The 9th International Conference "ENVIRONMENTAL ENGINEERING"
22–23 May 2014, Vilnius, Lithuania
SELECTED PAPERS
eISSN 2029-7092 / eISBN 978-609-457-640-9
Available online at *http://enviro.vgtu.lt*

Section: Water Engineering

Scour at layered river bed: reason of the structures failure

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Abstract

The prediction of damages and/or failure of the bridge structures in flow, because of the scour near foundations in plain rivers, is one of the main tasks for engineers. In spite of the problem importance – the scour development in time at stratified bed conditions is not studied well. The aim of the study is to propose new method and to estimate the influence of the river bed stratification on depth of scour near bridge structures in flow. The differential equation of equilibrium for bed sediment movement in clear water was used and a new calculation method for the scour development in time at vertical wall abutments in plain rivers at clear water and at stratified bed conditions with uniform grain-size sands layers was elaborated and confirmed by test results. This method allows one to calculate the scour depth in layers with different mean grain size, thickness and sequence combination. Relative depth of scour dependence on flow and stratified bed data is presented in figures. The calculation of scour depth near bridge 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. The most critical conditions for structures are when fine-sand layer is under a coarse-sand layer. Test results and method presented confirm that 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 the depth of scour calculation as it is accepted now and neglecting river bed stratification can lead to wrong results and possible structures failure.

Keywords: scour depth; river bed; layering; grain size.

1. Introduction

High floods in Europe during the last decade have destroyed a lot of bridge crossing structures because of the scoured foundations (England, Ireland, Italy, Czech Republic, Denmark, Spain, Portugal, Finland, etc.). The reason of the bridge structures failure can be the stratification of river bed. Literature analysis shows that in formulas or methods for depth of scour calculation at bridge piers, abutments, guide banks or spur dikes, only the top layer of the river bed soil data is being considered. In complex geological structure of the river bed with different soil layers, the depth of scour is increasing or reducing, depending on the thickness and sequence of the layers. Scour near engineering structures at stratified bed conditions is not studied well. Using the mean grain size on the top of the river bed for the depth of scour calculation, as it is accepted now and neglecting river bed stratification can lead to wrong results and possible structures destruction.

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

The aim of the study is to elucidate the influence of the river bed stratification on the scour depth at vertical wall abutments at clear water conditions with uniform grain-size sands layers. Tests were made with different hydraulic conditions and uniform grain-size sands with two layers and two mean size diameters and their different sequences.

The differential equation of equilibrium for bed sediment movement in clear water was used and a new calculation method for the scour development in time at vertical wall abutments in plain rivers at clear water and at stratified bed conditions with uniform grain-size sands was elaborated and confirmed by test results. This method allows one to calculate the scour depth in layers with different mean grain size, thickness and sequence combinations.

As the scour depth is developing, the local velocity V_{lt} is reducing and the critical one βV_{0t} is increasing. For computing scour depth at stratified bed conditions it is necessary to find those velocities on the top of every next layer. Formulas for local and critical velocities calculations are presented in this paper.

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http://dx.doi.org/10.3846/enviro.2014.076

The most critical conditions for structures occur when a fine-sand layer is under a coarse-sand layer. When the coarse-sand 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 at foundations under stratified bed conditions is the mean diameter of the second layer or of the next one, where the scour stops. 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 of the river bed can lead to wrong results and finally to considerable damages.

Methods for computing the depth of scour development with time (Eqns 10 and 12) at the abutments under stratified bed conditions are presented. The methods are confirmed by test results. To determine scour depth during the flood it is necessary to divide hydrograph in time steps with duration of 1 or 2 days and divide each time step in time intervals equal up to several hours or less. In laboratory tests time steps were divided for 20 time intervals. For each time step necessary to know: h_f – depth of water on floodplain; Q/Q_b – contraction rate of the flow; Δh – maximum backwater; d – grain size; H – thickness of the bed layer with d; γ – specific weight of bed material. As a result we have V_l, V_o, A, D, N_i, N_{i-1} and h_s at the end of time intervals and finally at the end of time step. For next time step flow parameters were changed because of the flood and because of the scour for previous time step.

2. Experimental setup

Tests were conducted in flume 3.5 m wide and 21 m long. Experimental data in flumes for open flow distribution between channel and floodplain was studied under open flow conditions.

The rigid bed tests were performed to investigate the changes in velocity and water level in the vicinity of the embankment and at the head of the elliptical guide banks.

Table 1. Test data for open flow conditions

Test	L, cm	h_f, cm	V, cm/s	Q, l/s	Fr	Re_c	Re_f
L1	350	7	6.4	16.6	0.078	7500	4390
L2	350	7	8.5	22.7	0.103	10010	6060
L3	350	7	10.	23.60	0.124	12280	7190
L7	350	13	7.5	35.48	0.066	13700	9740
L8	350	13	8.7	41.38	0.075	16010	11395
L9	350	13	9.9	47.10	0.087	14300	14300

During the sand-bed tests we studied the scour development in time at stratified bed conditions with different grain sizes for the first and the second layers. 1 m up and down of the bridge crossing introduction, the model had a sand-bed for studying scour process near the head of the elliptical guide banks. The tests were performed for contraction rate Q/Q_b = 3.66–4.05 (where Q is the flow discharge and Q_b is the discharge through the bridge opening under open-flow conditions). Depth of the water on the floodplain is 7 and 13 cm. Thickness of the layers with different grain size 0.24 and 0.67 mm with standard deviation equal to 4, 7 and 10 cm. The Froude number at open-flow conditions varied from 0.078 to 0.1243, densimetric Froude number – from 0.62 to 1.65, the slope of the flume was 0.0012. The opening of the bridge model was 80 cm. 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 hours step and within two steps, 7 hours each. The tests were carried out with one floodplain model and with one side contraction of the flow.

3. Local and critical velocities near abutments

In approach to contraction of the bridge the streamlines were bended by the embankment, and then the flow direction was parallel to it. Velocities along extreme streamline were falling to about minimum and then gradually increasing, spiral vortex system was developing. At the corner of the abutment were streamlines concentration, sharp water level drop and rapid increase of the velocity. Horizontal vortex was developing, reducing the opening of the bridge. In tests local velocities near abutment were at any contraction of the flow.

To calculate the local velocity we used the Bernoulli equation for two cross sections of a unit streamline. The formula for local velocity at the abutment for the plain river bed was:

$$V_l = \varphi\sqrt{2g\Delta h}\ , \tag{1}$$

where: φ – velocity coefficient, depending on the contraction rate of the flow; Δh – backwater value [1].

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

$$V_{0t} = \beta \cdot 3.6 d_i^{0.25} h_f^{0.25}, \tag{2}$$

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

As local velocity is reducing and critical velocity is increasing during scour depth development, the scour stops when local velocity becomes equal to the critical one. At this time the scour reaches the equilibrium stage.

The discharge across width of the scour hole before and after the development of the scour hole is $Q_f = kQ_{se}$, where Q_f – the discharge across width of the scour hole with the plain bed and Q_{se} – the discharge at any depth of scour h_s.

$$mh_s h_f V_{lt} = k\left(mh_{sl} h_f + \frac{mh_s}{2} h_{sl} \right) \cdot V_{lt}, \tag{3}$$

where: m – the steepness of scour hole; mh_{sl} – width of the scour hole; V_{lt} – local velocity with a plain bed [9]; h_f – water depth in the floodplain; k – a coefficient of changes in discharge because of the scour, which depends on the flow contraction [9].

The local velocity V_{lt} can be determined from Eqn. (3):

$$V_{lt} = \frac{V_l}{k\left(1 + \frac{h_s}{2h_f}\right)}, \tag{4}$$

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

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

where: β – reduction coefficient of the critical velocity at the bended flow determined by using Rozovskyi [11] approach.

When the first layer with grain size d_1 is removed, the scour continues in the second layer with grain size d_2.

To calculate depth of scour in the next layer it is necessary to find the local and critical velocities on the top of this layer Eqns (8) and (9), because those velocities are forming scour depth and not the velocities V_1 and V_0, Eqns (1), (2).

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

$$V_{lt2} = \frac{V_l}{k\left(1 + \frac{H_{d1}}{2h_f}\right)}, \tag{6}$$

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:

$$V_{02} = \beta 3.6 \cdot d_2^{0.25} h_f^{0.25} \left(1 + \frac{H_{d1}}{2h_f}\right)^{0.25}, \tag{7}$$

where: $V_{02} = \beta 3.6 d_2^{0.25} h_f^{0.25}$ – the critical velocity of the flow for the grain size d_2, since the layer with exactly this diameter lies on the top of the river bed.

4. Scour development in time at stratified river bed conditions by abutments

The differential equation for equilibrium bed sediment movement is used and scour development in time at vertical wall abutment in plain rivers at clear water and at stratified bed with uniform grain-size sand layers was elaborated and confirmed by test results. The parameter A_i in sediment discharge formula is decreasing with the increase of the scour depth.

$$A_i = \frac{5.62}{\gamma}\left[1 - \frac{k\beta V_0}{V_l}\left(1 + \frac{h_s}{2h_f}\right)^{1.25}\right] \cdot \frac{1}{d_1^{0.25} \cdot h_f^{0.25}\left(1 + \frac{h_s}{2h_f}\right)^{0.25}}, \tag{8}$$

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

The local velocity V_{lt} at the depth of scour h_s is calculated by Equation (4) and the critical velocity V_{0t} at the depth of scour h_s is estimated by Eqn. (5).

To calculate the scour development in time at stratified bed conditions, when depth of the scour h_s is more than the depth of the first layer H_{d1} with grain size d_1, it is necessary to go back to the top of the second layer with grain size d_2 and compute local V_{lt} and critical V_{0t} velocities and parameter A in the second layer H_{d2} with grain size d_2. The local and critical velocities on the top of the second layer are found by Eqns (6), (7).

$$A_2 = \frac{5.62}{\gamma}\left[1-\frac{k\beta V_{02}}{V_l}\left(1+\frac{H_{d1}}{2h_f}\right)^{1.25}\right]\cdot\frac{1}{d_2^{0.25}\cdot h_f^{0.25}\left(1+\frac{H_{d1}}{2h_f}\right)^{0.25}}, \quad (9)$$

where: γ – specific weight of the bed material; and H_{d1} – thickness of the first bed layer with d_1.

After integrating differential equation:

$$N_2 = \frac{t_i}{4D_2 h_f^2} + N_1, \quad (10)$$

where: $N_i = 1/6x_i^6 - 1/5x_i^5$; t_i – time interval,

$$D_i = \frac{a}{b} = \frac{\pi\cdot m}{2A_i\cdot V_l^4}, \quad (11)$$

Calculating the value of N_2 we find x_i and depth of scour in the second layer:

$$h_{s2} = 2\,h_f\,(x_2 - 1)\,k_m\,k_\alpha, \quad (12)$$

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

Calculating the value N_2, we find x_2 and depth of scour in the next layer: Depth of scour in two layers is equal

$$h_s = H_{d1} + h_{s2}, \quad (13)$$

Using Eqns (10), (12) and (13) depth of scour calculation can be continued with new flow and river bed parameters. If the depth of scour will be less than thickness of the second layer $h_s < Hd_2$, the scour stops at that layer, if $h_s > Hd_2$, the computing should be continued in the third layer with local and critical velocities on the top of the third layer, grain size d_3 and new parameter A_i.

5. Results

At stratified bed conditions when the first layer is scoured and the depth of scour $h_s > H_{d1}$ where the depth of the first layer with grain size d_1 – H_{d1}, scour continues in the second layer with grain size d_2 with another local and critical velocities on the top of the second layer Eqns (6), (7). Depending on the sequence of the layers the critical velocity V_{0t} is increasing, when the grain size of the second layer is coarser or reducing, when the grain size of the second layer is finer. Local velocity V_{lt} is reducing more rapidly, when the second layer is with fine grain size.

In Figs 1 and 2 depth of scour, local V_{lt} and critical V_{0t} velocities development in time, because of the scour with different sequence of the layers, are presented – fine grain layer on the top of the coarse grain size layer and vice versa. If scour depth is more than the depth of the second layer, it is necessary to find local and critical velocities on the top of the next layer when local velocity V_{lt} becomes equal to the critical one V_{0t}. The scour stops at any next layer.

At stratified bed conditions the sequence of the layers has the significant influence on the scour depth value. The scour development in two layers with different grain sizes d_1/d_2 or d_2/d_1 at the border of the two layers changes its intensity – rapid development, when the first coarse sand layer is scoured and scour is continued in the fine sand layer or slows down when scour is continued in the second coarse layer.

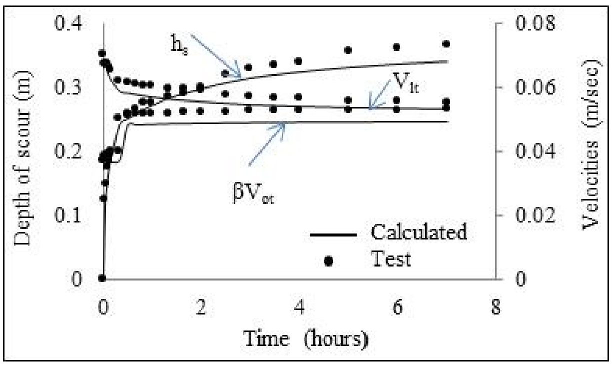

Fig. 1. Depth of scour, local and critical velocities development in time at stratified bed conditions, with d_1 = 0.24 mm in the first and d_2 = 0.67 mm in the second layer (Test AUL 1).

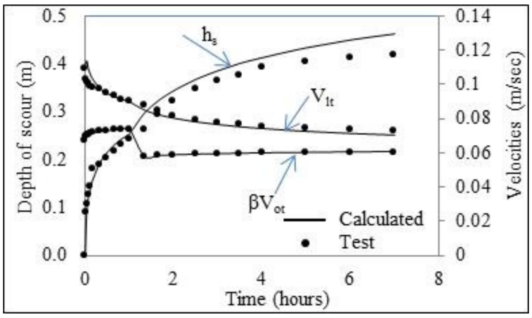

Fig. 2. Depth of scour, local and critical velocities development in time at stratified bed conditions, with $d_1 = 0.67$ mm and $d_2 = 0.24$ mm (Test AUL 5).

When the first layer is scoured out, the critical velocity is sharply reducing with smaller grain size diameter in that layer, or increasing with greater grain size. In the second layer the depth of scour development in time reduction or increase rate is depending on the grain size diameter.

With increase of relative depth of scour h_s/h_f at uniform sand bed, the ratio of critical to local velocity $\beta V_{0t}/V_{lt}$ is increasing and approaching to one, when the scour stops (Fig. 3).

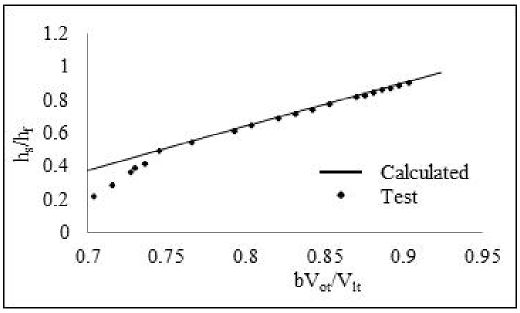

Fig. 3. Relative depth of scour development in time versus relative critical velocity in one uniform sand bed layer (Test AL 16)

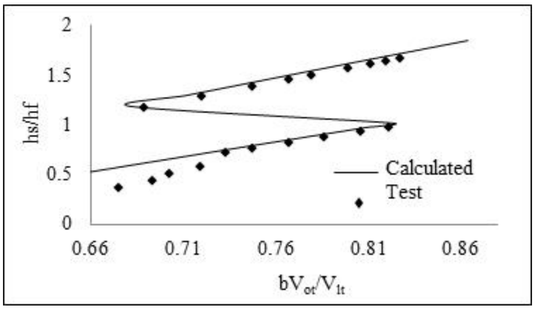

Fig. 4. Relative depth of scour development in time versus relative critical velocity stratified sand bed layers, when the first layer is with the grain size $d_1 = 0.67$ mm and the second layer is with the grain size $d_2 = 0.24$ mm (Test AUL 5).

In Fig. 4 the relative depth of scour h_s/h_f dependence on the ratio of critical to local velocity $\beta V_{0t}/V_{lt}$, at stratified bed conditions, when the first layer with the grain size $d_1 = 0.67$mm and the second layer with the grain size $d_2 = 0.24$mm is presented. On the border of the layers, when depth of scour is equal to the thickness of the layer, the velocity ratio $\beta V_{0t}/V_{lt}$ is reducing, because of the critical velocity reduction in the second layer with the grain size $d_2 = 0.24$ mm.

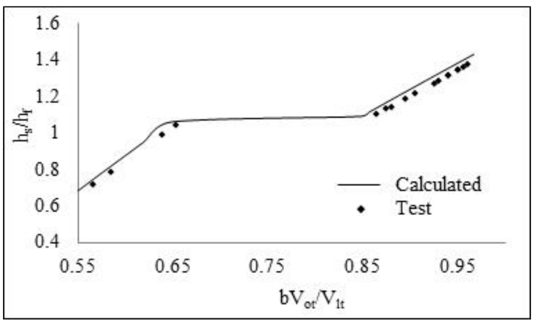

Fig. 5. Relative depth of scour development in time versus relative critical velocity at stratified sand bed layers, when the first layer is with the grain size $d_1 = 0.24$ mm and the second layer is with the grain size $d_2 = 0.67$ mm (Test AUL 2).

In Fig. 5 the relative depth of scour h_s/h_f dependence on the ratio of critical to local velocity $\beta V_{0t}/V_{lt}$ at stratified bed conditions, when the first layer with the grain size $d_1 = 0.24$ mm and the second layer with the grain size $d_2 = 0.67$ mm is presented. On the border of the layers, when depth of scour is equal to the thickness of the layer, the velocity ratio $\beta V_{0t}/V_{lt}$ is increasing, because of the critical velocity increasing in the second layer with the grain size $d_2 = 0.67$ mm.

6. Conclusions

In approach to the contraction of the bridge the streamlines were bended by the embankment, and then the flow direction was parallel to it. Velocities along extreme streamline were falling to about minimum and then gradually increasing, complex vortex system was developing. At the corner of the abutment were streamlines concentration, sharp water level drop, flow separation, rapid increase of the velocity and scour takes place. Horizontal vortex was developing, reducing opening of the bridge.

Methods for computing the depth of scour development with time at one layer on uniform river bed was presented earlier [9]. New methods for computing the depth of scour development with time (Equations 10 and 12) at the abutments under stratified bed conditions was elaborated. In Figs 1 and 2 depth of scour, local V_{lt} and critical V_{0t} velocities development in time, because of the scour with different sequence of the layers – fine grain size layer on the top of the coarse grain size layer and vice versa, are presented. If scour depth is more than the depth of the second layer, it is necessary to find local and critical velocities on the top of the next layer when local velocity V_{lt} becomes equal to the critical one V_{0t}. The scour stops at any next layer. The local velocity on the surface of the second layer is found by Eqns (6), (7) When the first layer is scoured out, the critical velocity is sharply reducing with smaller grain size diameter in that layer or increasing with greater grain size second layer; the depth of scour development in time reducing or increasing is depending on the grain size diameter (Figs 3 and 4). It was found that the most critical conditions for structures occur when a fine-sand layer occurs under a coarse-sand layer. As soon as the coarse sand layer has been scoured, the scour is rapidly developing in the next, fine-sand one. 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, in that case, the depth of scour is always greater when a fine-sand layer is under a coarse-sand layer(s) compared with the depth of scour obtained with the mean grain size on the top of the river bed. The calculation of the scour depth near hydraulic structures in flow by using only the data on 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.

References

[1] Rotenburg, I. S.; Poljakov, M. P.; Zolotarev, I. V.; Lavrovskij, V. A. 1965. *Bridge crossing design.* Moscow: Vyshaya Shkola (in Russian).

[2] Ettema, R. 1980. Scour at bridge piers, in *Papers – 3rd Congress of the Asian and Pacific Regional Division of the International Association for Hydraulic Research*; Bandung, Indonesia.

[3] Raudkivi, A. J.; Ettema, R. E. 1983. Clear water scour at cylindrical piers, *Journal of Hydraulic Engineering,* 3(109): 338–350. http://dx.doi.org/10.1061/(ASCE)0733-9429(1983)109:3(338)

[4] Kothyari, U. 1990. PhD Thesis, Civil Engineering department, University of Roorkee, Roorkee.

[5] Kothyari, U.; Ram, Chandra, J.; Garde, Kittur, G.; Ranga, Raju. 1992. Temporal variation of scour around circular bridge piers, *Journal of Hydraulic Engineering* 8(118): 1090–1103.

[6] Garge, R.; Kothyari, U. 1998. Scour around bridge piers, in *Pinsa 64. A. N4, Civil Engineering department*, University of Roorkee, Roorkee, 569–580.

[7] *FHWA-RD-99-188. 1999.* Effect of gradation and cohesion on bridge scour. *Vol.6 Abutment scour in uniform and stratified sand mixtures*, US Department of Transportation, Federal Highway Administration.

[8] Melville, B.; Coleman, S. 2000. *Bridge scour. Water Resources*, Highland Ranch, Colo.

[9] Gjunsburgs, B.; Neilands, R. 2004. Local velocity at bridge abutments on plain rivers, in *Proc. River Flow 2004, in Greco, Carravetta & Della Morte (eds)*, Napoly, Italy (1): 443–448.

[10] Gjunsburgs, B.; Jaundzems, G.; Govsha, E. 2010. Scour at elliptical guide banks under stratified bed conditions: equilibrium stage, in *Proceeding of International Scientific Conference People, Buildings and Environment*, Krtiny, 24–30.

[11] Rozovskij, J. L. 1957. *Water movement at the bend of the open flow*. Kiev, Academy of Science (in Russian).

[12] Gjunsburgs, B.; Neilands, R.; Govsha, E. 2006. Local scour at elliptical guide banks, in *Proceeding River Flow 2006 in Ferreura, Alves, Lean & Cardoso (eds),* Lisbon. Portugal (2): 1649–1655.

[13] Gjunsburgs, B.; Govsha, E.; Jaudzems, G. 2013. Influence of the River Bed Stratification on Scour at Foundations, in *Proceedings of the 35th IAHR World Congress: 35th IAHR World Congress*, China, Chengdu, 8–13 September, 2013. Chengdu: IAHR, Ministry of WR China, 1–9.