Stratified bed conditions impact on scour development at engineering structures

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Abstract

River flow contraction by engineering structures (intakes, embankment, abutments, spurs, guide banks) to flow leads to flow pattern modification, concentration of streamliners, sharp drop in water level, local increase in velocity, and development of scour hole. Damages or failure of engineering structures in flow because scour at the foundations under stratified bed conditions is an important problem, which is not studied well. The differential equation of equilibrium for the bed sediment movement for clear-water conditions is used and a method for computing the scour development with time at the elliptical guide banks is elaborated. The method is confirmed by experimental data. This method allows one to calculate the scour depth development under stratified bed conditions with different thickness and sequence of the layers. The most critical conditions for structures occur when a fine-sand layer is 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 calculation the depth of scour, neglecting stratification, can lead to the wrong results and possible damages and losses.

Keywords: scour, stratified bed, depth of scour, guide banks.

Introduction

Contraction of the river flow by bridge crossings leads to changes in the flow pattern and to a scour at the bridge piers, abutments, and guide banks. Elliptical guide banks are used to guide the flow and sediments in and out of the bridge opening, to reduce the flow separation at the alignment of the bridge, and to remove scour hole from the abutment and embankment. The concentration of streamlines, a local increase in velocity, and the development of a scour hole were observed at the upstream head of the elliptical guide banks.
During the past few decades, the equilibrium depth of scour at bridge piers, and spur dikes were studied by different authors: Breusers and Raudkivi (1991), Hoffmans and Verheij (1997), Melville and Coleman (2000), and May et al. (2002) and others. Scour at the abutments by Kothyari and Ranga Raju (2001), Hager et al. (2002), Armitage and McGahey (2004), Yanmaz and Celebi (2004), Gjunsburgs et al. (2001, 2004, 2006, 2010) and others. The influence of stratification on the scour depth near bridge structures is confirmed by Ettema (1980), Raudkivi and Ettema (1983), Kothyari et al. (1992), Garde and Kothyari (1998), FHWA-RD-99-188 (1999), Gjunsburgs et al.(2010).

Elliptical guide banks are used to guide the flow and sediments in and out of the bridge opening, to reduce the flow separation at the alignment of the bridge, and to remove scour hole from the abutment and embankment .The concentration of streamlines, a local increase in velocity, and the development of a scour hole were observed at the upstream head of the elliptical guide banks.

The differential equation of equilibrium for bed sediment movement in clear water was used, and a calculation method for the scour development at guide banks at stratified bed conditions is elaborated and confirmed by experimental data. This method allows one to calculate the scour depth development under stratified bed conditions, with different thickness and sequence of the layers. The most critical conditions for structures occur when a fine-sand layer is 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 calculation the depth of scour, neglecting stratification, can lead to the wrong results and possible damages and losses.

Experimental setup

The tests were carried out at the Transport Research Institute (Russia) in a flume 3.5 m wide and 21 m long.

Different forms of guide banks were studied by Latishenkov (1960), and he recommended to use elliptical guide banks as most acceptable in practice. The dimensions of the upper part of the elliptical guide bank, namely the turn and the length, were calculated according to the Latishenkov (1960) method, and they were found to depend on the contraction of the flow and the width of the main channel. The length of the lower part of the guide bank was assumed to be half of the calculated upper part.

The tests were carried out in the open flow conditions for studying the flow distribution between the channel and the floodplain with rigid and sand beds.

The tests with a rigid bed were performed for different flow contractions and Froude numbers in order to investigate the velocity and the changes in water level in the vicinity of the embankment, along it, and near a modeled elliptical guide bank.

The aim of the tests with a sand bed was to study the scour processes, the changes in the velocity with time, the influence of different hydraulic parameters, the contraction rate of the flow, the grain size of the bed material, and the scour development in time.

The openings of the bridge model were 50, 80, 120 and 200 cm. The contraction rate of the flow Q/Q_b (where 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 respectively from 1.56 to 5.69 at a depth of floodplain of 7 and 13 cm, and the Froude numbers varied from 0.078 to 0.134; the slope of the flume was 0.0012.

The tests with a sand bed were carried out in the clear-water conditions. The sand was placed 1 m up and down the contraction of the flume. The mean size of grains was 0.24 and 0.67 mm. The condition that $Fr_R= Fr_f$ was fulfilled, where Fr_R and Fr_f were the Froude numbers for the plain river and for the flume, respectively. The tests in the flume lasted for 7 hours, the vertical 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-h step and within two steps of the hydrograph, 7 hours each.

Table 1. Experimental data for open flow conditions in 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	0.0780	7500	4390
L2	350	7	8.58	22.70	0.0103	10010	6060
L3	350	7	10.30	23.60	0.1243	12280	7190
L4	350	7	8.16	20.81	0.0984	10270	5590/5660
L5	350	7	9.07	23.48	0.1094	11280	6140/6410
L6	350	7	11.10	28.13	0.1339	13800	7550/7840
L7	350	13	7.51	35.48	0.0665	13700	9740
L8	350	13	8.74	41.38	0.0756	16010	11395
L9	350	13	9.90	47.10	0.0876	14300	14300

At stratified bed conditions the tests were carried out with one flood plain model and one side contraction of the flow .the tests were performed for contraction rate $Q/Q_b= 3.66\text{-}4.05$ (where *q* is the flow discharge and Q_b is the discharge through opening under open-flow conditions). thickness of the layers with different grain size 0.24mm and 0.67mm, with standard deviation, was equal 4, 7 and 10cm. the Froude number at open-flow conditions varied from 0.078 to 0.1243, densimetric Froude numbers – from 0.62 to 1.65,the slope of the flume was 0.0012. The opening of the bridge model was 80cm. 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 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 accepted half of the upper part.

Method

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

$$\frac{dW}{dt} = Q_s \tag{1}$$

where W is the volume of the scour hole, t is time, and Q_s is the sediment discharge out of the scour hole.

In different tests, it was found that the shape of a scour hole is not changing and volume can be found by the equation:

$$W = \frac{1}{5}\pi m^2 h_s^3 \tag{2}$$

where m is the steepness of the scour hole and h_s is the depth of scour.

The left-hand part of Equation 1 can be written in the form:

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

where a = 3/5 πm^2.

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

$$Q_s = ABV_l^4 \tag{4}$$

where $B = mh_s$ is the width of a scour hole, V_l is the local velocity at the head of elliptical guide bank, and A is a parameter in the Levi (1969) formula.

The sediment discharge upon development of the scour is given by:

$$Q_s = Amh_s V_l^4 = b\frac{h_s}{\left(1+\frac{h_s}{2h_f}\right)^4} \tag{5}$$

where $b = AmV_l^4$.

Taking into account Equations 3 and 5, 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 and integrating the variables, we have:

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

After integration with new variables, $x = 1 + h_s/2h_f$, $h_s = 2h_f(x – 1)$, and $dh_s = 2h_f dx$, we have:

$$N_i = \frac{t_i}{4D_i h_f^2} + N_{i-1} \tag{8}$$

where $N = 1/6x_i^6 – 1/5x_i^5$ and t_i is the time interval.

Calculating the value of N_i, we find x_i and the depth of scour at the end of time interval:

$$h_s = 2h_f (x-1) k_m k_s k_\alpha \tag{9}$$

where k_m is a coefficient depending on the side-wall slope of the abutment (Yaroslavcev 1956), k_s is a coefficient depending on the abutment shape, and k_α is a coefficient depending on the angle of flow crossing (Richardson & Davis 1995).

To determine the development of scour depth during the flood, the hydrograph was divided into time steps with duration of 1 or 2 days, and each time step was divided into time intervals up to several hours. In the laboratory tests, the time steps were divided into 20 time intervals. For each time step, the following parameters must be determined: depth of water in the floodplain, contraction rate of the flow, maximum backwater, grain size, thickness of the bed layer with d, and specific weight of the bed material. As a result, we have V_l, V_0, A, D, N_i, N_{i-1}, and h_s at the end of time intervals and finally at the end the time step. For the next time step, the flow parameters changed because of the flood and the scour developed during the previous time step.

Under stratified bed conditions the parameter Ai_2 on the second layer is determinate as:

$$A_{2i} = \frac{5.62}{\gamma}\left[1 - \frac{\beta V_{02}}{V_{lel}}\left(1 + \frac{H_{d1}}{2h_f}\right)^{1.25}\right]\frac{1}{d_2^{0.25}\cdot h_f^{0.25}\left(1 + \frac{H_{d1}}{2h_f}\right)^{0.25}} \tag{10}$$

where $\frac{\beta V_{ot}}{V_{lt}} = \frac{\beta V_o}{V_l}\left(1 + \frac{h_s}{2h_f}\right)^{1.25}$,$V_{02}=\beta 3.6 d_2^{0.25} h_f^{0.25}$ 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.

The value of D_{2i} is calculating by using A_{2i} :

$$D_{2i} = \frac{a}{b} = \frac{\pi \cdot m}{1.67 A_{2i} \cdot V_{lel}^4} \tag{11}$$

After integrating Equation 19 with new variables, we obtain:

$$N_{2i} = \frac{t_i}{4 D_{2i} h_f^2} + N_1 \tag{12}$$

Calculating the value Ni_2, we find x_{i2} and the scour depth in the next layer:

$$h_{s2} = 2\, h_f\, (x_{i2} - 1)\, k_m \cdot k_\alpha \tag{13}$$

$hs_2 > Hd_2$, the calculations of scour depth should be continued, by using Equations 12 and 13.

Results

According to the tests at the head of the elliptical guide banks, the concentration of streamlines, a sharp drop in water level, and a rapid increase in velocity were determined. The local velocity at the head of guide bank was studied in tests with a rigid bed, at different contraction rates, and for different Froude numbers of the flow.

The local velocity was found from the formula (Gjunsburgs et al., 2004):

$$V_{lel} = \varphi_{el}\sqrt{2g\Delta h} \tag{14}$$

The critical velocity at the plain river bed is determined (Studenitcnikov, 1964) as:

$$V_0 = 3.6 d_i^{0.25} h_f^{0.25} \tag{15}$$

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

At homogeneous sand layer and at steady flow conditions (test EL5) , with increase the depth of scour, local velocity V_{lt} reduces and critical one V_{ot} increases (Figures 1,2).Velocities ratio ßVot/Vlt is increasing in time and approaching to one (Figure 3). Parameter A is reducing and D is increasing in time, sediment discharge out of scour hole is reducing(Figures 4,5,8) .According to test results and method of computing scour development in time, deformation of river bed stops as local velocity becomes to critical one.

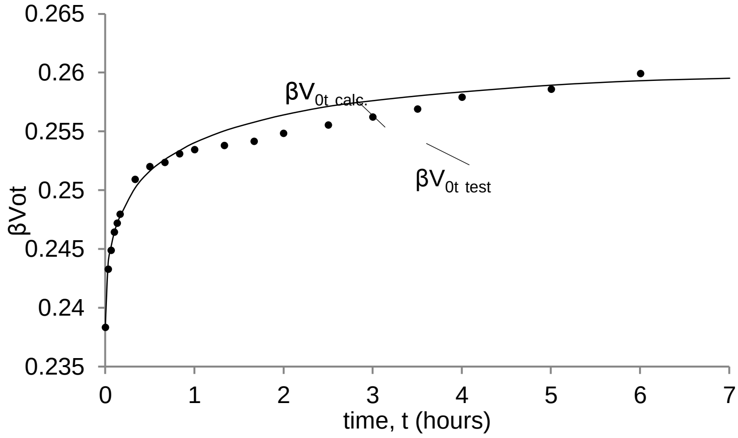

Figure1. Critical velocity development in time

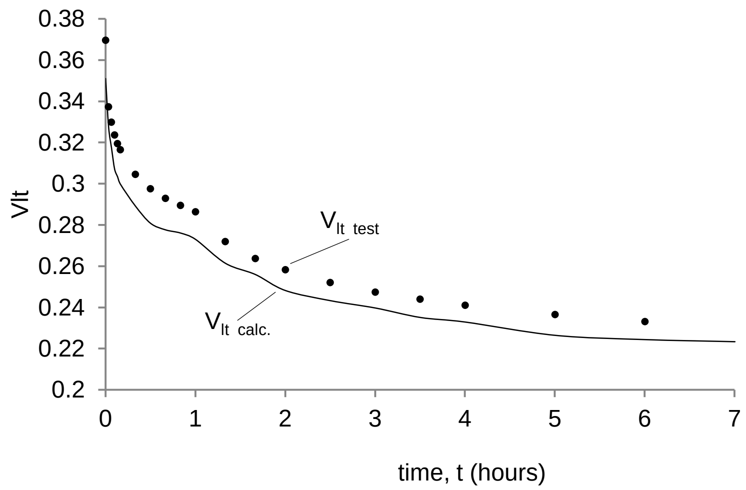

Figure 2. Local velocity development in time

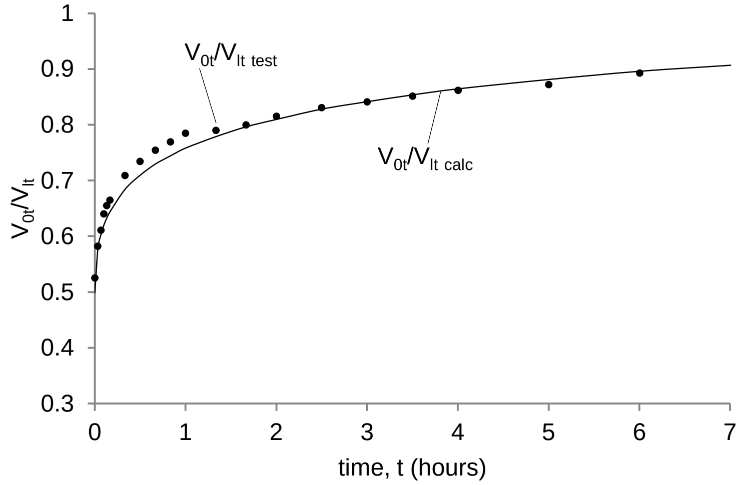

Figure 3. Velocities ratio ßVot/Vlt development in time

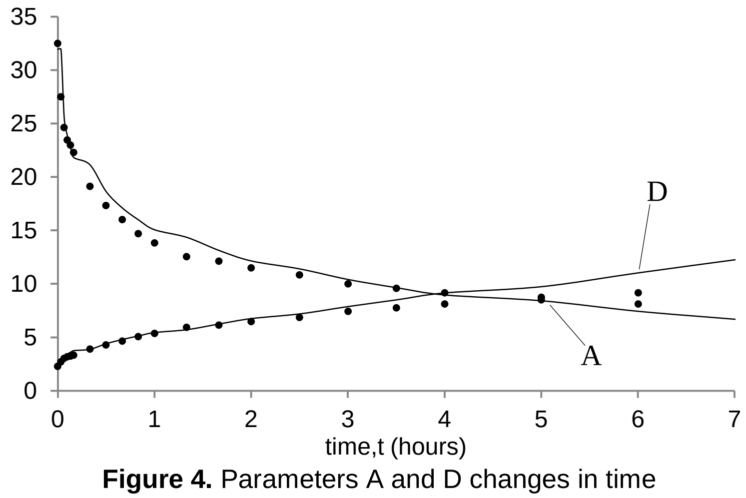

Figure 4. Parameters A and D changes in time

Under stratified bed conditions, depending on the sequence of the layers, the critical velocity βV_{0t} either increases, when the grains of the second layer are coarser, or reduces, when these grains are finer. The local velocity V_{lt} reduces more rapidly if the second layer has grains of a smaller size. With grain size reduction in the second layer the critical velocity reduces (Figure 6), and increases when grain size increases (Figure 7).

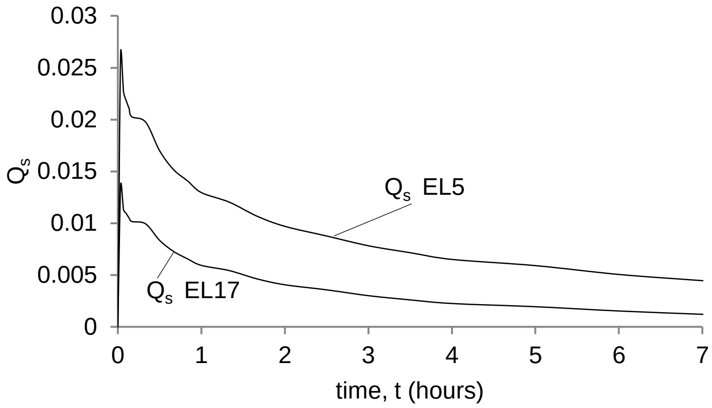

Figure 5. Sediment discharge out of scour hole changes in time; test EL5 with d= 0,24 mm, and test EL17 with d= 0,67mm.

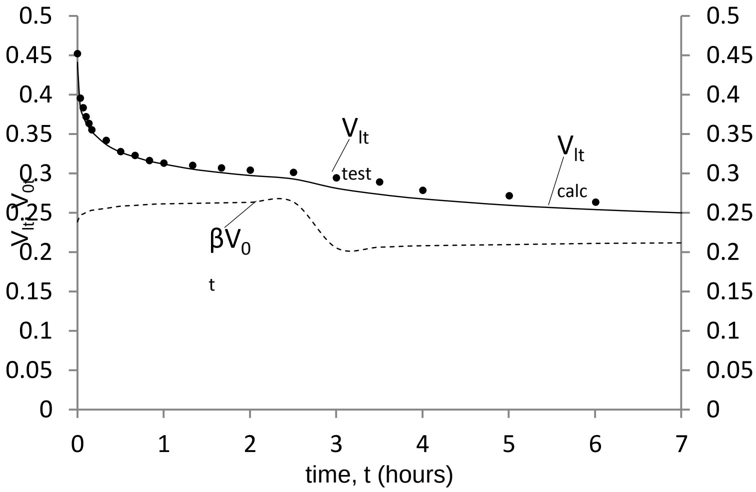

Figure 6. Local and critical velocities development in time under stratified bed conditions: with: first layer d_1=0,67mm and second one with d_2=0,24mm.

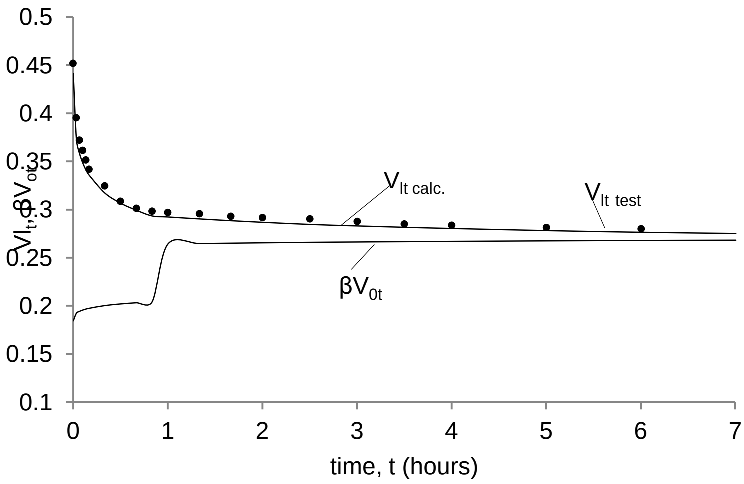

Figure 7. Local and critical velocities development in time under stratified bed conditions: with: first layer d_1=0,24mm and second one with d_2=0,67mm.

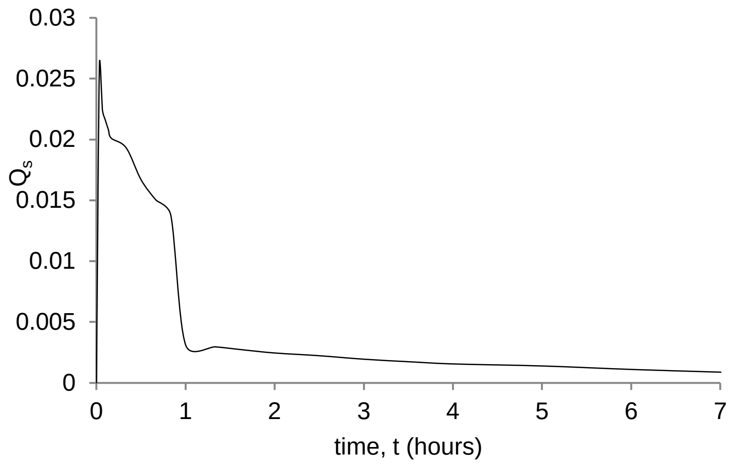

Figure 8. Sediment discharge out of scour hole changes in time under stratified bed with first layer d_1=0,24mm and second one with d_2=0,67mm, test EUL 5.

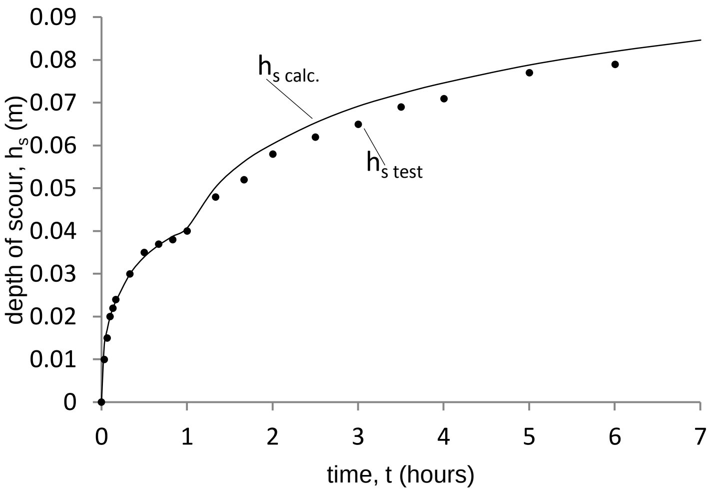

Figure 9. Scour development within time under stratified bed: first layer with d_1=0,67mm: and second layer with d_2=0,24mm

When fine sand layer is on the coarse sand layer, the depth of scour is less, but when fine sand layer under coarse sand layer the depth of scour is always is greater .When first layer is scoured away, depending on the grain size of the second layer, depth of scour is development in time is reducing or rapidly is increasing .The most critical conditions for structures occur when a fine-sand layer is under a coarse-sand layer coarse sand layer (Figure 9). 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 calculation the depth of scour, neglecting stratification, can lead to the wrong results and possible damages and losses.

Conclusion

At the upstream head of the elliptical guide bank, a streamline concentration, a local increase in velocity, vortex structure, increased turbulence, and the development of a scour hole are observed. The failure of guide banks because of scour leads to the flow redistribution and an unpredicted scour at the alignment of the bridge crossing; as a result, it can be the reason for failure of piers and/or abutments. The differential equation of equilibrium for the bed sediment movement for clear-water conditions is used and a method for computing the scour development with time at the elliptical guide banks is elaborated. The method is confirmed by experimental data. This method allows one to calculate the scour depth development under stratified bed conditions. The most critical conditions for structures occur when a fine-sand layer is 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 calculation the depth of scour, neglecting stratification, can lead to the wrong results and possible damages and losses.

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