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SCOUR AT ENGINEERING STRUCTURES UNDER STRATIFIED BED: DEVELOPMENT IN TIME

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Abstract

The scour at abutments and elliptical and straight guide banks with a stratified bed under steady and unsteady clear-water conditions was studied. Tests were performed with uniform sand, standard deviation, one or two layers of different grain diameters, and different sequence and thickness of the layers. New methods for computing the depth of scour development in time and elliptical guide banks under stratified bed conditions are presented. Method are confirmed by tests results. At a stratified river bed, the most critical conditions for structures occur when a fine-sand layer lies under a coarse-sand layer. According to the results obtained in tests and by the method presented, the depth of scour is always greater when a fine-sand layer is under a coarse-sand layer(s). Using the mean grain size on the top of the river bed for calculating the scour depth, neglecting stratification, can lead to wrong results and possible damages and losses.

Key words

Clear-water conditions, scour, steady a unsteady flow, stratified bed, uniform sand.

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1 INTRODUCTION

The damage of the engineering structures in river flow because of scour at the foundations always leads to considerable economic and environmental losses. The scour at stratified bed conditions can be one of the reasons for failure of structures, but this phenomenon has not yet been studied well.

The influence of stratification on the scour depth near bridge structures is confirmed by Ettema [1], Raudkivi and Ettema [2], Kothyari [3], Kothyari et al. [4], Garde and Kothyari [5], FHWA-RD-99-188 [6],Melvile & Coleman [7],Gjunsburgs tal.[8],[9],[10],[11],[12],[13].

The aim of the present study is to elucidate influence of the river bed stratification on the scour depth at elliptical guide banks under clear water conditions.

The tests were carried out for different hydraulic conditions and uniform sands, with two layers and two mean size diameters, and their different sequence.

The differential equation of equilibrium for bed sediment movement in clear water is used, and a calculation method for the scour development in time at the head of elliptical guide banks in the stratified bed conditions is elaborated and confirmed by experimental data. This method allows one to calculate the scour depth in layers with different mean grain size, thickness, and sequence combination.

At a stratified river bed, the most critical conditions for engineering structures occur when a fine-sand layer lies under a coarse-sand layer. As soon as the coarse layer has been scoured and removed by the flow, the scour is rapidly developing in the next fine-sand layer. In this case, the dominant grain size for computing the depth of scour at foundations under stratified bed conditions is the mean diameter of grains of the second layer or of the next one, where the scour stops. According to the results obtained in our tests and by the methods presented, the depth of scour is always greater when a fine-sand layer is under a coarse-sand one. The calculation of scour depth near hydraulic structures in flow by using only the data on grain size on the top of the river bed and neglecting the stratification of the river bed can lead to wrong results and finally to considerable damages and losses.

2 EXPERIMENTAL SETUP

The tests were carried out in a flume 3.5 m wide and 21 m long. Experimental data flumes in the open flow conditions are presented obtained in in Table 1.

The flow distribution between the channel and floodplain was studied under open flow conditions. The rigid bed tests were performed to investigate changes in the velocity and water level in the vicinity of the embankment and at the head of the elliptical guide banks. During the sand-bed tests, we studied the scour development in time at a stratified bed, with different grain sizes in the first and second layers. The area 1m up and down at a bridge crossing model had a sand-bed for studying scour processes near the head of the elliptical guide banks.

The tests were performed for the contraction rate Q/Qb= 3.66-4.05 (where Q is the flow discharge and Qb is the discharge through the bridge opening under open-flow conditions).

Tab. 1) Tests data for open flow conditions

№	L	hf	V	Q	Fr	Rec	Ref
	cm	cm	cm/s	l/s			
L1	350	7	6.47	16.60	0.078	7500	4390
L2	350	7	8.58	22.70	0.102	10010	6060
L3	350	7	10.30	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
L9	350	13	9.90	47.10	0.087	14300	14300

The depth of water on the floodplain was 7 and 13 cm. The thickness of the layers with different grain sizes 0.24and 0.67mm with a standard deviation was equal to 4, 7, and 10cm. The Froude number in the open-flow conditions varied from 0.078 to 0.1243, densimetric Froude numbers –from 0.62 to 1.65, and the slope of the flume was 0.0012. The opening of the bridge model was 80cm. The condition that FrR=Frf was fulfilled, where FrR and Frf are the Froude numbers for the plain river and for the flume, respectively. The tests in the flume lasted for 7 hours. The development of scour was examined for different flow parameters in time intervals within one 7-h step and within two steps, 7 hours each. 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, was calculated according to the Latishenkov (1960) 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 SCOUR DEVELOPMENT IN TIME UNDER STRATIFIED RIVER BED CONDITIONS

At the head of the guide banks, the concentration of streamlines, a sharp drop in water level, and a rapid increased in velocity were observed.

To calculate the local velocity, we used the Bernoulli equation for two cross sections of a unit streamline. The local velocity at the head of the guide banks for the plain river bed was found from the formula

$$V_{lel} = \varphi\sqrt{2g\Delta h} \tag{1}$$

where φ = velocity coefficient; Δh = backwater value [14].

The critical velocity at the plain river bed is determined as:

$$V_0 = \beta \cdot 3.6 d_i^{\,0.25} h_f^{\,0.25} \tag{2}$$

where d = mean grain size on the top of the river bed; h_f = water depth on the floodplain.

In modeling the scour development in time it was found that the discharge across width of the scour hole before and after the development the scour hole is $Q_f=Q_{se}$, where Q_f is the discharge across width of the scour hole with the plain bed and Q_{se} is the discharge with the equilibrium depth h_{equil}.

$$mh_{equil}h_f V_{lel} = \left(mh_{equil}h_f + \frac{mh_{equil}}{2} h_{equil} \right) \cdot V_{lt} \tag{3}$$

where m = the steepness of scour hole, mh_{equil} = width of the scour hole, V_{lel} = local velocity with a plain bed, h_f = water depth in the floodplain and V_{lt} = local velocity at the equilibrium scour depth h_{equil}.

The local velocity V_{lt} can be determined from Equation 3:

$$V_{lt} = \frac{V_{l\,el}}{\left(1 + \frac{h_{equil}}{2h_f}\right)} \tag{4}$$

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

$$V_{ot} = \beta \cdot 3.6 d_i^{0.25} h_f^{0.25} \left(1 + \frac{h_{equil}}{2h_f}\right)^{0.25} \tag{5}$$

where β = reduction coefficient of the critical velocity of the bended flow determined by using the Rozovskiy [15] approach.

The local velocity on the surface of the second layer is found by the formula:

$$V_{lt2} = \frac{V_{l\,el}}{1 + \frac{H_{d1}}{2h_f}} \tag{6}$$

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

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

$$V_{ot2} = \beta 3.6 \cdot d_2^{0.25} h_f^{0.25} \left(1 + \frac{H_{d1}}{2h_f}\right)^{0.25} \tag{7}$$

The differential equation for equilibrium bed-sediment movement under clear water conditions at the head of elliptical guide bank has the form:

$$\frac{dv}{dt} = Q_s \tag{8}$$

where $v = 1/5\pi m^2 h_s^3$ = volume of the scour hole; t = time; Q_s = sediment discharge out of the scour hole; h_s = depth of scour; m = scour hole steepness.

The left-hand part of Equation12 can be written as:

$$\frac{dv}{dt} = \frac{3}{5}\pi m^2 h_s^3 \frac{dh_s}{dt} = a h_s^2 \frac{dh_s}{dt} \tag{9}$$

The sediment discharge at the initial stage was determined by the Levi (1969) formula:

$$Q_s = AB \cdot V_{lel}^4 \tag{10}$$

where $B = mh_s$ = width of the scour hole; V_l= local velocity at the head of the guide bank with a plain bed; A = parameter in the Levi [16] formula.

The parameter A at the plain river bed was determined as:

$$A = \frac{5.62}{\gamma}\left(1 - \frac{\beta V_o}{V_{lel}}\right)\frac{1}{d_i^{0.25} \cdot h_f^{0.25}} \tag{11}$$

where γ = specific weight of sediments; $V_o = 3.6 d_i^{0.25} h_f^{0.25}$= critical velocity; d_i = grain size of the bed materials; h_f = water depth in the floodplain.

The sediment discharge upon development of the scour is:

$$Q_{si} = A_i \cdot mh_s \cdot V_{lt}^4 = b\frac{h_s}{\left(1+\dfrac{h_s}{2h_f}\right)^4} \tag{12}$$

where V_{lt} = local velocity at the depth of scour h_s, $b=A_i m V_l^4$.

The parameter $A_i$with scour depth developing in time was determined as:

$$A_i = \frac{5.62}{\gamma}\left[1-\frac{\beta V_o}{V_{lel}}\left(1+\frac{h_s}{2h_f}\right)^{1.25}\right]\cdot\frac{1}{d_1^{0.25}\cdot h_f^{0.25}\left(1+\dfrac{h_s}{2h_f}\right)^{0.25}} \tag{13}$$

$$\frac{\beta V_{ot}}{V_{lt}} = \frac{\beta V_o}{V_l}\left(1+\frac{h_s}{2h_f}\right)^{1.25}$$

Taking into account Equations 9 and 12, Equation 8 can be written as:

$$ah_s^2\frac{dh_s}{dt} = b\frac{h_s}{\left(1+\dfrac{h_s}{2h_f}\right)^4} \tag{14}$$

Separating and integrating the variables yields:

$$t = D_i\int_{x_1}^{x_2} h_s\left(1+\frac{h_s}{2h_f}\right)^4 dh_s \tag{15}$$

where $$D_i = \frac{a}{b} = \frac{\pi\cdot m}{1.67A_i\cdot V_l^4}$$

$$N_i = \frac{t_i}{4D_i h_f^2} + N_{i-1} \tag{16}$$

where $N_i=1/6x_i^6-1/5x_i^5$;t_i = time interval.

Calculating the value of N_i, we find x_i and scour depth:

$$h_s = 2h_f(x-1)\,k_m k_\alpha \tag{17}$$

where k_m= coefficient depending on the side-wall slope of the guide bank; k_α= coefficient depending on the angle of flow crossing.

To find the depth of scour in the second layer with a grain size d_2, we must know the local V_{lt} and critical V_{0t} velocities and parameters Ai_2, Di_2, Ni_2, Ni_1, x_2 and h_s in the layer H_{d2} with grain size d_2.

The parameter Ai in the second layer is determined as:

$$A_{i2} = \frac{5.62}{\gamma}\left[1-\frac{\beta V_{02}}{V_{lel}}\left(1+\frac{H_{d1}}{2h_f}\right)^{1.25}\right]\cdot\frac{1}{d_2^{0.25}\cdot h_f^{0.25}\left(1+\frac{H_{d1}}{2h_f}\right)^{0.25}} \tag{18}$$

where $V_{02}=\beta 3.6 d_2^{0.25} h_f^{0.25}$ 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.

D_{2i} is calculating by using A_{2i}:

$$D_i = \frac{a}{b} = \frac{\pi \cdot m}{1.67 A_i \cdot V_l^4} \tag{19}$$

After integrating Equation 15 with new variables, we obtain:

$$N_2 = \frac{t_i}{4D_2 h_f^2} + N_1 \tag{20}$$

Calculating the value Ni_2, we find x_2 and the scour depth in the next layer:

$$h_{s2} = 2\, h_f\, (x_2 - 1)\, k_m \cdot k_\alpha \tag{21}$$

4 RESULTS

The flow pattern at the head of the elliptical guide banks was modified. It was found in the testthat the flow velocities reduce almost to zero when approaching the bridge crossing construction and then gradually increase. 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. It is the local velocities near the guide banks that form the scour hole.

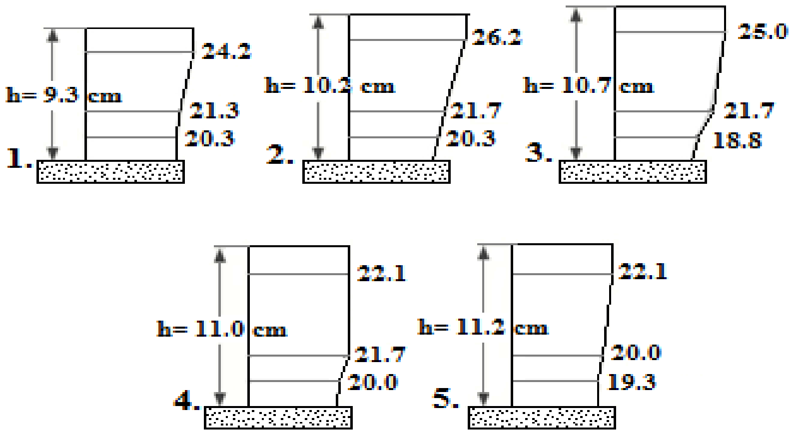

Fig. 1) Vertical distribution of velocities in time at the head of guide bank during the scour in 30 (1), 80 (2), 240 (3), 360 (4), and 420 min (5); test EL3.

With development of scour in time, under steady flow conditions, the local velocities reduces and becomes equal in vertical distribution at different depth of scour (Figure1).

Figure 2 illustrates the scour depth and respective variations in the local Vlt and critical V0t velocities, as measured experimentally and calculated in one layer with uniform sand.

Depending on the sequence of layers, the critical velocityV0t either increases, when the grains of the second layer are coarser, or reduces, when these grains are finer. The local velocity Vlt reduces more raidly if the second layer has grains of a smaller size.

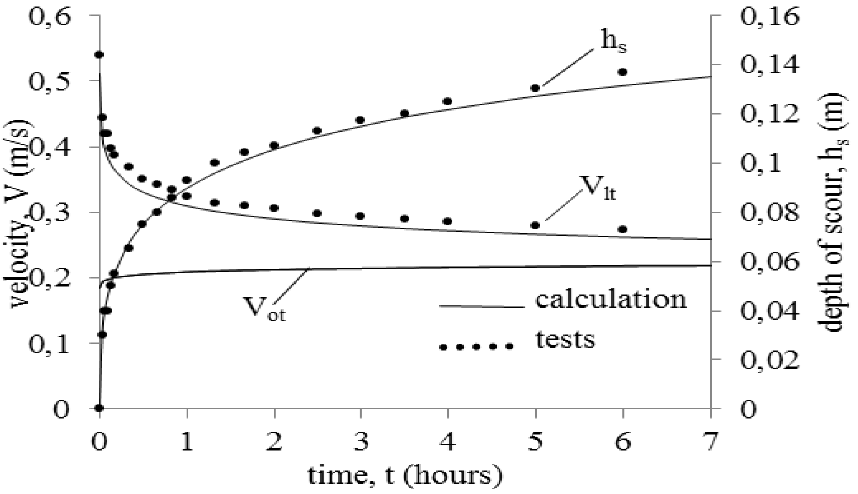

Fig. 2) Changes in scour depth and in the local and critical velocities V_{lt} and βV_0 varying with time under steady flow; one-sand layer; test EL 6.

Figures3 and 4 present the scour depth and variations in the localVlt and critical V0t velocitieswith time, ata different sequence of the layers –the layer with fine grains on the top of the coarse-grain layer, and vice versa.

Figure3 shows, as an example, the scourdepth and the developmentof local and critical velocities in time (test EUL5), in the first layer with d1=0.24 mm and in the second layer with d2= 0.67mm.

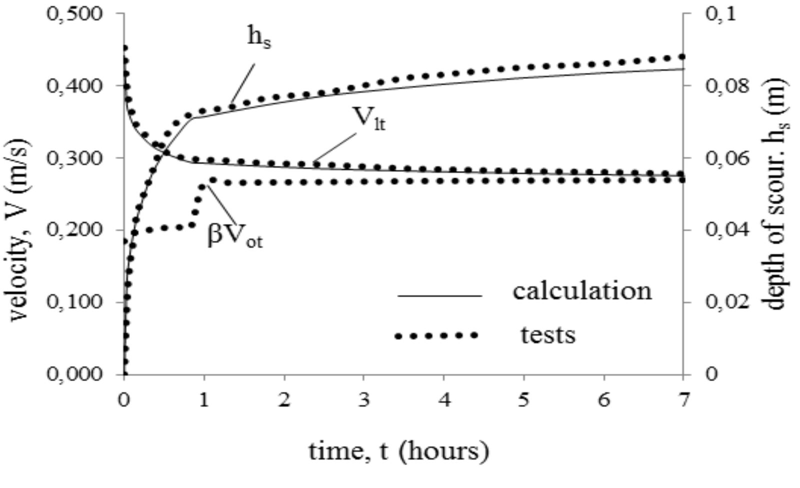

Fig. 3) Changes in scour depth and in the local V_{lt} and critical βV_{0t} velocities; $d_1 = 0.24$ mm in the first layer and $d_2 =$ 0.67mm in the second one:test EUL 5

The depth of scour develops rapidly in fine-sand layer; in the second, coarse-sand layer it continues, but more slowly. On the surface of the second layer, the critical velocity sharply increases with increasing grain size, and then the depth of scour development decreases.

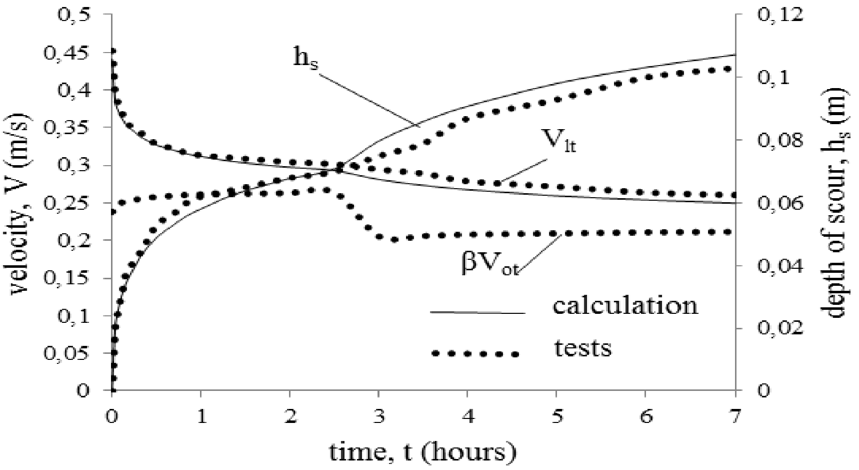

Fig. 4) Changes in scour depth and in the local V_{lt} and critical βV_{0t} velocities, with d_1 = 0.67 mm in the first layer and d_2 = 0.24 mm in the second one; test EUL2

In Figure 4, the scour depth andthedevelopment of local and critical velocities in time at adifferent sequence of the layers are shown (test EUL2).

The grain diameter was d1= 0.67 mm in the first layer and d2= 0.24 mm in the second one. It took more time to reach the surface of the second layer Hd1= 7 cm than in the previous test, EUL5, but the scouring in the second layer developed at a higher speed. On the top of the second layer, the critical velocity rapidly reduced owing to the decreased grain size (d2= 0.24 mm).

Table 2 presents a comparison between experimental and calculated data for the depth of scour with different sequence and thickness of the layers The values of scour depth measured in tests and computed by the method suggested agree satisfactorily.

On the border of two layers with different grain size,d1/d2or d2/d1, the scour development changes its intensity: the rapid scouring continues in the following fine-sand layer or slows down if the second layer is coarse. scour with different sequence and thickness of the layers agree satisfactorily.

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According to experimental results and the method proposed, the scour depth is greater if the coarse-grain layer lies on the top of the river bed and a fine-grain layer goes after it, and the depth is smaller if the fine-grain layer lies on the surface of the river bed (Table 2).

5 CONCLUSIONS

It was found that the scour depth depends on the river bed stratification, as well as on thethickness and sequence of the layers. The most criticalconditions for structures occur whea fine-sand layer occurs under a coarse-sand layer.

Tab. 2) Comparison between experimental and calculated values of scour depth under stratified bed conditions

Test	hf	d1	d2	H1	H2	hs test	hscalc	$\frac{h_{s\ test}}{h_{s\ alc}}$
	cm	**mm**	**mm**	**cm**	**cm**	**cm**	**cm**	
EUL1	7	0.67	0.24	4	46	8.0	8.46	0.86
EUL4	7	0.24	0.67	4	46	5.6	5.74	0.98
EUL2	7	0.67	0.24	7	43	10.3	10.73	0.96
EUL5	7	0.24	0.67	7	43	8.6	8.44	1.04
EUL3	7	0.67	0.24	10	40	12.4	12.13	1.02
EUL6	7	0.24	0.67	10	40	11.4	11.12	1.02
EUL7	13	0.24	0.67	4	46	6.6	6.97	0.89
EUL10	13	0.67	0.24	4	46	10.0	10.88	0.92
EUL8	13	0.24	0.67	7	43	9.4	9.99	0.95
EUL11	13	0.67	0.24	7	43	12.6	13.38	0.94
EUL9	13	0.24	0.67	10	40	13.6	14.58	0.93
EUL12	13	0.67	0.24	10	40	17.6	17.82	0.99

As soon as the coarse layer has been scoured, the scour is rapidly developing in the next fine-sand layer. In this case, the dominant value of grain size for computing the depth of scour at foundations under stratified bed conditions is the mean diameter of the second layer or of the next one, where the scour stops. According to the results obtained in tests and by the method presented, the depth of scour is alwaysgreater when a fine-sand layer is under a coarse-sand layer(s). The calculation of scour depth near hydraulic structures in flow by using only the data onthe mean grain size on top of the river bed and neglecting the stratification of the river bed can lead to wrong results and finally to considerable damages and losses.

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