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SCOUR AT ELLIPTICAL GUIDE BANKS UNDER STRATIFIED BED CONDITIONS: EQUILIBRIUM STAGE

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Abstract

The scour development in time and the equilibrium stage of scour near abutments and guide banks with a uniform layer and stratified bed conditions have been studied. At present, no methods are available for computing the depth of a local scour near the bridge crossing structures under complex geological conditions. The tests in flume were made with uniform layers and with two layers with different grain size. The sequence of layers can increase the scour depth and lead to damage or failure of bridge structures. A new method for computing the equilibrium scour depth at elliptical guide banks in the stratified river bed conditions is presented. The method is confirmed by test results.

Key words

Scour, stratified conditions, elliptical banks, scour geology

1 INTRODUCTION

Streamline concentration, local increase in velocity, circulation and vortex structures, an increased turbulence, and a scour hole are observed at the head of guide banks. According to different authors, the depth of scour at bridge structures depends on the grain size of the surface layer of the river bed. But this approach does not reflect the complexity of the geological structure of river bed, which can increase the scour depth and cause damage to bridge structures.

The influence of river bed stratification on the depth of scour was mentioned by Rotenburg et al. [1], Ettema [2], Raudkivi and Ettema [3], and Gjunsburgs et al. [4, 5], but there is no method for computing the local depth of scour near bridge structures under stratified bed conditions. In this study, a new method for computing the equilibrium depth of scour at elliptical guide banks under stratified bed conditions is presented. According to experimental

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and calculation results, in the stratified bed conditions, the grain size of a layer at which the scour stops is the main parameter for predicting the scour depth. If the surface layer with a grain size d_1 is scoured and the process is continued in the second layer with a grain size d_2, where $d_1<d_2$ and $h_{equil} < H_{d1} + H_{d2}$ (the scour stops at the second layer), the scour depth in the case of two layers is the same as that in one layer with d_2. If the scour stops in the second layer and $d_1>d_2$, $h_{equil}<H_{d1}+H_{d2}$, its depth is greater than in the case of a uniform layer with a grain size d_1. The sequence of layers with different diameters of grains is illustrated in Fig.1. The value of d_1 can exceed d_2 or vice versa.

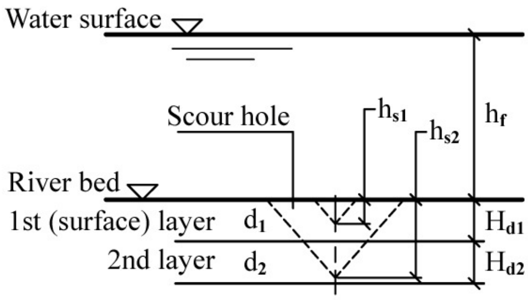

Fig. 1) Geology of the river bed formed by layers with different grain sizes

2 EXPERIMENTAL SETUP

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 rigid-bed tests were performed for different flow contractions and Froude numbers with the purpose of investigating the changes in velocity and water level near the embankment, along it, and near the modeled elliptical guide bank.

Tab. 1) Some experimental data for open flow conditions in a flume

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

During sand-bed tests, the time-dependent changes in velocities and scour depth, the effect of different hydraulic parameters, the flow contraction rate, the grain size of bed materials, and the scour process were studied. The tests were performed in a flume of width L = 350cm for the following bridge-model openings: 50, 80, 120, and 200 cm. The flow contraction rate Q/Q_b (where Q is the general discharge and Q_b is the discharge through the bridge opening under open-flow conditions) varied from 1.56 to 5.69 for the floodplain depth h_f = 7 and 13 cm, respectively; the Froude numbers varied from 0.078 to 0.134, R_c — from 7500 to 16010, and R_f — from 4390 to 14300, where R_c and R_f are the Reynolds numbers for the channel and floodplain, respectively; the slope of the flume was 0.0012. The sand was placed 1 m up and down the contraction point of the flume. The grain sizes were 0.24 and 0.67 mm, and the tests were performed with a uniform layer or with two layers of different thicknesses and grain sizes.

3 METHOD

3.1 Equilibrium depth of scour at elliptical guide banks

The scour depth at elliptical guide banks is equal to the equilibrium depth in the conditions when the local velocity becomes equal to the critical one. The local velocity at a plain river bed is found by the Bernoulli equation for two cross sections of the extreme unit streamline [6]. The discharge across the width of a scour hole before and after the development of scour is $Q_f=kQ_{se}$, where Q_f is the discharge across the width of a scour hole with the plain bed and Q_{se} is that with a depth h_{equil}

$$m \cdot h_{equil} \cdot h_f \cdot V_{l\,el} = k\left(m \cdot h_{equil} h_f \frac{m \cdot h_{equil}}{2} h_{equil} \right) V_{lt} \qquad (1)$$

where m is the steepness of the scour hole, h_{equil} is the depth of scour at the equilibrium stage, h_f is the depth of flow at the floodplain, $V_{l\,el}$ is the local velocity, and k is a coefficient of changes in discharge because of scour, which depends on the flow contraction [4]. The local velocity V_{lt} at an equilibrium stage of scour is determined from Eq. (1)

$$V_{lt} = \frac{V_{l\,el}}{k\left(1 + \frac{h_{equil}}{2h_f}\right)} \qquad (2)$$

The critical velocity V_{0t} at the equilibrium stage can be determined through the mean depth of flow $h_m = h_f(1+h_{equil}/2h_f)$ near elliptical guide banks at that stage:

$$V_{0t} = \beta \cdot 3.6 d_i^{0.25} h_f^{0.25} \left(1 + \frac{h_{equil}}{2h_f}\right)^{0.25} \qquad (3)$$

where β is a coefficient of reduction in the critical velocity due to vortex structures, d_i is the grain size of the bed materials, and $V_0=3.6d_i^{0.25}h_f^{0.25}$ is the critical velocity at the plain bed [7].

The scour at the equilibrium stage stops when the local velocity V_{lt} (Eq. 2) becomes equal to the critical velocity V_{0t} (Eq. 3)

$$\frac{V_{l\,el.}}{k\left(1+\frac{h_{equil}}{2h_f}\right)} = \beta \cdot 3.6 d_i^{\,0.25} h_f^{\,0.25} \left(1+\frac{h_{equil}}{2h_f}\right)^{0.25} \tag{4}$$

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

$$h_{equil} = 2h_f \left[\left(\frac{V_l}{\beta V_0} \right)^{0.8} - 1 \right] \cdot k_\alpha \cdot k_m \tag{5}$$

where k_α 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 floodplain depth, 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.

3.2 Equilibrium depth of scour at elliptical guide banks under stratified bed conditions

The geology of the river bed is complicate and usually is formed by layers with different thickness and grain sizes (Fig. 2).

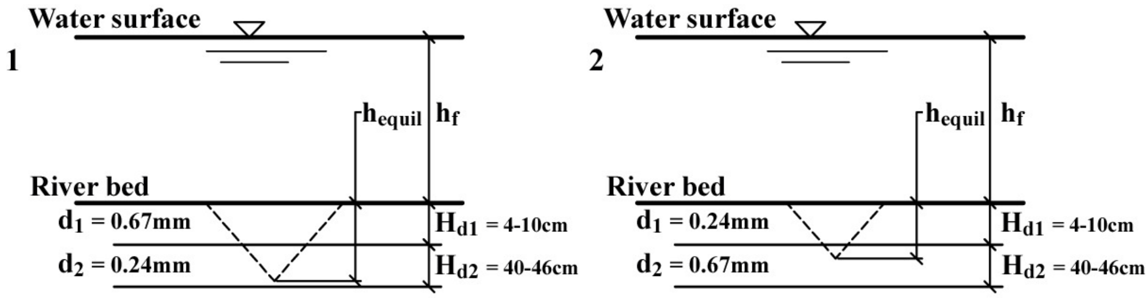

Fig. 2) Two layers with different test grain sizes

When the scour depth $h_{equil}<H_{d1}$, equation (5) can be used; however, when $h_{equil}>H_{d1}$, the scour develops in the second layer with a grain size d_2. If $h_{equil}>H_{d1} + H_{d2}$, 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 in the uniform layer. At the initial stage, the equilibrium scour depth h_{equil} is calculated by Eq. (5). When $h_{equil}>H_{d1}$, 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

$$V_{lt1} = \frac{V_{l\,el}}{k\left(1+\frac{H_{d1}}{2h_f}\right)} \tag{6}$$

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,

$$V_{01} = \beta 3.6 \cdot d_2^{\;0.25} h_f^{\;0.25}\left(1+\frac{H_{d1}}{2h_f}\right) \tag{7}$$

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.

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

$$h_{s2} = 2h_f\left[\left(\frac{V_{lt1}}{V_{01}}\right)^{0.8} - 1\right]\cdot k_\alpha \cdot k_m \tag{8}$$

At $h_{s2}<H_{d2}$, the scour stops, and the equilibrium scour depth is

$$h_{equil} = H_{d1} + h_{s2} \tag{9}$$

If $h_{s2}>H_{d2}$, the calculation could be continued using Eq. (8).

4 RESULTS

The test results are presented in Table 1. The EL 4-6 tests were performed with one uniform layer with a mean diameter of 0.24 mm, the EL16-18 tests with a mean diameter of 0.67mm, and the EUL 1-6 tests were carried out with two layers of different thickness with grain sizes d_1= 0.24 mm and d_2= 0.67 mm.

Tab. 2) Test results for elliptical guide banks

Test	$\frac{Q}{Q_b}$	d_1 (mm)	d_2 (mm)	H_{d1} (cm)	H_{d2} (cm)	t (h)	$h_{s\ test}$ (cm)	$h_{s\ calc}$ (cm)	$\frac{h_{s\ test}}{h_{s\ calc}}$	h_{equil} (d_1) (cm)	h_{equil} (d_2) (cm)	h_{equil} (*layers*) (cm)
EL4	3.66	0.24	-	50	-	7	7.6	8.40	0.905	10.43	-	-
EL5	3.87	0.24	-	50	-	7	11.0	11.00	1.000	14.10	-	-
EL6	3.78	0.24	-	50	-	7	14.0	13.51	1.036	17.65	-	-
EL16	3.66	0.67	-	50	-	7	6.1	5.60	1.084	5.90	-	-
EL17	3.87	0.67	-	50	-	7	8.4	8.35	1.005	8.91	-	-
EL18	3.78	0.67	-	50	-	7	12.2	10.50	1.162	11.78	-	-
EUL1	3.66	0.67	0.24	4	46	7	8.2	8.48	0.966	5.90	10.43	10.43

EUL2	3.87	0.67	0.24	7	43	7	10.7	10.85	0.986	8.91	14.10	14.10
EUL3	3.78	0.67	0.24	10	40	7	12.4	11.97	1.035	11.78	17.65	17.65
EUL4	3.66	0.24	0.67	4	46	7	5.6	5.74	0.975	10.43	5.90	5.90
EUL5	3.87	0.24	0.67	7	43	7	8.6	8.44	1.018	14.10	8.91	8.91
EUL6	3.78	0.24	0.67	10	40	7	11.4	11.03	1.033	17.62	11.78	11.78

The opening of the bridge model was 80 cm and the floodplain depth was 7 cm. The tests lasted for 7 hours. The scour depth developed in 7 hours was prolonged to an equilibrium stage by using the method elaborated by Gjunsburgs et al. [4]. The equilibrium scour depth in tests with uniform layer was respectively 10.43, 14.10, and 17.65 cm with mean grain-size diameters 0.24 mm and 5.90 cm and 8.91 cm and 11.78 cm with a 0.67 mm diameter. The Froude numbers of the open flow were 0.078, 0.104, and 0.124. The tests with two layers were performed for different thicknesses and grain sizes of layers. In the EUL1, EUL2, and EUL3 tests, the first and the second layers had grain sizes of 0.67 and 0.24 mm, respectively (Fig. 2). When the layer was scored and $h_s > H_{d1}$, the equilibrium scour depth, both determined in tests and calculated by Eq. (8), was the same if one layer had d_1 = 0.24 mm. This fact evidences the important role played by the grain size of the second layer, d_2 = 0.24 mm; the depth of scour increases rapidly in the second layer ($d_2 < d_1$) in spite of the presence of the upper layer with diameter d_1 = 0.67 mm. The calculated depth of scour with the grain size existing on the bed surface gives smaller values. In the EUL4, EUL5, and EUL6 tests, the first layer had the grain size d_1 = 0.24 mm and the next layer had d_2= 0.67 mm. When the first layer was scoured and $h_s > Hd_1$, the equilibrium depth of scour became equal to that found for one layer with the grain size 0.67 mm. The determined equilibrium depth of scour was smaller than that used in the formulae with d_1 = 0.24 mm on the surface.

5 CONCLUSIONS

The scour development in time and the equilibrium stage of scour at abutments and guide banks under stratified bed conditions have been studied. The method for computing the equilibrium depth of scour under these conditions is presented (Eq. 8). The method is confirmed by test results (Table 1).

According to the method and test results, the equilibrium depth of scour at elliptical guide banks strictly depends on the sequence of the bed layers with different grain sizes.

When the first uniform coarse sand layer is scoured $h_s > H_{d1}$ (Fig. 2), the equilibrium depth of scour becomes equal to its value achieved in the second uniform fine sand layer with a grain size d_2. If the first fine sand layer is scoured (Fig. 2), the equilibrium scour depth is equal to that in the second coarse sand layer (Table 1).

In the stratified bed conditions, the use of grain-size parameters of the river bed material on the surface for calculating the equilibrium scour depth yields incorrect results.

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