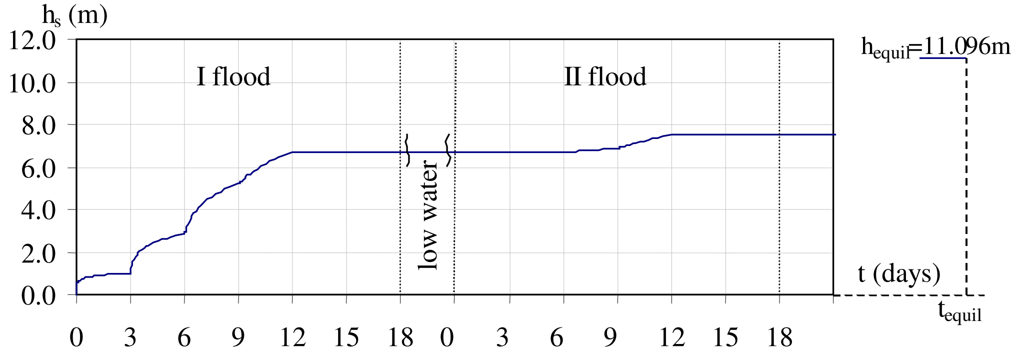

Fig.8. Development of scour depth with time during two floods

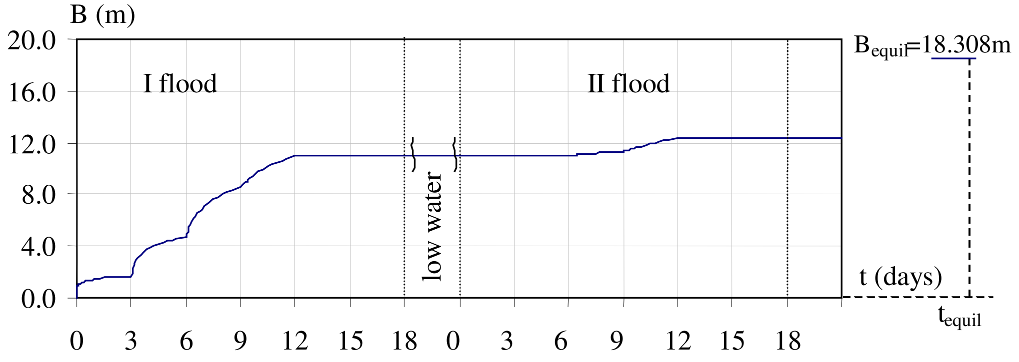

Fig.9. Development of scour hole width with time during two floods

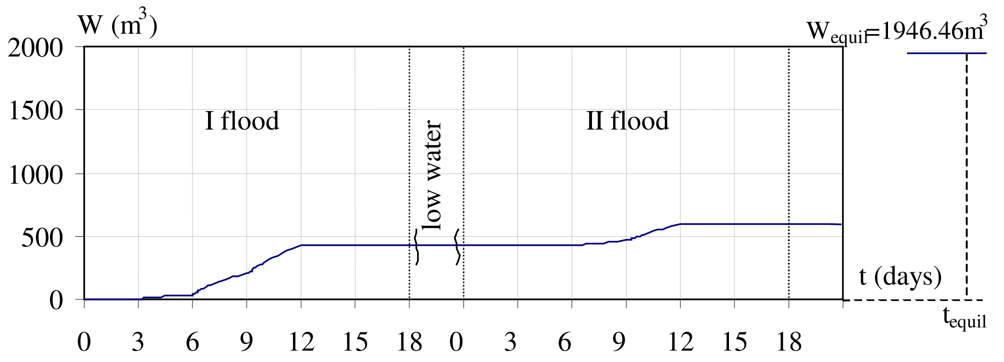

Fig.10. Development of scour hole volume with time during two floods

Initial data for calculation of equilibrium depth of scour: $h_f = 2.3$ m; $Q/Q_b = 1.42$; $\Delta h = 0.406$ m. Coefficient $\varphi = 0.8116$ according to Fig. 1. The local velocity at the abutments can be found according to Eq. (1):

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

The velocity at which the sediment movement starts is found from Eq. (4):

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

According to Fig. 2, the coefficient $k = 0.9311$. We assumed that $k_m = 1$, $k_s = 1$, $k_\alpha = 1$, and the slope of the scour hole wall $m = 1.65$. The equilibrium depth of scour according to Eq. (7) is

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

The equilibrium width of the scour hole is: $B_{equil} = m\cdot h_{equil} = 1.65\cdot 11.096 = 18.308m$.
The equilibrium volume of the scour hole is:

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

The calculated depth of scour after two floods with a 1% probability is $h_s = 7.484m$ and the equilibrium depth of scour is $h_{equil} = 11.096m$.

The risk factor of abutment scour after two floods with 1% probability is $h_s/h_{equil} = 7.484/11.096\cdot 100\% = 67.44\%$.

Conclusions

In tests, concentration of streamlines, a sharp drop in water level, a local increase in velocity, vortex structure and scour hole are observed at the corner of the abutment. Local velocity together with vortex structure is forming the scour hole.

The new method of computing equilibrium depth, width and volume of scour hole was presented.

A method for stability estimation of the abutments by computing risk factor was proposed. Risk factor is determined as a ratio between the scour depth, width and volume computed after one, two or several floods and equilibrium depth, width and volume of the scour hole. By risk factor we can estimate the current stability of the abutment in the period of maintenance or predict/compute it's stability at the design stage. Stability of the abutments on plain rivers depends on the value of the risk factor. The closer current depth value of the scour hole are to the equilibrium value of the scour hole, the more is risk factor and less is the stability of the construction.

Dependence of the relative equilibrium depth of scour hole from different hydraulic and riverbed parameters is presented graphically. The relative equilibrium depth of scour is depending on contraction of the flow, relative grain size and stratification of the bed materials, Froude number referred to the slope, relative local velocity, relative depth of the flow at the floodplain, kinetic parameter of the flow under the bridge, side-wall slope of the abutment, shape of the abutment and angle of the flow.

This study was partly financially supported by the European Social Fund within the National Programme "Support for the carrying out doctoral study programme's and post-doctoral researches", project "Support for the development of doctoral studies at Riga Technical University".

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Gjunsburgs B., Neilands R. un Govsha E. Maksimālais izskalojuma dziļums pie tilta balstiem.

Vietējais izskalojums pie tiltu balstiem rodas, ja palienas upes plūsma plūdu laikā tiek saspiesta ar tilta pieeju. Izskalojums var izraisīt ievērojamus tilta bojājumus, pat konstrukcijas sabrukšanu. Šajā rakstā tiek piedāvāta jauna maksimālā izskalojuma dziļuma pie tilta balsta upes palienā aprēķina metode. Ir veikta metodes analīze un ir parādītas relatīvā maksimālā izskalojuma dziļuma atkarības no galvenajiem hidrauliskajiem un upes gultnes parametriem. Relatīvais maksimālais izskalojuma dziļums ir atkarīgs no plūsmas saspiešanas, relatīvā grunts diametra un sadalījuma pa slāņiem, Froude koeficienta attiecībā pret slīpumu, relatīvā vietējā plūsmas ātruma, relatīvā ūdens dziļuma upes palienā, plūsmas kinētiskā parametra zem tilta, balsta sānu sienu slīpuma, balsta formas un plūsmas leņķa attiecībā pret balstu. Tiek piedāvāta metode tilta balsta stabilitātes noteikšanai, aprēķinot riska faktoru. Riska faktoru var aprēķināt kā attiecību starp izskalojuma dziļumu, platumu un tilpumu aprēķinātu pēc viena, diviem vai vairākiem plūdiem un izskalojuma bedres dziļuma, platuma un tilpuma maksimālām vērtībām. Pēc riska faktora lieluma var novērtēt esošā tilta balsta stabilitāti apkalpošanas perioda laikā vai arī aprēķināt balsta stabilitāti projektēšanas stadijā.

Gjunsburgs B., Neilands R. and Govsha E. Equilibrium depth of scour at the bridge abutments.

The flow in plain rivers contracted by bridge crossing in floods leads to scour at bridge abutments, piers, or guide banks and can cause considerable damage and losses. New method for computing equilibrium depth of scour at the abutments on plain rivers is presented in this paper. Analysis of the method is made and dependence of the relative equilibrium depth of scour from main hydraulic and riverbed parameters is presented. The relative equilibrium depth of scour is depending on contraction of the flow, relative grain size and stratification of the bed materials, Froude number referred to the slope, relative local velocity, relative depth of the flow at the floodplain, kinetic parameter of the flow under the bridge, side-wall slope of the abutment, shape of the abutment and angle of the flow crossing. Method of estimation of stability of the abutment by computing risk factor was proposed. Risk factor is determined as a ratio between the scour depth, width and volume computed after one, two or several floods and equilibrium parameters of the scour hole. By risk factor we can estimate the current stability of the abutment in the period of maintenance or predict/compute its stability at the design stage.

Гюнсбург Б., Нейланд Р. и Говша Е. Пределъная глубина размыва у устоев мостов.

Местний размыв у устоев мостов возникает вовремя наводнение, когда переход моста сжимает поток реки. Размыв может повредить или совсем разрушить конструкцию моста. В статье представлен новий метод расчета пределъной глубины размыва у устоев мостов на равнинных реках. Выполнен анализ методики и представлены зависимости относителъной пределъной глубины размыва от основных гидравлическых и русловых параметров потока. Относительная пределъная глубина размыва зависит от сжатия потока, относительного размера грунта и слоистого строения грунта, коэффициента Фруда по отношению к наклону, относительной местной скорости, относительной глубины воды на пойме, *кинетического параметра потока под мостом, уклона боковой стены устоя, формы устоя и пересечение потока. Представлена методика расчета устойчивости устоев через определение фактора риска который представляет отношение глубины, ширины или обёма воронки размыва определенной с учетом фактора времени к предельным параметрам воронки размыва. Изпользование фактора риска необходимо использовать при проектирование сооружений или при оченке состояния конструкции за интересующий период эксплуатации.*