Impact flow and bed layering on equilibrium depth of scour at elliptical guide banks

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Abstract. In the paper is present study the equilibrium scour at elliptical guide banks at different Fr number of the open flow, contraction, uniform or stratified bed model. A new approach for calculation equilibrium depth of scour at elliptical guide banks is elaborated and method for calculation equilibrium depth of scour bed at elliptical guide banks is presented. Analysis of the test, calculation and computer modelling results is made to estimate impact on relative equilibrium depth of scour: Fr number of the flow, local Froude number - FrVl, FrV equal, flow contraction, relative time, thickness and sequence of the bed layers. Relative equilibrium depth of scour is increasing with increase of Fr number of the open flow, local FrVl number, FrV equal at equilibrium depth of scour, relative time of scour, flow contraction and with different thickness and sequence of the bed layers. Calculation equilibrium depth of scour with the approach flow velocity and using the grain size only on the top of the bed or for the next layer calculate depth of scour with the same velocity, as it accepted nowadays, and neglecting changes of the flow parameters during the scour, bed layering can lead to wrong results and damages and losses.

1. Introduction

Structures failure due to scour near the foundations are the flow modification in floods and during the scour, flow contraction, layering of the river bed and type, size and shape of the structures. Equilibrium scour depth at bridge piers, abutments, and spur dikes is studied by Raudkivi and Ettema (1983), Sturm and Janjua (1994), Ahmed and Rajaratnam (2000), Radice et al. (2002), Coleman et al. (2003), Kwak et al. (2004), Joko and Lim (2006), Ballio et al. (2009), Cardoso and Fael (2010), Ghani et al. (2011), Guo (2014), Sheppard et al. (2014), Evangelista et al. (2017) and the others. Impact on the equilibrium depth of scour at elliptical guide banks open flow Fr number, local Froude number- FrVl, Froude number at equilibrium stage of scour, densimetric Froude number, flow contraction, relative time and thickness and sequence of the layers is studied.

Relative equilibrium depth of scour is increasing with increase of the open flow Fr number, local FrVl number, relative time of scour, flow contraction and bed stratification, as changes the thickness and sequence of the bed layers. Calculation equilibrium depth of scour using approach flow velocity and only the grain size on the top of the bed or for the next layer to calculate depth of scour with the same
flow velocity as for first layer, as it is excepted nowadays, and neglecting changes of the flow parameters during development of the scour hole in time, can lead to wrong results, damages and losses.

2. Experimental set-up
The tests were carried out in a flume 3.5 m wide and 21 m long. The flow distribution between the channel and the floodplain was studied under open-channel flow conditions (Table 1).

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 elliptical guide banks, 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. The opening of the bridge model was 50, 80, 120, and 200 cm.

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 7 and 13 cm.

The Froude numbers varied from 0.078 to 0.134. The flume slope was 0.0012.

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 bridge model contraction of the flumes.

The mean size of grains was 0.24 and 0.67 mm with a standard deviation. The scour development in time for the bed material with different grain size thickness or sequence layers was studied. Duration of the tests, with different flow parameters, bed materials and layers thickness and sequence was 7 and 14 hours.

| Test | \( L \) cm | \( h_f \) cm | \( V \) cm/s | \( Q \) l/s | \( Fr \) | \( Re_c \) | \( Re_f \) |
|------|-------------|-------------|-------------|-----------|--------|--------|--------|
| L1   | 350         | 7           | 6.47        | 16.60     | 0.780  | 7500   | 4390   |
| L2   | 350         | 7           | 8.58        | 22.70     | 0.010  | 10010  | 6060   |
| L4   | 350         | 7           | 8.16        | 20.81     | 0.098  | 10270  | 5590/5660 |
| L5   | 350         | 7           | 9.07        | 23.48     | 0.109  | 11280  | 6140/6410 |
| L6   | 350         | 7           | 11.10       | 28.31     | 0.134  | 13800  | 7550/7840 |
| L7   | 350         | 13          | 7.51        | 35.48     | 0.067  | 13700  | 9740   |
| L8   | 350         | 13          | 8.74        | 41.38     | 0.076  | 16010  | 11395  |
| L9   | 350         | 13          | 9.90        | 47.10     | 0.088  | 14300  | 14300  |

3. Method
The scour depth at elliptical guide banks is equal to the equilibrium depth of scour in the conditions when the local velocity becomes equal to the critical one.

The water discharge for unit width flowing over the scour hole does not change in time, according to tests results, then the scour hole development does not alter the streamlines paths, the depth integrated velocity averaged over the whole scour hole width, assuming free surface and a triangular shape for the scour hole transverse section.

The local velocity at a plain river bed is found by the Bernoulli equation for two cross sections of the extreme unit streamline. The discharge across the width of a scour hole before and after the development of scour is:
local and critical velocities on the top of the second layer must be calculated. The scour develops in the second layer with a grain size can be used; however, when the depth of scour is less than thickness of the bed layer, the scour develops in the third layer with a grain size. When the depth of scour is less than thickness of the bed layer, the backwater value, and the grain size of the bed materials, and is a coefficient depending on the flow crossing angle and is the critical velocity due to vortex structures, is the grain size of the bed materials, and is the critical velocity at the plain bed (Studenithcnikov, 1964).

The critical velocity at the equilibrium stage can be determined through the mean depth of flow near elliptical guide banks at that stage:

\[ V_{\text{cr}} = 1.15 \beta g^{0.5} \left( h_f d_f \left( 1 + \frac{h_{\text{equil}}}{2h_f} \right) \right)^{0.25} = \beta V_0 \left( 1 + \frac{h_{\text{equil}}}{2h_f} \right)^{0.25} \]  

(3)

where \( \beta \) is a coefficient of reduction in the critical velocity. The scour at the equilibrium stage stop when the local velocity \( V_l \) (Eq. 2) becomes equal to the critical velocity \( V_{\text{cr}} \) (Eq. 3):

\[ \frac{V_{l,el}}{1 + \frac{h_{\text{equil}}}{2h_f}} = \beta \cdot 3.6 \left( h_f d_f \right)^{0.25} \left( 1 + \frac{h_{\text{equil}}}{2h_f} \right)^{0.25} \]

(4)

From Eq. 4, the equilibrium depth of scour at elliptical guide banks is found:

\[ h_{\text{equil}} = 2h_f \left[ \left( \frac{V_l}{\beta V_0} \right)^{0.8} - 1 \right] \cdot k_{\text{cr}} \cdot k_m \]

(5)

where \( k_{\text{cr}} \) is a coefficient depending on the flow crossing angle and \( k_m \) is a coefficient depending on the side-wall slope of guide banks.

According to Eq. (5), the equilibrium depth of scour depends on the contraction rate of flow, backwater value, and the grain size of river bed. With increase in the grain size, the equilibrium depth of scour reduces.

The geology of the river bed is complicated and may be is formed by layers with different thickness and grain sizes. When the depth of scour is less than thickness of the bed layer \( h_{\text{equil}} < H_{d1} \), equation (5) can be used; however, when the depth of scour is greater than thickness of the bed layer \( h_{\text{equil}} > H_{d1} \), the scour develops in the second layer with a grain size \( d_2 \). If the depth of scour is greater than thickness of the second bed layer \( h_{\text{equil}} > H_{d1} + H_{d2} \), the scour develops in the third layer with a grain size \( d_3 \), and so on.

Then, the equilibrium scour depth is different from that is with one uniform layer. When \( h_{\text{equil}} > H_{d1} \), the scour develops in the second layer with \( d_2 \). Now, to determine the equilibrium depth of scour the local and critical velocities on the top of the second layer must be calculated.

The local velocity on the surface of the second layer is found by the formula:
where $H_{d1}$ is the thickness of the first layer of the river bed.

The critical velocity is determined from the medium depth of flow $h_{mid} = h_f(1 + H_{d1}/2h_f)$ on the floodplain with a scour depth equal to the thickness of the first bed layer:

$$
V_{01} = \beta 3.6 \cdot d_2^{0.25} h_f^{0.25} \left(1 + \frac{H_{d1}}{2h_f}\right)
$$

(7)

where $V_0 = \beta 3.6 d_2^{0.25} h_f^{0.25}$ is the critical velocity of flow for the grain size $d_2$, since the layer with exactly this diameter lies on the top of the river bed.

In the second layer the scour hole is forming new velocities with $V_0$ on the top of the second layer, not velocities at plain bed, as assumed by different authors.

Then, the scour depth in the second layer is determined as:

$$
h_{s2} = 2h_f \left[\left(\frac{V_{h1}}{V_{01}}\right)^{0.8} - 1\right] \cdot k_a \cdot k_m
$$

(8)

If $h_{s2} > H_{d2}$, but the scour stops in that layer, the equilibrium scour depth is

$$
h_{equil} = H_{d1} + h_{s2}
$$

(9)

4. Results

Local flow modification at the head of the elliptical guide bank lead that local Froude number $Fr_{V1} = V_l / (g h_f)^{0.5}$, local $Fr_{V2}$ numbers at the end of test and $Fr_{V\text{equil}}$ at equilibrium depth of scour are changes, compare with Froude number of the open flow. With increase of the flow contraction the local Froude number $Fr_{V2}$ increasing (Fig.1) and leads to the increase of the relative equilibrium depth of scour (Fig.2).

![Figure 1. Local Froude number $Fr_{V1}$ dependence from flow contraction rate $Q/Q_b$ (at different Fr numbers of the open flow)
Figure 2. Relative equilibrium depth of scour \( \frac{h_{\text{equil}}}{h_f} (1) \) and relative depth of scour at the end of the test \( \frac{h_s}{h_f} (2) \) versus local Froude number - \( Fr_{Vl} \).

Computer modeled relative equilibrium depth of scour \( \frac{h_{\text{equil}}}{h_f} \) is increasing with flow contraction as well as relative depth of scour \( \frac{h_s}{h_f} \) measured in test. (Fig.3).

Figure 3. Relative equilibrium depth of scour \( \frac{h_{\text{equil}}}{h_f} \) and relative depth of scour at the end of the 7 hour long tests \( \frac{h_s}{h_f} \) versus flow contraction \( \frac{Q}{Q_b} \).

When the depth of scour is less than thickness of the bed layer \( h_{\text{equil}} < H_{d1} \), equation (5) can be used; however, when the depth of scour is greater than thickness of the bed layer \( h_{\text{equil}} > H_{d1} \), the scour develops in the second layer with a grain size \( d_2 \). Local velocity on the top of the second layer is changed and can be calculated by equation (6) and new value of the critical velocity by equation (7). If the depth of scour is greater than thickness of the second bed layer \( h_{\text{equil}} > H_{d1} + H_{d2} \), the scour develops in the third layer with a grain size \( d_3 \), and new values of the local and critical velocities and so on.

With increase thickness of the first layer with \( d = 0.67 \text{mm} \) the relative depth of scour is reducing. Depth of scour is depending from thickness and sequence of the layers with different grain size, when the depth of scour is greater than thickness of the bed layer \( h_{\text{equil}} > H_{d1} \), the scour develops in the second layer with a grain size \( d_2 \). Sequence of the bed layers and thickness impact on equilibrium depth of scour. The first layer with different thickness \( H_{d1} \) is changing from 0 to 14 cm with \( d_1 = 0.67 \text{mm} \) and the second one is with thickness \( H_{d2} = 50 \text{cm} \) (\( d_2 = 0.24 \)).

Relative equilibrium depth of scour \( \frac{h_{\text{equil}}}{h_f} \) is increasing with increase of relative time of scour \( \frac{t_{\text{equil}}}{t_{\text{test}}} \) (Fig.4).
Figure 4. Relative equilibrium depth of scour $h_{\text{equil.}}/h_f$ versus relative time of scour $t_{\text{equil.}}/t_{\text{test}}$

In Fig.5 is presented changes of ratio of the relative grain size $d/h_s$ (where $d$ is grain size, $h_s$ depth of scour at the tests at different contraction rate of the flow) at uniform bed.

Figure 5. Relative grain size of the bed $d/h_s$ changes at verification of the contraction rate of the flow

Depth of scour is always greater when the fine-sand layer is under the coarse sand layer, and smaller when the fine-sand layer is on the top of the coarse sand layer. According to the results obtained in tests and by the method elaborated, the depth of scour is always greater when a fine-sand layer is under a coarse-sand layer.

Figure 6. Influence relative thickness of the bed layer $h_s/h_f$ on relative depth of scour $H_{di}/h_f$ (Tests EL23, EL15)
At stratified bed conditions the sequence of the layers has the significant influence on the scour depth value and can be reason of the bridge failure.

With increase of the thickness of the first coarse sand layer \( (d_1=0.67\text{mm}) \) the relative depth of scour is reducing (Fig.6).

5. Conclusion
Method for calculation equilibrium depth of scour at uniform and stratified river bed at elliptical guide banks is presented (Eqs.5, 8).

Analysis of the test, calculation and computer modelling results is made to estimate impact on relative equilibrium depth of scour: Fr number of the flow, local Froude number- \( Fr_{v1} \), \( Fr_{v,\text{equil}} \) at equilibrium depth of scour, flow contraction, relative time, thickness and sequence of the bed layers.

Local flow modification at the head of the elliptical guide bank lead that local Froude number \( Fr_{v1} = V/ (g h_0)^{0.5} \), local \( Fr_{v,\text{equil}} \) numbers at the end of test and \( Fr_{v,\text{equil}} \) at equilibrium depth of scour are increasing, compare with Froude number of the open flow. Local Froude number is depending on flow contraction (Fig.1) and with increase of the local Froude number relative equilibrium depth of scour is increasing (Fig.2). Relative equilibrium depth of scour is depending on flow contraction (Fig.3) and relative time of scour (Fig.4). Depth of scour is always greater when the fine-sand layer is under the coarse sand layer, and smaller when the fine-sand layer is on the top of the coarse sand layer.

Relative equilibrium depth of scour is increasing with increase of local Fr number, relative time of scour flow contraction and bed stratification with different thickness and sequence of the bed layers. When the depth of scour is less than thickness of the bed layer \( h_{\text{equiv}}<H_{d1} \), equation (5) can be used; however, when the depth of scour is greater than thickness of the bed layer \( h_{\text{equiv}}>H_{d1} \), the scour develops in the second layer with a grain size \( d_2 \). Local velocity on the top of the second layer is changed and can be calculated by equation (6) and new value of the critical velocity by equation (7). If the depth of scour is greater than thickness of the second bed layer \( h_{\text{equiv}}>H_{d1} + H_{d2} \), the scour develops in the third layer with a grain size \( d_3 \), and new values of the local and critical velocities and so on.

With increase of the thickness of the first coarse sand layer (with \( d_1=0.67\text{mm} \)) the relative depth of scour is reducing (Fig.6).

Calculation equilibrium depth of scour with the approach flow velocity and at river bed layering, using the grain size only on the top of the bed or for the next layer calculate depth of scour with the approach flow velocity, as it excepted nowadays, and neglecting changes of the flow parameters during the scour, river bed layering can lead to wrong results and damages and losses.

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