SCOUR, LOCAL AND CRITICAL VELOCITIES AT THE ABUTMENTS ON PLAIN RIVERS

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Abstract

Local flow modification near engineering structures such as – local velocity, flow separation, circulation, vortex structures, and increased turbulence, leads to local scour near foundations. Local flow velocity is forming the scour hole at the structures, but not approach flow velocity as it is accepted now by different authors. Based on test results, comparison of local velocity with approach flow velocity is presented. At steady flow conditions, when scour is developing in time, the local velocity is reducing and the critical velocity is increasing, but when the local velocity becomes equal to a critical one, the scour stops. According to test results and formulas, it presented that the value of the local and the critical velocities depend on contraction rate, depth, grain size, Froude number of flow and the river bed stratification. The value of the relative scour depth is dependent on local to critical velocities ratio at the initial stage, when there is no scour. Formulas for calculation of local and critical velocities are presented and confirmed by test results.

Key words

Local; critical; approach velocity; scour depth

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1 INTRODUCTION

The aim of the study is to elucidate the influence of the local and critical velocities on the scour depth at vertical wall abutments under clear water conditions in plain rivers.

Literature analysis shows that there is no one opinion in which velocity is forming scour hole and no methods for computing local (maximum) velocity at the abutments.

In formulas or methods for calculation the depth of scour at abutments, the mean velocity of approach flow is used or Froude number with that velocity – Laursen & Toch [1], Froelich [2], Richardson et al. [3], Melville [4], Melville & Coleman [5], Kothyari & Ranga Raju [6], Radice et al. [7] and the others. Presence of maximum (local) velocity near abutments is confirmed by Latishenkov [8] in laboratory tests.

In approach to the bridge, contraction streamlines are bended by embankment, in such a way that flow direction is parallel to it. Velocities along extreme streamline were falling to about minimum and then gradually increasing, as circulation and spiral vortex structures are developing. At the corner of the abutment are streamline concentrations, sharp water level drop and rapid local increase of the velocity. Local flow modification of the flow near the structures form the scour hole, but not the approach flow as it is accepted by different authors [9].

According to the test results and formula presented the local velocity is dependent on the characteristics of the flow, backwater value, contraction rate of the flow, depth of scour, flood parameters and type of the structure [9].

At steady flow, the local velocity is reducing in time, while at the same time the critical velocity near the structure in the flow is increasing. Critical velocity near structure in flow is always less than critical velocity of approach flow because of the flow separation, circulation, vortex structures, and increased turbulence. The value of the relative scour depth is dependent on the ratio of local to critical velocity at the initial stage, when there is no scour. According to test results and presented formulas, the relative local and critical velocities are changing in time and depend on contraction rate, depth, grain size, Froude number of the flow and the river bed stratification. Formula for local velocity was proposed. Tests were carried out for different hydraulic conditions, contraction rates, Froude number of the open flow, densimetric Froude numbers, different depths of the flow model in uniform sand, stratified bed conditions, with different sequence, and thickness of the layers with different grain sizes. Presented formulas were confirmed by test result.

2 LABORATORY SET-UP

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 local velocity and water level near the embankment, along it, and near the model of the abutment.

Sand was placed 1 m up and down according to contraction of the flumes. The mean grain size was 0.24 and 0.67 mm in the first flume and 0.5 and 1.0 mm in the second, which were obtained through standard deviation. The condition $Fr_R = Fr_f$ was fulfilled, where Fr_R = Froude number for plain river, and Fr_f = Froude number in flume.

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
L2	350	7	8.58	22.70	0.10	10010	6060
L4	350	7	8.16	20.81	0.098	10270	5590/5660
L1	350	7	6.47	16.60	0.078	7500	4390
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

Tests duration in flume was 7 hours, vertical scale – 50. 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, Re_c — from 7500 to 16010, and Re_f — from 4390 to 14300, where Re_c and Re_f are the Reynolds numbers for the channel and floodplain, respectively; the slope of the flume was 0.0012.

3 THE METHOD

At the corner of the abutments, there are the streamlines concentration, a sharp drop in water level, and a rapid increase in velocity were observed.

To calculate the local velocity, we used the Bernoulli equation for two cross sections of extreme unit streamline. The local velocity at the nose corner of the abutments, for the plain river bed was found using the formula [9]:

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

where φ is the velocity coefficient; Δh is the backwater value [10].

Tests results with different width of the opening, discharge, depth and Froude numbers of the flow are in good agreement with formula for maximum backwater value [10].

The critical velocity at the plain river bed is determined as [11]:

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

where β is reduction coefficient of the critical velocity on the bended flow [12]; d is mean grain size on the top of the river bed; h_f is water depth on the floodplain.

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 the discharge with any depth of scour:

$$m \cdot h_S \cdot h_f \cdot V_l = k\left(m \cdot h_S h_f + \frac{m \cdot h_S}{2} h_S\right) V_{lt} \tag{3}$$

where m is the steepness of the scour hole; h_s is the depth of scour; h_f is the depth of flow at the floodplain; V_l is the local velocity at plain river bed; V_{lt} is the local velocity at any depth of scour.

The local velocity V_{lt} at any depth of scour is determined from Eq. (3):

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

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

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

where β is the coefficient of reduction in the critical velocity due to flow modification, d_i is the grain size of the bed; $V_0 = 3.6 d_i^{0.25} h_f^{0.25}$ is the critical velocity at the plain bed.

The scour stops when the local velocity V_{lt} (Eq. 4) becomes equal to the critical velocity βV_{0t} (Eq. 5).

The geology of the river bed is complicate and usually is formed by layers with different thickness and sequence of different grain size (Fig.1). To use grain size parameters only on the top of the river bed to calculate depth of scour leads to wrong results and possible bridge failure.

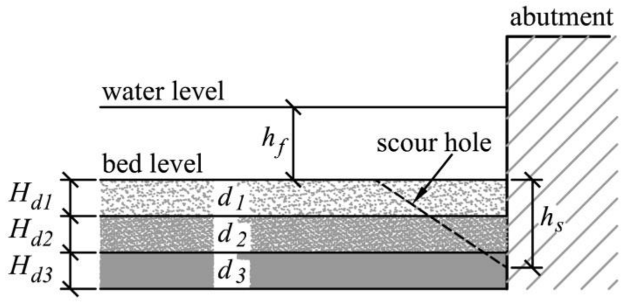

Fig. 1: Stratified river bed

When $h_s > H_{d1}$, the scour develops in the second layer with d_2. Therefore, the local and critical velocities which are on the top of the second layer must be found.

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

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

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 grain size d_2 is on the top of the river bed.

4 RESULTS

It was found in the tests that the extreme streamline is bent. Flow velocities reduce almost to zero when approaching the bridge crossing and then gradually increase. The flow pattern at the abutments is modified. At the corner of the abutment were streamlines concentration, sharp water level drop and rapid increase of the velocity. Because of the flow separation at the abutments corner, opening of the bridge is reducing.

With development of scour in time, under steady flow conditions, the local velocity is reducing and the critical one is increasing. Velocities become more equal with increase in depths of scour (Fig. 2).

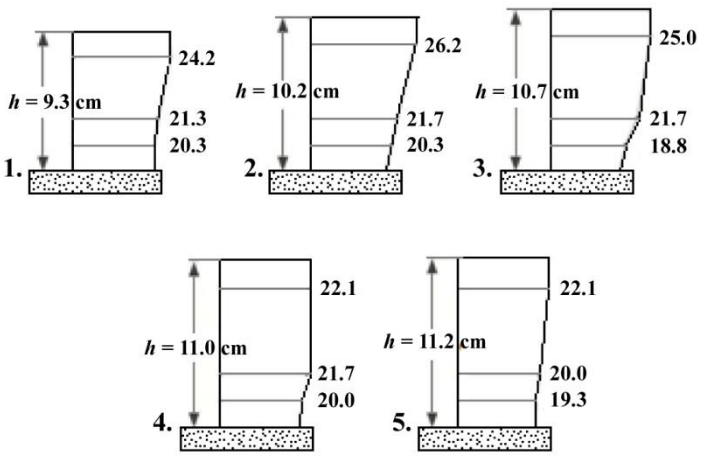

Fig. 2: Vertical distribution of velocities in time during the scour in 30 (1), 80 (2), 240 (3), 360 (4), and 420 min (5).

Fig. 3 illustrates the scour depth and respective variations in the local V_{lt} and critical βV_{0t} velocities, as measured experimentally and calculated in one layer with uniform sand.

With the depth of scour development in time, when the first layer is scoured out the critical velocity is sharply reducing, with smaller grain size, or increasing, with greater grain size in the second layer of the river bed (Figs. 4, 5).

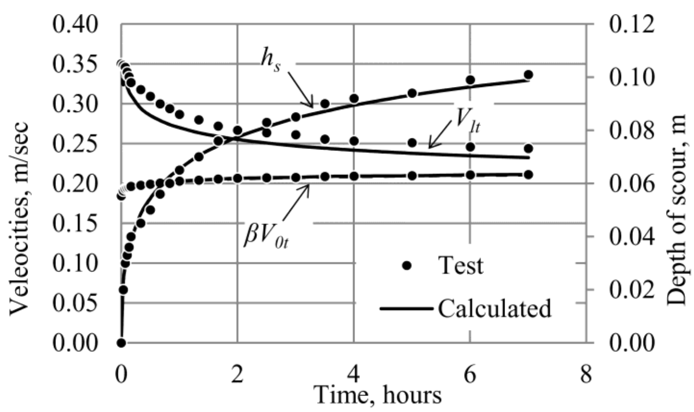

Fig. 3: Scour depth, local and critical velocities development in time at steady flow, with one uniform bed layer (Test AL 4).

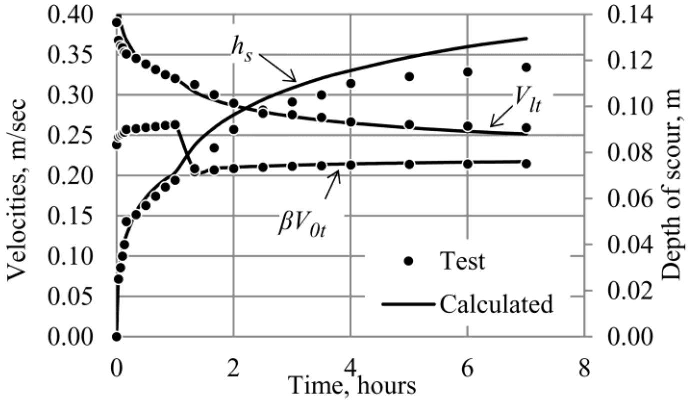

Fig. 4: Depth of scour, local and critical velocities development in time at stratified bed conditions, with d_1 = 0.67 mm in the first and d_2 = 0.24 mm in the second layer (Test AUL 5).

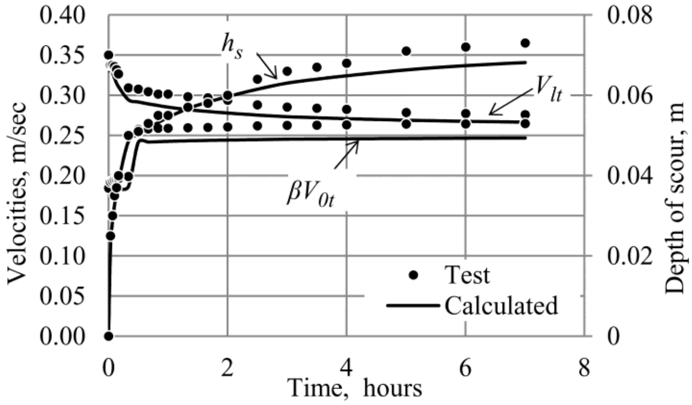

Fig. 5: Depth of scour, local and critical velocities development in time at stratified bed conditions, with d_1 = 0.24 mm in the first and d_2 = 0.67 mm in the second layer (Test AUL5).

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. 6).

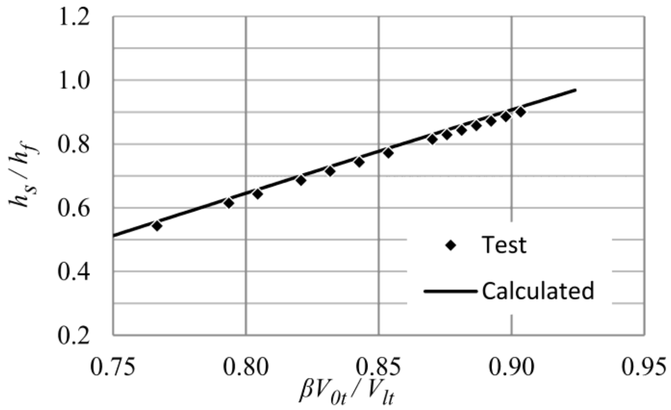

Fig. 6: Relative depth of scour development in time versus relative critical velocity $\beta V_{0t}/V_{lt}$ in one uniform sand bed layer (Test AL 16).

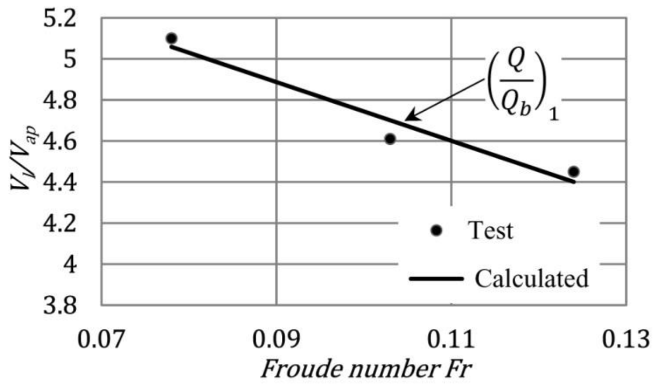

Fig. 7: Ratio of the local to approach flow velocity versus Froude number (Tests AL 4,5,6)

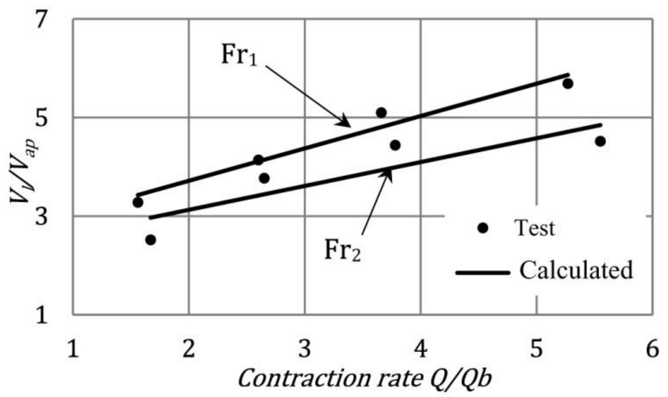

Fig. 8: Ratio of the local to approach flow velocity versus contraction rate of the flow.

5 CONCLUSIONS

Local velocity is forming the scour hole at any structure in flow, but not the approach velocity as it is accepted now.

The local velocity is dependent on the characteristics of the flow, backwater value and contraction rate of the flow, depth of scour, floods parameters and type of the structure. Eq. (1) is proposed to calculate the local velocity at vertical wall abutments at the plain bed.

The local velocity V_{lt} at any stage of scour is determined by Eq. (3) and the critical velocity V_{0t} through the mean depth of flow $h_m = h_f\ (1 + h_{equil} / 2h_f)$ near abutments is similarly determined by Eq. (4).

At stratified bed conditions, when $h_s > H_{d1}$, the scour develops in the second layer with d_2. The local and critical velocities on the top of the second or next layer can be determined by Eqs. (6, 7). Presented formulas were confirmed by test result.

The ratio $V_l / V_{ap.}$ (local to approach velocity) is dependent on contraction rate and on the Froude number of the flow (Figs. 7, 8). With increased contraction rate of the flow and with increased Froude number, the difference between local and approach velocity of the flow is increasing.

REFERENCES

[1] Laursen, E.M. & Toch, A. Scour around bridge piers and abutments. Bulletin 4. *Jowa Institute of Hydraulic Research*, Jowa, USA,1956.

[2] Floelich, D.C. Abutment scour prediction. *Presentation. Transport Research Board.* Washington, DC., 1989.

[3] Richardson, E.V., Simons, D. B. & Julien, P. Y. *Highways in the river environment. FHWA – H* 190 – 016, Federal Highway administration, U.S. Department of Transportation, Washington, DC, 1990.

[4] Melville, B.W. Pier and abutments scour: integrated approach. *Journal of hydraulic engineering* **123**(2), pp. 125 – 136,1997.

[5] Melville, B.W. &Coleman, S.E Bridge scour. *Water resources publication, LCC,* Highland Ranch, Colorado, USA, 2000.

[6] Kothyari, U.C. & Ranga Raju, K.G. Scour around spur dikes and bridge abutments. *Journal of hydraulic research,* **39**(4), pp. 367 – 374, 2001.

[7] Radice, A., Franzetti, S. & Ballio, F. Local scour at bridge abutments. *Proceedings of the International Conference on Fluvial Hydraulics, River Flow 2002, Louvian – La – Neuve,* pp.1059 – 1068, 2002.

[8] Latishenkov A.M., Questions of Artificially Contracted Flow. Moscow: Gosstroiizdat (in Russian), 1956.

[9] Gjunsburgs,. B., Neiland, R. Local velocity at bridge abutments on plain rivers. Proc. of River Flow 2004, Napoli, Italy, in Greco, *Carravetta & Della Morte (eds),* London: Taylor & Francis Group, **1**. pp.443-448, 2004.

[10] Rotenburg I.., Poljakov, M.., Zolotarev, IV., Lavrovskij, V.A. *Bridge crossing design*. Moscow, Vysshaya Shkola, 1965 (in Russian), 1965.

[11] Studenitchnikov B. *Scouring Capacity of Flow and Methods of Channel Calculation*. Moscow, Stroiizdat, (in Russian), 1964.

[12] Rozovskij, I.L. Investigation of cross circulation at curved river flow. *Meteorology and hydrology*, **6**, (In Russian), 1957.