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Equilibrium time of scour near structures in plain rivers

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Abstract

The equilibrium depth of scour is an important parameter for estimation of the foundation depth. The equilibrium depth of scour development under steady flow is depending on time and can be reached in equilibrium time. The aim of the study is to find the equilibrium time near elliptical guide banks at clear water and uniform river bed, which allows to predict the equilibrium depth of scour near structures in flow. The literature analysis shows that there are no methods or formulas to calculate equilibrium time of scour near elliptical guide banks. In formulas for equilibrium time calculation at piers or abutments the different parameters 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 and relative depth. The differential equation of the bed sediment movement in clear water was used and method for computing equilibrium time of scour near elliptical guide banks was elaborated. New hydraulic threshold criterion is proposed for calculation of equilibrium time of scour. Computer modeling results were compared with equilibrium time of scour calculated by the presented method and they were in good agreement.

Keywords: local scour; equilibrium time; contraction rate of the flow.

1. Introduction

In the equilibrium time of scour prediction it is important to know how to calculate the equilibrium depth of scour, in order to predict depth of the bridge foundations (calculate how deep the foundation need to be in the river bed), for example, to appoint the foundation pile length of the structures in river flow. Incorrect prediction depth of foundations for abutments, piers, guide banks or spur dikes can lead to severe damages of the bridge structures and be the reason of considerable economical and financial losses.

The equilibrium time of scour at bridge piers, abutments and spur dikes were studied by Ballio and Orsi [1], Lauchlan *et al.* [2], Coleman *et al*. [3], Gjunsburgs and Neilands [4], Dey and Barbhuiya [5], Grimaldi *et al.* [6], Cardoso and Fael [7], Gjunsburgs *et al*.[8], Ghani *et al.* [9] and others.

The threshold criteria are used for equilibrium depth of scour calculation. The threshold criteria, proposed early and known from literature: for calculations when in a 24 hours period the depth of scour increases less than 5% of the pier diameter [10] or less than 5% of the flow depth or abutments length [3] or less than 5% of the 1/3 of the pier diameter [6]. Proposed threshold criterion for equilibrium time of scour is only depending on the size of the bridge structure, and not considering hydraulic parameters of the flow.

Those approaches are conservative, because they do not take into account any flow and geological conditions, near the structure, on which the equilibrium time of scour is depending on. Analysis of the literature shows that there are no methods or formulas to predict equilibrium time of scour near elliptical guide banks. In formulas for 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 and relative depth.

The aim of the study is to find the equilibrium time of scour near elliptical guide banks at clear water conditions and uniform sand bed in plain rivers.

The differential equation of the bed sediment movement in clear water was used and a method for computing equilibrium time of scour near elliptical guide banks was elaborated. New hydraulic threshold criterion is proposed to determine the equilibrium time of scour.

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The test results (with duration of 7 hours) were prolonged by computer modeling till equilibrium stage of scour, using calculation method of scour development in time near elliptical guide banks [11]. Computer modeling results were compared with calculation results of equilibrium time of scour by the presented method and they are in good agreement (Table 2).

2. Experimental setup

The tests were carried out in a flume 3.5 m wide and 21 m long. Experimental data for the open-flow conditions are presented in Table 1. The tests were carried out under open flow conditions, studying the flow distribution between the channel and the floodplain.

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

Table 1. Test data for open flow conditions

Test	L, cm	h, cm	V, cm/s	Q, l/s	Fr	Re_c	Re_f
L1	350	7	6.47	16.60	0.078	7500	4390
L2	350	7	8.58	22.70	0.103	10010	6060
L3	350	7	10.3	23.60	0.124	12280	7190
L7	350	13	7.51	35.48	0.066	13700	9740
L8	350	13	8.74	41.38	0.075	16010	11395

The tests were carried out under open flow conditions, studying the flow distribution between the channel and the floodplain.

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 sand bed tests were carried out under clear-water conditions. The sand was placed 1 m up and down the contraction of the flume. The mean grain size was 0.24 and 0.67 mm. The tests with stratified bed conditions were performed for contraction rate Q/Q_b = 3.66–4.05 (where Q is the flow discharge and Q_b is the discharge through the bridge opening under open-flow conditions). Thickness of the layers with different grain size 0.24 and 0.67 mm with standard deviation were equal 4, 7 and 10 cm. The condition that $Fr_R = Fr_f$ was fulfilled; where Fr_R and Fr_f are the Froude numbers for the plain river and for the flume, respectively. The tests in the flume lasted for 7 hours, the length scale was 50 and the time scale was 7. With respect to the real conditions, the test time was equal to 2 days. This was the mean duration of time steps into which the flood hydrograph was divided. The development of a 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. The tests were carried out with one floodplain model and one side contraction of the flow, and with two identical or different floodplain models and two sides.

The tests were carried out with one floodplain model and one side contraction of the flow. The dimension of the upper part of an elliptical guide bank, namely the length calculated according to the Latishenkov [12] method and was found to be dependent on the flow contraction rate and the main channel width. The length of the lower part of the guide bank was assumed to be half of the upper part.

3. Method

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 – 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.

The volume and shape of the scour hole are independent of the contraction rate of the flow [11].

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

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

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 [13] 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 [13] formula.

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

$$Q_f = Q_{sc}, \tag{4}$$

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. Now we have:

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

where mh – the width of the scour hole; h_f – water depth in the floodplain; h_s – the scour depth; and V_{lt} – the local flow velocity at scour depth h_s.

From Eqn. (5) the local velocity for any depth of scour is

$$V_{lt_{el}} = \frac{V_l}{1 + \frac{h_s}{2h_f}}, \tag{6}$$

The critical velocity at the plain bed V_0 can be determined by the Studenitcnikov [14] formula $V_0 = 3.6 d_i^{0.25} h_f^{0.25}$, where: d_i – 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

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

where: β – coefficient of critical velocity reduction near structure, because of flow circulation.

At a plain river bed the formula for $A = A_I$ reads Eqn. (3)

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

where: γ – specific weight of the sediments.

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

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

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

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

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

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 Equations (2) and (10), the differential Eqn. (1) can be written in the form

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

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

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

$$D_i = \frac{a}{b} = \frac{3}{5} \frac{\pi \cdot m \cdot}{A_i \cdot V_{l\,el}^4}, \quad (13)$$

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

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

$$t = 4D_i h_f^2 (N_i - N_{i-1}), \quad (14)$$

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.

Using the equilibrium depth of scour in Eqns (9), (13) and (14) it is possible to find equilibrium time of scour near elliptical guide banks

$$t_{equil} = 4D_{equil.} . h_f^2 \left(N_{equil.} - N_{i-1}\right), \quad (15)$$

The sequence to calculate the equilibrium time of scour is the next:

The equilibrium depth of scour at elliptical guide banks is found [11]:

$$h_{equil} = 2h_f \left[\left(\frac{V_{lel}}{\beta V_o}\right)^{0.8} - 1\right] \cdot k_\alpha \cdot k_m, \quad (16)$$

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.

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

When local velocity V_{lt} becomes equal to critical velocity βV_{0t}, $A_{equil} = 0$, $D_{equil} = \infty$ and $t_{equil} = \infty$, criteria to evaluate threshold is needed to appoint to calculate equilibrium time of scour.

4. Results

At the head of the elliptical guide bank, we observe the concentration of streamlines, a sharp drop in water level, and a local increase in the velocity. Locally modified flow near the guide banks is forming the scour hole. Fig. 1 illustrates the scour depth h_s and respective variations in the local V_{lt} and critical βV_{0t} velocities, as measured experimentally and calculated in steady flow and layer with uniform sand. With the scour depth increase, the local velocity is reducing and the critical one is increasing (Fig. 1).

Ratio of critical velocity to local one at the head of elliptical guide bank is accepted as threshold criteria in equilibrium time of scour calculation. According to computer modelling results the scour stops when local velocity V_{lt} becomes equal to critical velocity βV_{0t} or ratio of those velocities becomes equal to 1, and equilibrium is equal to infinity. The threshold criterion checked and accepted equal to $\beta V_{0t} / V_{lt} = 0{,}985222$ for calculation equilibrium time of scour.

$$\frac{\beta V_{ot}}{V_{ltel}} = \frac{\beta V_o}{V_{lel}} \left(1 + \frac{h_{equil.}}{2h_f}\right)^{1.25} = 0{,}985222. \quad (17)$$

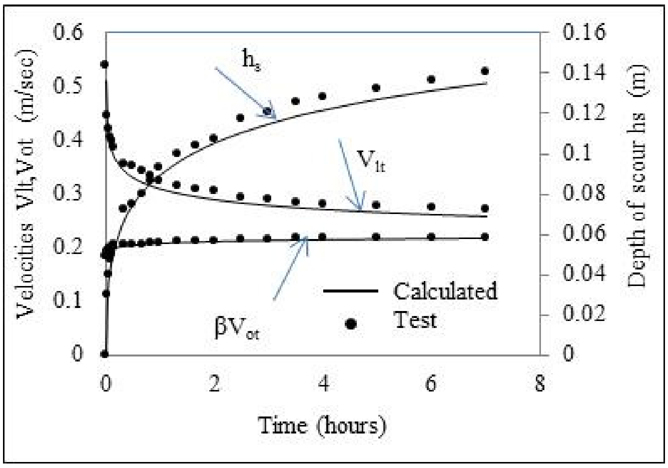

Fig. 1. Changes in scour depth and in the local and critical velocities V_{lt} and βV_{0t} varying with time under steady flow with one-sand layer, test EL 6.

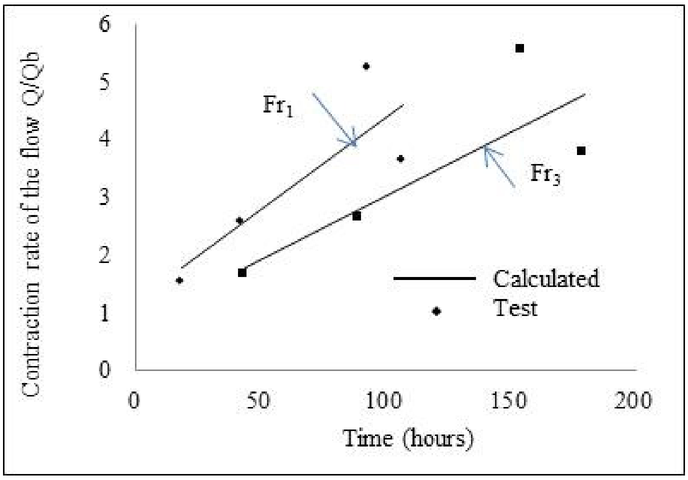

Fig. 2. Dependence of the equilibrium time of scour from the contraction rate of the flow Q/Q_b.

Theoretical analysis of the method presented and test results confirmed the influence contraction rate of the flow, Froude number, bed layering, relative local and critical velocities ratio, relative depth of scour on equilibrium time of scour.

The ratio of the critical velocity to local one $\beta V_0/V_l$ is depending on contraction rate of the flow Q/Q_b.

With contraction rate of the flow the equilibrium time of scour is increasing (Fig. 2).

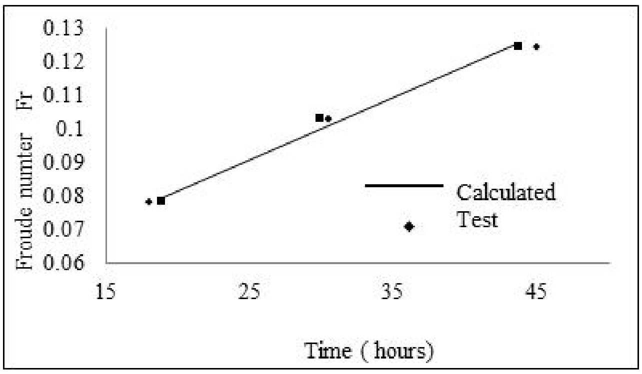

Fig. 3. Froude number influence on equilibrium time of scour.

With increase of the Froude number of the flow the equilibrium time of scour is increasing (Fig. 3).

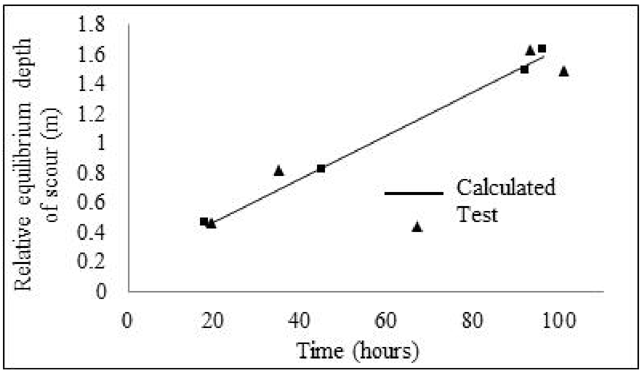

Fig. 4. Relative equilibrium depth of scour versus equilibrium time of scour.

To reach greater relative equilibrium depth of scour greater equilibrium time is needed (Fig. 4).

Table 2. Comparison equilibrium time of scour calculated by computer modelling and by proposed methods

TEST	Q/Q_b	D	N_i-N_{i-1}	$t_{comp.}$	$t_{form.}$	t_c/t_f	bV_{ot}/V_{lt}	Fr
EL1	5.27	104.71	1.894853	96	93.33	1.028608	0.985222	0.078
EL4	3.66	166.54	1.37121	92.1	107.42	0.857382	0.985222	0.078
EL7	2.6	450.468	0.198985	45	42.96	1.047486	0.985222	0.078
EL10	1.56	957.28	0.041959	18	18.89	0.952885	0.985222	0.078
EL2	5.69	52.27997	5.458999	132	134.2504	0.983237	0.985222	0.103
EL5	3.87	47.48666	4.089851	100.8	91.35798	1.103352	0.985222	0.103
EL8	2.69	130.7591	1.553792	90	95.57231	0.941695	0.985222	0.103
EL11	1.66	619.5014	0.102817	30.5	29.96214	1.017951	0.985222	0.103
EL3	5.55	40.54003	8.137144	153.6	155.1756	0.989846	0.985222	0.1243
EL6	3.78	39.31817	9.722891	151.2	179.8275	0.840806	0.985222	0.1243
EL9	2.65	55.0838	3.468266	84	89.8677	0.934707	0.985222	0.1243
EL12	1.67	467.5394	0.198961	45	43.75755	1.028394	0.985222	0.1243

Using threshold criteria Eqn. (17), equilibrium depth of scour h_{equil} Eqn. (16), A_{equil}, D_{equil}, N_{equil} and finally equilibrium time t_{equil} Eqn. (15) is calculated. Computer modelling of scour development in time near elliptical guide banks was used [11] to prolong test results to equilibrium depth and time of scour. Comparison equilibrium times calculated by computer modelling and by Eqn. (15) have been made; results are in good agreement (Table 2).

5. Conclusions

The flow pattern at the head of the elliptical guide banks is modified, the concentration of streamlines, a sharp drop in water level, a local increase in the velocity, vortex structures, circulation and scour hole was observed. Locally modified flow near the head of the guide banks is forming the scour hole.

The equilibrium depth of scour development under steady flow is depending on time and can be reached in equilibrium time. An analysis of the literature shows that there are no methods or formulas to calculate equilibrium time of scour near elliptical guide banks.

The differential equation of the bed sediment movement in clear water was used and a method for computing equilibrium time of scour near elliptical guide banks was elaborated. The test results (with duration of 7 hours) were prolonged by computer modelling till equilibrium stage of scour, using method of calculation scour development in time near elliptical guide banks [11]. With the scour depth increase, the local velocity is reducing and the critical one is increasing. According to the computer modelling, the scour stops when the local velocity V_{lt} becomes equal to the 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 new threshold criterion as $\beta V_{0t} / V_{lt} = 0.985222$ is checked and accepted for equilibrium time of scour calculation. Using the new threshold criteria in Equation (17), h_{equil}, A_{equil}, D_{equil}, N_{equil} and finally t_{equil} by Eqn. (15) is calculated.

Computer modelling results were compared with equilibrium time of scour, calculated by the method presented Eqn. (15) and they are in good agreement (Table 2).

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