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Effect of the river bed stratification on scour at guide banks

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ABSTRACT: *The failure of guide banks because of scour at stratified bed conditions leads to the flow redistribution and an unpredicted scour at the alignment of the bridge crossing; as a result, this can be the reason for failure of piers and/or abutments. In spite of the importance and complexity of the phenomena, the equilibrium stage of scour at the elliptical guide banks under stratified bed has not been studied yet. Based on the condition that at an equilibrium stage of scour is when the local velocity becomes equal to the critical one, formulas for calculating the equilibrium depth of scour at the head of elliptical guide banks at uniform sand and stratified bed is elaborated. The most critical conditions for structures is when fine-sand layer is under coarse-sand layer. When the coarse layer is scoured away, the depth of scour is rapidly developing in the next fine-sand layer. In this case, the dominant grain size for calculating the depth of scour under stratified bed conditions is the mean diameter of the second layer or of the next one, where the scour stops. According to the analysis results the depth of scour is always greater when a fine-sand layer is under coarse-sand layer(s.) The calculation of scour depth near hydraulic structures in flow by using the grain size on the top of the river bed and neglecting the stratification can lead to wrong results and finally to considerable damages and losses. An analysis of the results shows that the equilibrium depth of scour depends on the hydraulic and river bed parameters: contraction rate of the flow, Froude number of the open flow, grain size of the bed material, the stratified bed conditions, the local velocity, shape of the guide banks, the flood probability, water depth on the floodplain, the angle of flow crossing, and the slope of the side wall of the guide bank.*

Key words: scour, stratified river bed, guide banks, local velocity

I INTRODUCTION

At the head of the elliptical guide banks, a streamline concentration, a local increase in velocity, a vortex structures, an increased turbulence, and the development of a scour hole are observed.

The size, shape, length, and other parameters of guide banks were studied by different authors: Latishenkov (1960), Rotenburg (1965), Neil (1973), Breadley (1978), Richardson and Simons (1984), Lagasse et al. (1999) and others. The scour development with time at the abutments, elliptical and straight guide banks during multiple floods was investigated by Gjunsburgs et al. (2001, 2004, 2006, 2007, 2008).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). In spite of the problem importance, the scour at the stratified bed conditions near guide banks is not studded yet. Unpredicted scour under stratified bed conditions can be the reason of the structures failure.

The local velocity with vortex structures forms a scour hole near the guide banks. It was found in tests that the local velocity depends on the contraction rate of the flow and the maximum value of backwater; it reduces due to scour development in time. The critical velocity depends on the depth of flow and grain size of bed materials; it increases during scour development in time. In the present study, a formula for calculating the local velocity and its changes during the scour is proposed and confirmed by tests.

The equilibrium depth of scour at uniform sand, and stratified bed was when the local velocity becomes equal to the critical one. The method of scour development with time elaborated by Gjunsburgs et al. (2006, 2007) confirms the equilibrium stage of scour in the conditions $V_{lt}= \beta V_{0t}$ (where V_{lt} and V_{0t} are the local and critical velocities, respectively) at the end of scour.

Method for computing equilibrium depth of scour at stratified bed conditions is presented. The most critical conditions for structures occur when a fine-sand layer is under a coarse-sand layer. When the coarse layer is scoured, the depth of scour is rapidly developing in the next fine-sand layer. In this case, the dominant grain size for computing the depth of scour under stratified bed conditions is the mean diameter of the second layer or the next one where scour stops.To use for calculation depth of scour the grain size which is top of the river bed and neglecting stratification can lead to wrong results and finally to considerable damages and losses.

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

Test	L	h_f	V	Q	Fr	Re_c	Re_f
	cm	cm	cm/s	l/s			
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	28.31	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

Table1: Experimental Data for Open Flow Conditions in a Flume

During the sand-bed tests at uniform bed conditions, we studied the changes in the velocities and scour depth with time, the effect of different hydraulic parameters, the flow contraction rate, the grain size of the bed material, and the scour process. The tests were performed for the following openings of the bridge model: 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 through the bridge opening under open-flow conditions) varied respectively from 1.56 to 5.69, for the floodplain depth 7 and 13 cm, and the Froude numbers varied from 0.078 to 0.134; the slope of the flume was 0.0012.

During the sand-bed tests development in time at stratified bed conditions, we studied the scour with different grain sizes for the first and the second layers. The area 1m up and down at the bridge crossing model had a sand-bed for studying scour process near the head of the elliptical guide banks. The tests with stratified bed conditions 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 the bridge opening under open-flow conditions). Thickness of the layers with different grain size 0.24mm and 0.67mm, with standard deviation, were equal 4, 7 and 10cm. The Froude number at open-flow conditions varied from 0.078 to 0.1243 and densimetric Froude numbers –from 0.62 to 1.65.The sand-bed tests were carried out under clear water conditions..

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 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 and with two identical or different floodplain widths and two side contractions. The position of the main channel was varied for different tests.

The dimensions of the upper part of an elliptical guide bank, namely the turn and the length, were calculated according to the Latishenkov (1960) method, and were found to depend on the flow contraction and the main channel width. The length of the lower part of the guide bank was assumed to be half of the calculated upper part.

According to the tests results, with increase in the scour depth, the local velocity under steady flow conditions reduces, and the critical velocity increases

III METHOD

The local velocity with vortex structures forms a scour hole at the head of the elliptical guide banks. To calculate the local velocity, we used the Bernoulli equation for two cross sections of the unit streamline:

$$V_{l\,el} = \varphi_{el}\sqrt{2g\Delta h} \qquad (1)$$

where V_{lel} is the local velocity at the plain bed, φ_{el} is a velocity coefficient depending on the contraction rate of the flow (Fig.1), and Δh is the maximum backwater value(Rotenburg et al.,1965):

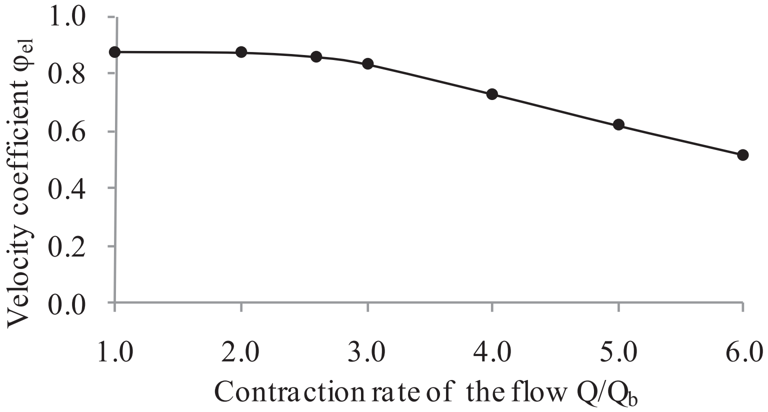

Figure 1: Velocity coefficient φ_{el} versus the flow contraction rate.

In Table 2 the drop in water levels (Δz) and the values of maximum backwater (Δh) under rigid-bed conditions in the vicinity of the head of the elliptical guide bank are presented. Comparison between the backwater values obtained in the tests and calculated by the Rotenburg (1965) formula gave good results.

Test	$\frac{Q}{Q_b}$	Δh_{exp}	Δh_{calc}	$\frac{\Delta h_{exp}}{\Delta h_{calc}}$	Δz	Δh_{exp}
N°		cm	cm		cm	cm
EL1	5.27	1.95	2.220	0.88	2.15	0.91
EL2	5.69	3.42	3.620	0.94	3.00	1.14
EL3	5.55	3.52	3.950	0.89	3.70	0.95
EL4	3.66	1.09	1.189	0.92	1.10	0.99
EL5	3.87	1.85	1.795	1.03	1.75	1.06
EL6	3.78	2.50	2.350	1.06	2.42	1.03
EL7	2.60	0.48	0.557	0.86	0.55	0.87
EL8	2.69	0.97	0.993	0.98	1.02	0.95
EL9	2.65	1.55	1.280	1.21	1.38	1.12
EL10	1.56	0.33	0.380	0.87	0.35	0.94
EL11	1.66	0.36	0.455	0.79	0.40	0.90
EL12	1.67	0.60	0.530	1.13	0.56	1.07

Table 2: Water level drops and the values of maximum backwater obtained in tests and calculations

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

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

where h_{equil} is the depth of scour at the equilibrium stage, h_f is the depth of water in the floodplain, and V_{lt} is the local velocity any stage of scour.

The local velocity at the head of the elliptical guide bank can be determined from Equation (2)

$$V_{lt} = \frac{V_{l\,el.}}{1 + \frac{h_{equil}}{2h_f}} \tag{3}$$

The critical velocity was found by the Studenitcnikov (1964) formula:

$$V_0 = 3.6 d_i^{\,0.25} h_f^{\,0.25} \tag{4}$$

where d_i is the grain size of the bed material.

The critical velocity V_{0t} at the equilibrium stage of scour was found through the mean depth of the flow:

$$V_{0t} = \beta 3.6 d_i^{0.25} h_f^{0.25} \left(1 + \frac{h_{equil}}{2h_f}\right)^{0.25} \tag{5}$$

Using Equations 3 and 5, a formula for the equilibrium depth of scour at the elliptical guide banks is derived

$$h_{equil} = 2h_f \left[\left(\frac{V_l}{\beta V_0}\right)^{0.8} - 1\right] \cdot k_\alpha \cdot k_m \tag{6}$$

where k_α is a coefficient depending on the angle of flow crossing and k_m is a coefficient depending on the side-wall

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

$$V_{lt2} = \frac{V_{lel}}{1 + \frac{H_{d1}}{2h_f}} \tag{7}$$

where H_{d1} is the thickness of the first layer of the river bed.

The critical velocity is equal to:

$$V_{02} = \beta 3.6 \cdot d_2^{0.25} h_f^{0.25} \left(1 + \frac{H_{d1}}{2h_f}\right)^{0.25} \tag{8}$$

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.

The scour depth in the second layer is determined as:

$$h_{s2} = 2h_f \left[\left(\frac{V_{lt2}}{V_{02}}\right)^{0.8} - 1\right] \cdot k_\alpha \cdot k_m \tag{9}$$

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

$$h_{equil} = H_{d1} + h_{s2} \tag{10}$$

where H_{d1} is the thickness of the first layer of the river bed.

At stratified bed conditions, when calculated depth of scour by Equation (6) is less than thickness of the first layer $h_{sequil} < Hd_1$, the scour stops at that layer, but when $h_{s\ equil} > Hd_1$, the scour develops with the new flow parameters V_{lt2} and V_{0t2} and the grain size d_2 in the second layer (Equations 9, 10). At the second and next layers scour stops when the local velocity V_{lti} becomes equal the critical one V_{0ti}.

IV RESULTS

A comparison of the local velocity values obtained in the tests and calculated by Equation.1 is presented in Table 3. It is seen that the experimental and calculated values show good agreement.

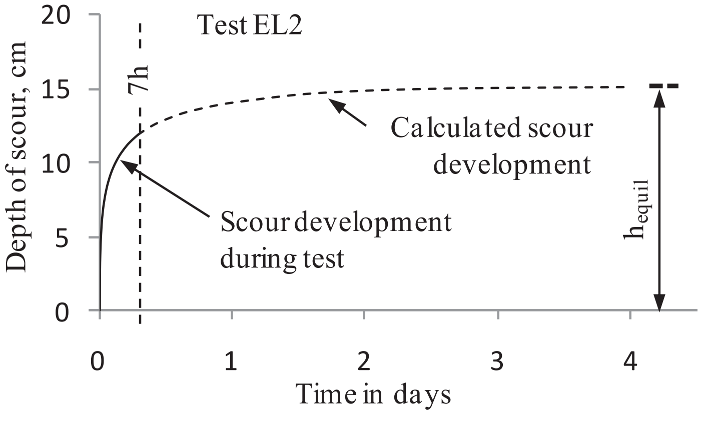

Figure 2: Scour depth development in time: test and calculation results; test EL2.

According to Equations (6, 9) the equilibrium depth of scour depends on the depth of water on floodplain, the local and critical velocities, grain size, river bed stratification, the angle of flow crossing, and the wall-side slope of the guide bank. The values of the velocities and depth of the floodplain must be found for the floods of designed probability.

The tests lasted for 7 hours, and the equilibrium stage of scour was not reached during this time. Using the method for calculating the scour development with time elaborated by Gjunsburgs et al. (2006, 2007), the test duration was prolonged up to the achievement of equilibrium stage at $V_{lt} = \beta V_{0t}$ (Fig. 2).

Test	$\frac{Q}{Q_b}$	Δh_{calc}	$V_{l\ el\ test}$	$V_{l\ el\ calc}$	$\frac{V_{l\ el\ test}}{V_{l\ el\ calc.}}$
№		cm	cm/s	cm/s	
EL1	5.27	2.220	39.10	36.20	1.080
EL2	5.69	3.620	46.40	46.80	0.990
EL3	5.55	3.950	49.70	52.10	0.957
EL4	3.66	1.189	36.90	35.10	1.050
EL5	3.87	1.795	44.00	45.20	0.974
EL6	3.78	2.350	51.00	53.90	0.948
EL7	2.60	0.557	28.40	26.70	1.065
EL8	2.69	0.993	37.80	37.50	1.008
EL9	2.65	1.280	43.00	51.20	0.840
EL10	1.56	0.380	23.90	22.30	1.074
EL11	1.66	0.455	26.10	23.00	1.136
EL12	1.67	0.530	28.20	30.70	0.920
EL13	4.05	1.420	38.20	32.45	1.178
EL14	3.99	1.800	43.40	37.50	1.160
EL15	4.05	2.700	52.70	49.40	1.070
EL16	3.66	1.189	36.90	35.10	1.051
EL17	3.87	1.795	44.00	45.20	0.975
EL18	3.78	2.350	51.00	53.90	0.946
EL19	4.46	1.476	36.50	33.00	1.110
EL20	3.21	0.769	31.40	28.30	1.110

Table 3: Comparison of the local velocities obtained in tests and calculated.

According to the tests a result, with increase in the scour depth, the local velocity under steady flow conditions reduces, and the critical β velocity increases (Fig.3).

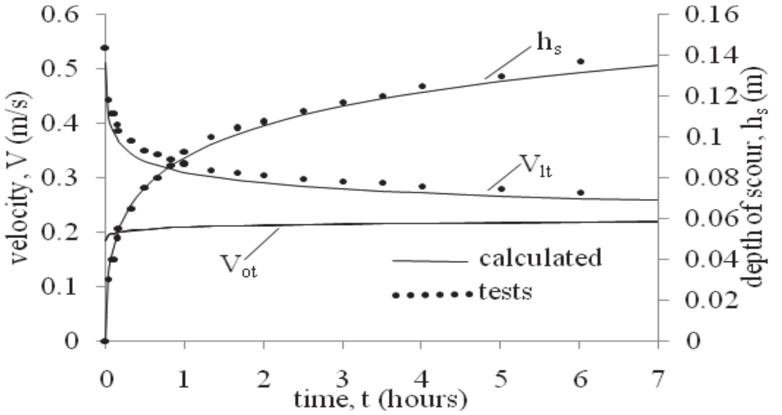

Figure 3: Changes in scour depth and in the local and critical velocities V_{lt} and βV_0 varying with time under steady flow; one sand layer-test EL 6.

At stratified bed conditions when the first layer is scoured and the depth of scour $h_s > H_{d1}$ (Fig.4), where H_{d1} is the depth of the first layer with grain size d_1, scour continues in the second layer with grain size d_2, with new local and critical velocities on the top of the second layer (Equations 7,8). Depending on the sequence of the layers the critical velocity V_{0t} is increasing, when the grain size of the second layer is coarse or reducing, when the grain size of the second layer is finer (Fig.5). Local velocity V_{lt} is reducing more rapidly, when the second layer is with fine grain size.

Comparison of test and calculated results for stratified bed conditions with layers of different thickness and sequence (Table 4) shows that depth of scour is more in case of the coarse grain size layer is on the top of the river bed and fine grain sand layer is following after it and less in case of the fine grain size layer is on the surface of the river bed. Using the grain size d_{50} on the top of the river bed for depth of scour calculation can lead to the wrong results.

Froude number of the open flow in flume- Fr, Froude number with the local velocity at the head of the elliptical guide bank- Fr_{vl}, Froude number at the end of the tests, with depth of scour hs- Fr_{vlt}, densimetric Froude number, densimetric Froude number with local velocity- Fr_{dvl} are presented in the Table 5.

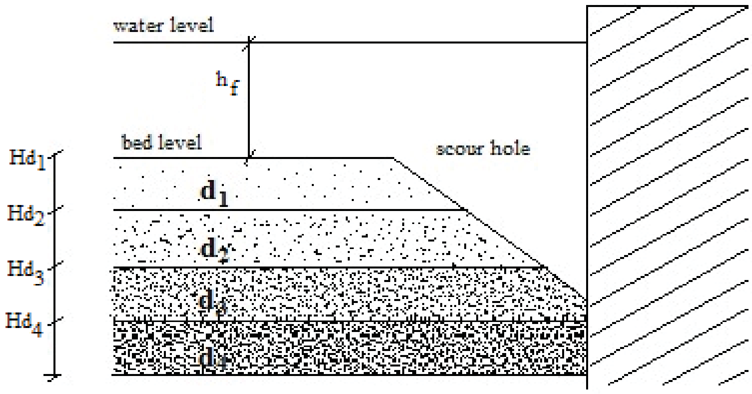

Figure 4: Scour under stratified bed condition

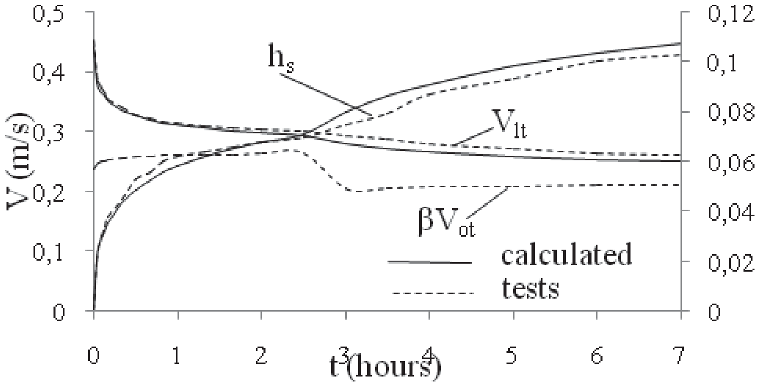

Figure 5: Changes in scour depth and in the local V_{lt} and critical βV_{0t} velocities, with $d_1 = 0.67$ mm in the first layer and $d_2 = 0.24$mm in the second one; test EUL 2.

According to experimental results and the method proposed, the scour depth is always 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.

Test	d_1	d_2	H_{d1}	H_{d2}	$h_{s\ test}$	$h_{s\ calc}$	$\frac{h_{s\ test}}{h_{s\ calc}}$
№	mm	mm	cm	cm	cm	cm	
EUL2	0.67	0.24	7	43	10.3	10.73	0.96
EUL5	0.24	0.67	7	43	8.6	8.44	1.04
EUL3	0.67	0.24	10	40	12.4	12.13	1.02
EUL6	0.24	0.67	10	40	11.4	11.12	1.02
EUL8	0.24	0.67	7	43	9.4	9.99	0.95
EUL11	0.67	0.24	7	43	12.6	13.38	0.94
EUL9	0.24	0.67	10	40	13.6	14.58	0.93

Table 4: Comparison between experimental and calculated values of scour depth under stratified bed conditions

Analysis of the formulas presented shows that the local velocity depends on the maximum backwater value and the relative maximum backwater is a function of the following parameters (Rotenburg et.al, 1965):

$$\frac{\Delta h}{h_f} = f\left(\frac{Q}{Q_b};\ P_K;\ P_{KB};\ \frac{Fr}{i_0};\ \frac{h}{h_f}\right) \tag{12}$$

where Q/Q_b is the contraction rate of the flow, $P_K = V^2/gh_f$ is the kinetic parameter of open flow, $P_{KB} = V^2_b/gh_b$ is the kinetic parameter of the flow under the bridge, $Fr/i_0 = V^2/gLi_0$ is the Froude number ratio to the slope of river bed, h is the flow depth, h_f is the depth of the floodplain, h_b is the depth of flow under the bridge, V is the approach flow velocity, V_b is the flow velocity under the bridge, L is the width of the river, and i_0 is the slope of the river bed.

Test №	Q/Q_b	d_1/d_2	$\frac{V_l}{\beta V_0}$	$\frac{V_l}{V_{lt}}$	$\frac{V_{0t}}{V_0}$	Fr	Fr_{Vl}	Fr_{Vlt}	Fr_{d1}	Fr_{d2}	$\frac{h_{s7}}{h_f}$	h_{equil} cm
EUL1	3.66	0.67/0.24	1.55	1.42	1.09	0.078	0.445	0.234	0.62	3.54	0.87	10.43
EUL2	3.87	0.67/0.24	1.85	1.64	1.12	0.1035	0.531	0.215	0.82	4.24	1.20	14.10
EUL3	3.78	0.67/0.24	2.14	1.79	1.16	0.1245	0.617	0.204	0.99	4.91	1.74	17.65
EUL4	3.66	0.24/0.67	2.00	1.74	1.15	0.078	0.445	0.162	1.04	5.90	1.08	5.90
EUL5	3.87	0.24/0.67	2.40	2.00	1.19	0.1035	0.531	0.152	1.37	7.06	1.57	8.90
EUL6	3.78	0.24/0.67	2.77	2.26	1.23	0.1245	0.617	0.146	1.65	8.20	2.00	11.80
EUL7	4.05	0.24/0.67	1.37	1.29	1.06	0.066	0.340	0.209	0.72	3.67	0.49	7.53
EUL8	3.99	0.24/0.67	1.56	1.43	1.09	0.075	0.384	0.197	0.84	4.17	0.70	11.13
EUL9	4.05	0.24/0.67	1.89	1.67	1.13	0.087	0.466	0.183	0.95	5.06	1.08	17.35
EUL10	4.05	0.67/0.24	1.77	1.58	1.12	0.066	0.340	0.145	1.20	6.11	0.81	15.17
EUL11	3.99	0.67/0.24	2.02	1.75	1.15	0.075	0.384	0.138	1.40	6.96	1.00	19.59
EUL12	4.05	0.67/0.24	2.45	2.05	1.19	0.087	0.466	0.128	1.59	8.45	1.39	27.73

Table 5: Relative velocities and Froude numbers change at the scour under stratified bed conditions with layers of different thickness

An analysis of the results obtained both in tests and by using Equations (6, 9) shows that the depth of scour depends on the open flow conditions, contraction rate of the flow, local velocity, Froude number of open flow, flow depth, grain size, stratified bed conditions, type and shape of the structure, probability of the flood, and (according to the data published in the literature) on the angle of bridge crossing and the slope of side-wall of the guide banks.

In the general form, the relative equilibrium depth of scour is a function of the following parameters:

$$\frac{h_{equil}}{h_f} = f\left(\frac{Q}{Q_b};P_K;P_{Kb};\frac{Fr}{i_0};\frac{h}{h_f};\frac{d_i}{h_f};H_{strat};\frac{V_l}{\beta V_o};k_m;k_s;k_\alpha\right) \tag{13}$$

With increase in the contraction rate, Froude number of the open flow, relative depth, and local velocity, the depth of the equilibrium scour increases. Whereas, with increase in the ratio of Froude number to river slope and in the relative grain size of bed material, the depth of equilibrium scour decreases. The influence of the coefficient depending on the angle of flow crossing and that depending on the side-wall slope of the guide bank was studied by other researchers(Richardson and Simons,1984).It was found that the scour depth depends on river bed stratification, thickness and sequence of the layers. The most critical conditions for structures occur when a fine-sand layer is under a coarse-sand layer. When the coarse layer is scoured away, the depth of 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 the second layer or of the next one, where the scour stops. According to the results obtained in tests and the formulas presented, the depth of scour is always greater when a fine-sand layer is under a coarse-sand layer(s). The calculation of scour depth near hydraulic structures in flow by using the mean 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.

V 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. Based on the conditions that the local velocity becomes equal to the critical one, at an equilibrium stage of scour, a formula for computing the equilibrium depth of scour at stratified bed conditions at the head of elliptical guide banks was deduced (Equations 6, 9, 10). For each test, the time of scour development was increased up to the achievement of the equilibrium stage, by using the method developed by Gjunsburgs et al. (2006, 2007). 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 a method presented, the depth of scour is always greater when a fine-sand layer is under coarse-sand layer(s) (Table 4). In this case, the dominant grain size for computing the depth of scour at foundations under stratified bed conditions is the mean diameter top of the river bed and neglecting the stratification of the river bed can lead to wrong results and finally to considerable damages.

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