Time of equilibrium scour evolution at guide banks

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ABSTRACT

We are going to present an analytical solution for equilibrium time of scour for uniform or stratified riverbed at the elliptical guide banks at clear water conditions. The aim of this study is therefore to find the equilibrium time of scour near elliptical guide banks by using the differential equation of the bed sediment movement in clear water. Formulae for equilibrium depth of scour for different riverbed conditions is presented. Hydraulic threshold criterion is proposed for calculation of equilibrium time of scour, instead of criteria for which refer only on the size of the bridge structure or flow depth. The method presented and test results confirmed the influence contraction rate of the flow, Froude number, different grain sizes, ratio relative local and critical velocities, and relative depth of scour on equilibrium time of scour. The test results of scour evaluation in time with duration of seven hours were prolonged until the equilibrium stage of scour by using developed computer model EROBO and compared with equilibrium time of scour calculated by the method presented, and they were in good agreement.
Keywords: scour, equilibrium time, elliptical guide banks

INTRODUCTION

Incorrect prediction of the depth of foundations for abutments, piers, guide banks or spur dikes may lead to severe damages of the structures and cause considerable economic and financial losses.

This is usually done by computing the equilibrium scour depth, but equally important and less studied, is the prediction of time needed to achieve the equilibrium scour depth, which will be termed here as equilibrium time of scour.

The equilibrium time of scour at bridge piers, abutments and spur dikes were studied, among others, by Ballio and Orsi (2001), Coleman et al. (2003), Dey and Barbhuiya (2005), Cardoso and Fael (2010), Gjunsburgs et al. (2010), Ghani et al. (2011) and Lauva (2015).

The first problem to be faced is to define such a time, and consequently the equilibrium scour depth. In clear water conditions, scouring will never cease completely.

Therefore, equilibrium conditions have to be defined with reference to conditions in which the scouring pace has reduced to a negligible value. Threshold criteria are used for evaluating the equilibrium conditions of scour. The various threshold criteria, proposed in the literature usually assume that equilibrium has been reached when in a 24 hours period the depth of scour increases less than 5% of the pier diameter according to Melville and Chew (1999) or less than 5% of the flow depth or abutments length (Coleman et al., 2003) or again less than 5% of the pier diameter divided by 3 (Grimaldi et al., 2006). All these criteria for equilibrium time of scour refer only on the size of the bridge structure.

Therefore, there is still the need for computing equilibrium time without having to resort to an experimental investigation. Analysis of the literature shows that until today there are no methods or formulas to predict equilibrium time of scour at uniform or stratified river bed near elliptical guide banks while in the available formulas for calculating equilibrium time of scour at piers or abutments some important parameters of the flow and river bed are not taken into consideration: contraction rate of the flow, Froude number, bed layering sediment movement parameters, local flow modification, relative local and critical velocities ratio, relative depth.

The aim of this study is therefore to find the equilibrium time of scour near elliptical guide banks in clear water conditions using the differential equation of the bed sediment movement in clear water. The solution to the equation describes the scour evolution in time, and this allows to easily finding the equilibrium time.

In the course, a new hydraulic threshold criterion is proposed to determine the equilibrium time of scour.

Tests duration in flume was 7 hours, vertical scale of the tests – 50 and then the time scale was 7. Test time converted in real conditions was equal 2 days. That was mean duration of time steps on which hydrograph of flood was divided and used for scour calculation in natural conditions by our method. The condition $Fr_R = Fr_f$ were fulfilled, where Fr_R = Froude number for low-land river, Fr_f = Froude number in flume

To validate the analytical solution developed, experimental tests were run. For practical reasons the test could not be run until equilibrium, but up to a duration of 7 hours. After checking that the analytical solution was well reproducing the scour evolution in time by the experimental tests, the analytical solution alone has been used to compute the equilibrium time.

Formulae for equilibrium depth of scour for different riverbed conditions as for uniform and stratified riverbed is used for equilibrium time prediction. The test results of scour evaluation in time with duration of seven hours prolonged by computer modeling scour process until the equilibrium stage of scour by using computer model

ERОBO, based on early-developed model, and compared with equilibrium time of scour calculated by the method presented, and they were in good agreement.

EXPERIMENTAL SETUP

The tests were carried out in 3.5 m wide and 21 m long flume under open flow conditions, studying the flow distribution between the channel and the floodplain.

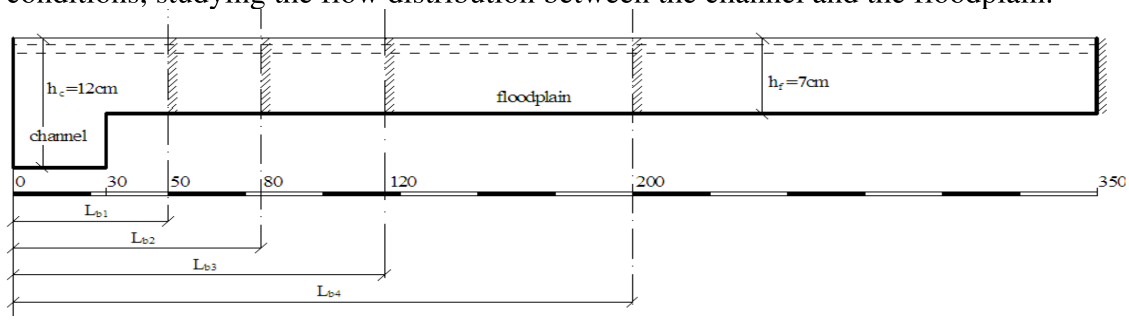

Fig.1 Cross section of the flume

The rigid bed tests were performed for different flow contractions and Froude numbers in order to investigate the velocity and the water level changes near the guide banks. The aim of the sand bed tests was to study the scour process, the changes in the local velocity, and the effect of different hydraulic parameters like: the flow contraction rate, the grain size, stratification of the model bed, to obtain finally the scour development in time.

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, depth of water on floodplain was 7 and 13 cm and the Froude numbers varied from 0.078 to 0.134. The uniform and not uniform sand bed tests were carried out under clear-water conditions. The sand was placed starting 1 m upstream and until 1 m downstream the contraction of the flume. The mean grain sizes used were 0.24 and 0.67 mm. The tests with stratified bed conditions performed for contraction rate $Q/Q_b= 3.66\text{-}4.05$ with one layer with different grain size 0.24 and 0.67 mm or with stratified bed with layers of different grain size and with thickness of the layers equal 4, 7 and 10 cm. The tests in the flume lasted for 7 hours. The development of scour was examined with different constant flow parameters in time intervals of 7-hours.

THE MODEL

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

$$\frac{dW}{dt} = \frac{Q_s}{1-p}, \tag{1}$$

where: W – the volume of the scour hole at elliptical guide bank, which, according to the test results, is equal to $1/5\pi m^2 h_s^3$; t – time; and Q_s – the sediment discharge out of the scour hole, p - the bed porosity.

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

$$\frac{dW}{dt} = \frac{3}{5}\pi m^2 h_s^2 \frac{dh_s}{dt} = ah_s^2 \frac{dh_s}{dt}, \tag{2}$$

where: h_s – the scour depth; m – the steepness of the scour hole; $a=3/5\pi m^2$.

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

$$Q_s = AB \cdot V_{l\ el}^4, \tag{3}$$

where: $B = mh_s$ describes width of the scour hole; V_l – the local velocity at the elliptical guide banks with a plain bed; and A – a parameter in the Levi [8] formula. The results of the basic research by Levi and by Studenicnikov have been compared, with some of the better known equivalents results achieved by Meyer-Peter and Müller, and by Shields.They were in good agreement [9].

The parameter A depends on the scour, local velocity V_l, critical velocity βV_0 and grain size of the bed material changing in time:

$$A_i = \frac{5.62}{\gamma}\left[1 - \frac{\beta V_0}{V_{l\,el}}\left(1+\frac{h_s}{2h_f}\right)^{1.25}\right] \cdot \frac{1}{d_i^{0.25} \cdot h_f^{0.25}\left(1+\frac{h_s}{2h_f}\right)^{0.25}}, \tag{4}$$

where: $\frac{\beta V_{ot}}{V_{lt\,el}} = \frac{\beta V_o}{V_{lel}}\left(1+\frac{h_s}{2h_f}\right)^{1.25}$.

The sediment discharge upon development of the scour is:

$$Q_s = A_i \cdot mh_s \cdot V_{lt\ el}^4 = b\frac{h_s}{\left(1+\frac{h_s}{2h_f}\right)^4}, \tag{5}$$

where: $b = A_i m V_{l\,el}{}^4$.

The hydraulic characteristics, such as the contraction rate of the flow, the velocities βV_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 (5), the differential equation (1) can be written in the form

$$a h_s^2 \frac{dh_s}{dt} = b \frac{h_s}{\left(1+\frac{h_s}{2h_f}\right)^4}, \tag{6}$$

After separating the variables and integration of Eq. (6), we have:

$$t = D_i \int_{x_1}^{x_2} h_s \left(1+\frac{h_s}{2h_f}\right)^4 dh_s, \tag{7}$$

$$D_i = \frac{a}{b} = \frac{3}{5}\frac{\pi \cdot m \cdot}{A_i \cdot V_{l\ el}^4}, \tag{8}$$

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:

$$t = 4D_i h_f^2 \left(N_i - N_{i-1}\right), \tag{9}$$

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.

Equilibrium time of scour near elliptical guide banks is at equilibrium depth of scour:

$$t_{equil} = 4D_{equil.} h_f^2 \left(N_{equil.} - N_{i-1}\right), \tag{10}$$

where: $N_{equil} = 1/6x_{equil.}^6 - 1/5x_{equil.}^5$, $N_{i-1} = 1/6x_{i-1}^6 - 1/5x_{i-1}^5$, $x_{equil.} = 1 + h_{equil.} / 2h_s$ are the relative equilibrium depths of scour.

The equilibrium depth of scour at elliptical guide banks is found [10]:

$$h_{equil} = 2h_f \left[\left(\frac{V_{lel}}{\beta V_o}\right)^{0.8} - 1\right] \cdot k_\alpha \cdot k_m, \tag{11}$$

where: $V_0 = 3.6 d_i^{0.25} h_f^{0.25}$ is the critical velocity at the plain bed; k_α – a coefficient depending on the flow crossing angle; and k_m – a coefficient depending on the side-wall slope of guide banks.

To calculate depth of scour in the next layer it is necessary to find the local and critical velocities on the top of this layer, because those velocities are forming scour depth but not velocities V_l and V_0. The local velocity on the surface of the second layer is found by the formula:

$$V_{lt2} = \frac{V_{l\,el}}{1+\frac{H_{d1}}{2h_f}} \tag{12}$$

where H_{d1} = the thickness of the first layer of the riverbed with the grain size d_1.

The critical velocity on the top of the second layer is equal to:

$$V_{02} = \beta 3.6 \cdot d_2^{\,0.25} h_f^{\,0.25} \left(1+\frac{H_{d1}}{2h_f}\right)^{0.25} \tag{13}$$

where $V_{02}=\beta 3.6 d_2^{0.25} h_f^{0.25}$ = the critical velocity of flow for the grain size d_2, since the layer with exactly this diameter lies on the top of the riverbed.

The scour depth in the second layer is determined as:

$$h_{S2} = 2h_f \left[\left(\frac{V_{lt2}}{\beta V_{ot2}} \right)^{0.8} - 1 \right] \cdot k_\alpha \cdot k_m , \qquad (14)$$

At stratified bed conditions, if $h_{s2} < H_{d2}$, the scour stops in this layer, and the equilibrium scour depth is:

$$h_{equil} = H_{d1} + h_{s2} \qquad (15)$$

Using value h_{equil} it is possible to find values A_{equil}, D_{equil}, N_{equil} and finally t_{equil}.

RESULTS

According to the computer modeling, the scour stops when local velocity V_{lt} becomes equal to critical velocity βV_{0t} or ratio of those velocities becomes equal to 1, if that happens $A_{equil} = 0$, $D_{\text{equil}} = \infty$ and equilibrium time goes to infinity $t_{\text{equil}} = \infty$. The hydraulic threshold criterion, instead of geometrical one, is proposed for calculation of equilibrium time of scour. The threshold criterion checked and accepted equal to $\beta V_{0t} / V_{lt} = 0.985222$ for calculation equilibrium time of scour.

$$\frac{\beta V_{ot}}{V_{lt\,el}} = \frac{\beta V_o}{V_{lel}} \left(1 + \frac{h_{equil.}}{2h_f} \right)^{1.25} = 0{,}985222 \ . \qquad (16)$$

The test results were prolonged by computer modeling until equilibrium stage of scour, using method of calculation scour development in time near elliptical guide banks [10]. Comparison equilibrium times calculated by computer modeling and by the method presented have been made; results are in good agreement.

Analysis of the method presented and test results confirmed the influence contraction rate of the flow, Froude number, different grain sizes, ratio relative local and critical velocities, and relative depth of scour on equilibrium time of scour.

With increase of contraction rate of the flow Q/Q_b the equilibrium time of scour is increasing. Tests were made with grain size d=0.67 mm (see Table 1)

Table 1. Influence contraction rate of the flow on equilibrium time of scour.

TEST	*Q/Qb*	*hequil*/hf	*Di*	*Xi*	*tcomp.*	*tform.*	*tcalc.*/**tco.**	*Fr2*	*bVo/Vl*
EL2	5.69	1.399	89.804	1.679	42	46.78	1.11388	0.103	0.515
EL5	3.87	1.273	109.584	1.617	39	41.63	1.06744	0.103	0.541
EL8	2.69	0.886	216.703	1.426	24	26.35	1.09773	0.103	0.633
EL11	1.66	0.156	873.163	1.065	1.5	1.19	0.79428	0.103	0.911

With Froude number increase the equilibrium time of scour is increasing (see Table 2).

Table 2. Froude number impact on equilibrium time of scour

TEST	Q/Q_b	$h_{equil.}/h_f$	N_i-N_{i-1}	$t_{comp.}$	$t_{form.}$	$t_{calc.}/t_{com.}$	Fr	bV_o/V_l
EL1	5.27	0.96	0.33	27.60	30.68	1.11	0.078	0.61
EL2	5.69	1.40	1.11	42.00	46.78	1.11	0.103	0.52
EL3	5.55	1.59	1.73	51.00	52.47	1.03	0.124	0.48

Equilibrium time of scour at grain size d=0.67 mm (Table 1) is less than at grain size d=0.24 mm (Table 3). With increased difference between critical velocity and local one bV_o/V_l the equilibrium time of scour is increasing. With increased relative depth of scour, the equilibrium time of scour is increasing (Tables 1-2).

Table 3. Equilibrium time of scour at grain size d=0.24 mm

TEST	$h_{equil.}/h_f$	D_i	X_i	N_i-N_{i-1}	$t_{comp.}$	$t_{form.}$	$t_{calc.}/t_{co.}$
EL12	2.17	52.28	1.80	5.46	132.0	134.25	0.98
EL15	2.02	47.49	1.72	4.09	100.8	91.35	1.10
EL18	1.54	130.76	1.39	1.55	90.0	95.57	0.94
EL21	0.65	619.50	1.22	0.10	30.5	29.96	1.02

Comparison of calculated equilibrium time by Eq. (10) and computer modeled presented in Fig.2

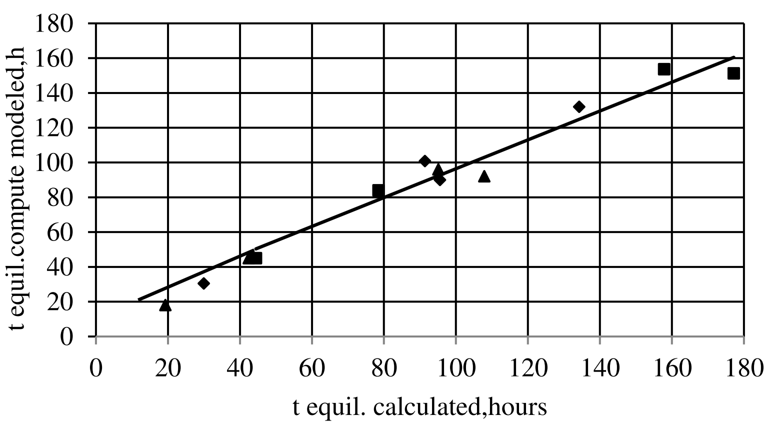

Fig.2 Comparison of calculated and computer modeled equilibrium time of scour

CONCLUSIONS

The model for calculation equilibrium time of scout near elliptical guide banks in clear water conditions was presented for uniform and stratified riverbed.

According to the computer modeling, the scour stops when local velocity V_{lt} becomes equal to critical velocity βV_{0t} or ratio of those velocities becomes equal to 1, if that happens A_{equil} = 0, $D_{equil} = \infty$ and equilibrium time goes to infinity $t_{equil} = \infty$. The hydraulic threshold criterion as $\beta V_{0t}/V_{lt}$ = 0.9852, instead of geometrical one, is checked and accepted for equilibrium time of scour calculation. Using the threshold criteria (16), h_{equil}, A_{equil}, D_{equil}, N_{equil} and finally t_{equil} for uniform or stratified riverbed were calculated. Analysis of the method presented and test results confirmed the influence contraction rate of the flow, Froude number, different grain sizes, ratio relative local and critical velocities, and relative depth of scour on equilibrium time of scour. Tests duration in flume was 7 hours, vertical scale of the tests – 50 and then the time scale was about 7. Test time converted in real conditions was equal 2 days. That was mean duration of time steps on which hydrograph of flood was divided and used for scour calculation for natural bridge crossing conditions by early presented method. The condition $Fr_R = Fr_f$ were fulfilled, where Fr_R = Froude number for low-land river, Fr_f = Froude number in flume. Comparison all test results and calculated by our model for 7 hours duration presented in published paper- Evangelista, S., Govša, J., Greco, M., Gjunsburgs, B. (2017, and that allowed us to prolong by computer modeling till equilibrium stage of scour near elliptical guide banks [Gjunsburgs, B. (2006)] and compare calculated results using (Eq. 10). Tests result are in good agreement with calculated data (Tables 1-3,Fig.2).

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