Velocity modification at the bridge abutments because scour

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Abstract. At the corner of the abutment were streamline concentration, sharp water level drop and rapid increase of velocity. Formula for calculation local velocity at the abutments is elaborated. Local velocity is depending on open flow parameters, backwater value, rate of contraction by bridge crossings and depth of scour. Relative local flow modification at the bridge abutment at plain river bed, relative local and critical velocities changes during scour at steady and unsteady flow, uniform bed and at bed layering is studied. Comparison of the local velocity with approach flow and mean velocity under the bridge opening was made. The local velocity $V_l$ is reducing and the critical velocity $V_0t$ is increasing because of the scour within the time step at steady or at unsteady flow. When relative local velocity $\beta V_0t/V_l$ becomes equal to one the scour stops. For unsteady flow local and critical velocities are different at any steps of hydrograph because of the increased flow discharge and the scour depth. Dependence of the relative local and critical velocities at steady and unsteady flow, development in time and because of the scour, impact layering of the river bed is presented in paper in Figures and compared with tests results.

1. Introduction

The contraction flow by the bridge structures, such as abutments, piers, as well as guide banks, and spur dikes, leads to the flow and velocities modification in the vicinity of the abutment and is one among another reasons for scouring.

Approaching the bridge contraction, the streamlines are bended by an embankment, and the flow goes parallel to it. The flow velocities along the extreme streamline drop almost to minimum values and then gradually increase, which is accompanied by circulation and development of different vortex structures. At the corner of the abutment, is streamline concentration, sharp water level drop, rapid local increase of the velocity and local scour.

Currently in formulas and methods for calculation depth of scour at abutments is used mean velocity of approach flow or Froude number calculated with that velocity.

Scour near bridge structures were studied by Froehlich (1989), Richardson and Davis (1995), Kothuari and Ranga Raju (2001), Coleman et al. (2003), Rahman and Haque (2003), Gjunsburgs and Neilands (2004), Dey and Barbhuiya (2005), Grimaldi et al. (2006), Ghani et al. (2011), Guo (2014), Sheppard at all. (2014) Link at all. (2017) and the others.
The local and critical velocities are changing at the steady and at the unsteady flow because of the scour. The local velocity \( V_l \) is reducing and the critical velocity \( V_0 \) is increasing due to scour within the time step at steady flow. For the next time step local and critical velocities are different because of the unsteadiness of the flow, increased discharge and the scour depths developed in the previous time interval. Relative velocities \( V_l/V_b, V_0/V_b, V_0/V_l, \beta V_0/V_l \) changes in time at steady and unsteady flow, uniform bed and at bed layering and relative depth of scour \( h_s/h_f \) is studied. Relative local velocity ratio \( \beta V_0/V_l \) is increasing in time during the scour and when becomes equal to one (critical velocity become equal to local one \( \beta V_0=V_l \)) the scour stops.

2. Experimental set-up
Tests with fixed bed of the model were made for different contraction of the flow to investigate velocity and water level changes in approach to the embankment, along to it and near the model of the abutment.

With sand bed – to study scour process, velocity changes in time, influence of hydraulic parameters, rate of contraction of the flow, grain size of the bed material and time on the scour. In tests openings of the bridge model were – 50, 80, 120, 200 cm in the flume. Contractions of the flow \( Q/Q_b \), where \( Q \) - discharge of the flow, \( Q_b \) - discharge of the flow in bridge opening in open flow conditions, were changing from 1.25 to 5.69, depth of the floodplain was – 7 and 13 cm, Froude numbers were from 0.078 to 0.151, for steady or unsteady flow. Slope of the first flume – 0.0012.

Tests with sand bed were made for clear water conditions. Sand was placed 1 m up and down contraction of the flumes. The mean grain size was 0.24 and 0.67 mm in flume with standard deviation with uniform or stratified river bed model. The condition \( Fr_R = Fr_f \) were fulfilled, where \( Fr_R \) = Froude number for plain river, \( Fr_f \) = Froude number in flume. Tests duration in flume was 7 and 14 hours.

3. Method
To calculate the local velocity, we used the Bernoulli equation for two cross sections of an extreme unit streamline. The local velocity at the nose corner of abutments, for the plain river bed, was found from the following formula:

\[
V_l = \varphi \sqrt{2g \Delta h}
\]  

(1)

where \( \varphi \) is velocity coefficient, \( \Delta h \) is water level difference at the corner of the abutment.

According to tests results velocity coefficient \( \varphi \) in Eq.(1) was depending on flow contraction (Fig. 1).

![Figure 1. Coefficient \( \varphi \) dependence on flow contraction \( Q/Q_b \)](image)

The discharge across the width of a scour hole at the abutment before and after the scour is determined as follows:

\[
Q_f = kQ_{sc}
\]  

(2)
where \( Q_f \) is a discharge across the width of the scour hole with a plain bed, \( Q_{sc} \) is the discharge across the scour hole with a scour depth \( h_s \), and \( k \) is a coefficient of changes in discharge because of scour.

Equation (2) can be written as:

\[
 mh_f V_l = k \left( mh_f h_s + \frac{m h_s}{2} h_s \right) V_l
\]

(3)

where \( mh_s \) is the width of the scour hole, \( h_f \) is a water depth in the floodplain, \( V_l \) is local velocity at plain bed near abutment, \( h_s \) is the scour depth, and \( V_{lt} \) is the local flow velocity at a scour depth \( h_s \).

The average depth \( h_m \) of scour hole is:

\[
 h_m = \frac{W}{b} = \frac{m h_s \cdot h_f + m h_s \frac{h_s}{2}}{m h_s} = h_f \left( 1 + \frac{h_s}{2 h_f} \right)
\]

(4)

where \( W \) is the volume of the scour hole, \( b \) is the width of the scour hole.

From Eq. (3) the local velocity at any depth of scour hole is:

\[
 V_{lt} = \frac{V_l}{k \left( 1 + \frac{h_s}{2 h_f} \right)}
\]

(5)

As it was found in tests, the coefficient \( k \) is depending on contraction rate of the flow (Fig.2)

![Figure 2. Coefficient k dependence from contraction rate of the flow](image)

The critical velocity for the plane bed \( V_0 \) can be determined by the Studenitsenikov’s (1964) formula

\[
 V_0 = 1.15 g^{0.5} \left( h_f d \right)^{0.25}
\]

(6)

With the scour hole development, the corresponding value of the critical velocity \( V_{0s} \) for any scour depth \( h_s \) can be determined considering the average flow depth \( h_f (1 + h_s (2 h_f)) \), with coefficient \( \beta \), the effects arising because the bended flow due to the contraction:

\[
 V_{0s} = 1.15 \beta g^{0.5} \left( h_f d \left( 1 + \frac{h_s}{2 h_f} \right) \right)^{0.25} = \beta V_0 \left( 1 + \frac{h_s}{2 h_f} \right)^{0.25}
\]

(7)

\( \beta \) is reduction coefficient of the critical velocity in bended flow.
At bed layering, when \( h > H_{d1} \) (\( H_{d1} \) is the thickness of the first layer with \( d_1 \)) depth of scour is developing by new local and critical velocities which is on the top of the second layer. The local velocity on the surface of the second sand layer with depth \( H_{d1} \) is found by the formula:

\[
V_{h2} = \frac{V_{l}}{k \left( 1 + \frac{H_{d1}}{2h_f} \right) ^{0.25}}
\]  

(8)

where \( H_{d1} \) is the thickness of the first layer of the river bed with grain size \( d_1 \).

The critical velocity on the top of second layer is determined using the average depth of flow \( h_m = h_f \left( 1 + \frac{H_{d1}}{2h_f} \right) \), with a scour depth \( H_{d1} \) equal to the thickness of the first bed layer:

\[
V_{02} = \beta 3.6 \cdot d_2^{0.25} h_f^{0.25} \left( 1 + \frac{H_{d1}}{2h_f} \right)^{0.25} = V_0 \left( 1 + \frac{H_{d1}}{2h_f} \right)^{0.25}
\]  

(9)

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.

Local and critical velocities are changing in time. The local velocity \( V_l \) is reducing and the critical velocity \( V_{0t} \) is increasing because of the scour within the time step at steady flow. For the next time step of hydrograph, at unsteady flow, local and critical velocities are different because of the increased discharge of the flow and the scour depth developed in the first step. Is found dependence of the local and critical velocities from unsteadiness of the flow, grain size of the bed material layering river bed.

4. Results

As result of flow modification at the corner of the abutment is local increase in velocities. The difference between average local flow velocity and approach one with increase of the contraction rate of the flow is increasing (Fig.3).

![Figure 3](image-url)

Figure 3. Local and approach velocities ratio at different contraction rate of the flow

Comparison of the flow velocity under the model of the bridge \( V_b \) and local velocity at the abutment \( V_l \) (Fig.2) show that with increase of the contraction rate of the flow the difference between them is reducing.
At steady and unsteady flow, the ratio between local velocity at any depth of scour to local velocity at plain bed $V_{lt}/V_l$ is reducing in time as depth of scour increases. Local velocity $V_{lt}$ is reducing in time, than relative velocity $V_{lt}/V_l$, where $V_l$ is local velocity at plain model bed, is also reducing in time. At the unsteady flow, at the second step of hydrograph, when depth on the floodplain is increasing the the relative local velocity also is reducing (Fig.5).

**Figure 6.** Relative critical velocity $V_{0t}/V_o$ development in time at unsteady flow (Test TL 5)

Ratio of the critical velocity at any depth of scour to critical velocity at plain bed in time is increasing because of increases the depth of the flow due to the scour development in time (Fig.6).
Value of the scour depth is depending on ratio local to critical velocities $V_l/\beta V_o$ and it changes with development scour hole in time at steady and unsteady flow conditions.

**Figure 7.** Relative local velocity at plain bed changes with contraction rate of the flow

**Figure 8.** Relative velocity $\beta V_o/V_{lt}$ versus relative depth of scour $h_s/h_f$ at steady flow (Test AL4)

**Figure 9.** Local velocity versus critical velocity $\beta V_o/V_{lt}$ at unsteady flow in time of scouring

At plain bed, with the increase of the contraction rate of the flow, the difference between local and critical velocities is increasing (Fig.7).
At steady and unsteady flow with increase of the relative depth of scour $h_s/h_f$ the relative local velocity $V_l/\beta V_{ot}$ ratio is reducing (Fig.7) and scour stops, in case, the ration of the velocities becomes equal to 1.

At unsteady flow, with two steps of hydrograph, the ratio of the relative local velocity in changes in time and increased from step to step (Fig.9).

**Figure 10.** Local velocity $V_l$ and critical velocity $V_{0t}$ changes in time at steady flow and stratified bed conditions (in first layer $d_1=0.67\text{mm}$ and at the second layer $d_2=0.24\text{mm}$, Test AUL5)

**Figure 11.** Local velocity $V_l$ and critical velocity $V_{0t}$ changes in time at steady flow and stratified bed conditions (in first layer $d_1=0.24\text{mm}$ and at the second layer $d_2=0.67\text{mm}$, Test AUL3)

On the top of the next layer with grain size $d$ finer that in the first layer critical velocity is reducing, but when first layer is with $d_1=0.67\text{mm}$ and the second one $d_2=0.24\text{mm}$ (Fig.10), and increasing when first layer is with $d_1=0.24\text{mm}$ and the second one $d_2=0.67\text{mm}$ (Fig.11). When the critical velocity become equal to local one $\beta V_{0t}=V_l$ the scour stops.

**5. Conclusion**

According to the experimental data, at the corner of the abutment were streamline concentration, sharp water level drop and rapid increase of velocity and local scour hole is developed. Formula for local velocity at plane bed is presented. The local and critical velocities are changing at the steady and at the unsteady flow in time during the scour. Local velocity at plain bed is depending on flow contraction and backwater value.
The local velocity $V_l$ at any stage of scour is determined by Eq. (5) and the critical velocity $V_{cr}$ through the mean depth of $h_m = h_f(t + h_{qual}/2h)$ near abutments by Eq. (7).

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. (8, 9).

The ratio $V_l/V_{ap}$ (local to approach velocity) is depending on flow contraction and Froude number of the open flow (Fig.3). With increase contraction rate of the flow the difference between local and approach velocity of the flow is increasing and with increase the Froude number is decreasing. Among another factors local velocity, but not approach velocity, is forming the scour hole.

Velocities $V_{h_l}, V_{h_0}$ and relative ones $V_l/V_{h_l}, V_0/V_{h_0}, V_{w0}/V_{h_l}$, $\beta V_0/V_{h_l}$ are changing in time at steady and unsteady flow and bed layering (Fig.4 - 9). Relative velocity ratio $\beta V_0/V_{h_l}$ impact on relative depth of scour $h_s/h_f$, at steady and unsteady flow, is presented (Fig 8,9). With increase of the relative depth of scour $h_s/h_f$ the velocities $\beta V_0/V_{h_l}$ is increasing, and in case the ratio of the velocities become equal to 1, the scouring will stop.

River bed layering impact on local and critical velocities change in time during the scour hole development and depending on sequence of the layer with different grain size (Fig.10, 11). Presented formulas for calculation local and critical velocities at uniform flow and stratified river bed, development relative velocities in time at steady and unsteady flow were confirmed by test result.

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