Contraction rate, flow modification and bed layering impact on scour at the elliptical guide banks

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Abstract. Flow contraction by the bridge crossing structures, intakes, embankments, piers, abutments and guide banks leads to general scour and the local scour in the vicinity of the structures. Local scour is depending on flow, river bed and structures parameters and correct understanding of the impact of each parameter can reduce failure possibility of the structures. The paper explores hydraulic contraction, the discharge redistribution between channel and floodplain during the flood, local flow modification and river bed layering on depth, width and volume of scour hole near the elliptical guide banks on low-land rivers. Experiments in a flume, our method for scour calculation and computer modelling results confirm a considerable impact of the contraction rate of the flow, the discharge redistribution between channel and floodplain, the local velocity, backwater and river bed layering on the depth, width, and volume of scour hole in steady and unsteady flow, under clear water condition. With increase of the contraction rate of the flow, the discharge redistribution between channel and floodplain, the local velocity, backwater values, the scour depth increases. At the same contraction rate, but at a different Fr number, the scour depth is different: with increase in the Fr number, the local velocity, backwater, scour depth, width, and volume is increasing. Acceptance of the geometrical contraction of the flow, approach velocity and top sand layer of the river bed for scour depth calculation as accepted now, may be the reason of the structures failure and human life losses.

1. Introduction
Elliptical guide banks are used to guide the flow and sediments through a bridge opening, to reduce the flow separation at the alignment of the bridge, and to remove the scour hole from the abutment and embankment. The concentration of streamlines, flow modification as a local increase in velocity, and the development of a scour hole were observed at the upstream head of the elliptical guide banks. Impact of hydraulic contraction rate, discharge redistribution between channel and floodplain during the flood, flow modification and bed layering impact on scour at the elliptical guide banks on low-land rivers is not studied at all.

Equilibrium scour depth at bridge piers, abutments, and spur dikes were studied and a several books were published by Breuser & Raudkivi (1991), Hoffmans & Verheij (1997), Melville & Coleman (2000), and May et al. (2002). For determining the scour at the abutments, new approaches were elaborated by Kothyari & Ranga Raju (2001), Yanmaz & Celebi (2004), Olivetto & Hager (2002), and Gjunsburgs et al. (2001, 2004, 2005, 2006).

In some studies, the impact of contraction flow rate is disregarded (Breusers and Raudkivi (1991), Melville (1997), Kothyari and Ranga Raju (2001), Oliveto and Hager (2002), Coleman et al. (2003)
and others); in other studies of the scour at the abutments, the contraction flow is calculated as a ratio of geometrical parameters, such as embankment length $L_a$ to the channel width $L_c$ or abutment length, or as a geometrical obstruction ratio coefficient (see Liu et al. (1961), Gill (1972), Floehlich (1997), Lim (1997), Rahman and Haque (2003), Balio et al. (2009)). The hydraulic contraction rate of the flow was suggested by Rotenburg et al. (1965) as a ratio between the total discharge $Q$ and discharge under the bridge or the blocked part of it $Q_b$ for the discharge in floodplain in natural conditions. Sturm and Janjua (1994), Kouckhakzadeh and Townsend (1997) show that the ratio of the flow obstructed by abutment $Q_a$, to the flow at a specific width near the tip of abutment $Q_w$, is a significant parameter in estimating the equilibrium scour depth.

Flow at the structures is modified: velocities, backwater and the depth of flow increases. In formulas or methods for calculation depth of the scour at abutments are used mean velocity of the approach flow or Froude number with that velocity, or mean velocity of the flow where abutment is placed – Laursen & Toch (1956), Froelich (1989), Richardson et al. (1990), Melville (1997), Melville & Coleman (2000), Kothyari & Ranga Raju (2001), Radice et al. (2002). Presence of maximum (local) velocity near elliptical guide banks is confirmed by Latischko (1960) in laboratory tests. The modified flow with increased local velocities is forming the scour at the structures, but not the mean velocity as accepted by different authors. The paper presents formula for local velocity at the elliptical guide banks, comparison with mean velocity of the flow at different Fr numbers and it impact on depth of scour.

The influence of stratification of the river bed on the scour depth near bridge structures is confirmed by Rotenburg (1965), Ettema (1980), Raudkivi and Ettema (1983), Kothyari (1990), Kothyari et al. (1992), Garde and Kothyari (1998), FHWA-RD-99-188 (1999), Melville & Coleman (2000), Gjunsburgs et al. (2010) and others, but there is no methods or formulas for depth of scour calculation at river bed layering at elliptical guide banks. This study confirmed that using the mean grain size on the top of the river bed for calculation of the depth of scour, as it is accepted now by different authors, and neglecting layering of the river bed can lead to the collapse of the structures and losing of human lives.

Study of the impact of contraction rate, flow modification and a river bed layering is based on the tests, computer modeling results and method of calculation of the scour at the elliptical guide banks in time (Gjunsburgs et al. 2004, 2006, 2010).

2. Experimental setup
The tests were carried out in a 3.5 m wide and 21 m long flume. The tests under free surface flow conditions were carried out to study the flow distribution between the channel and the floodplain.

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 embankment, along it, and near the modelled elliptical guide banks.

| Tests | $L$ 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 | 0.103 | 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 |
The aim of the sand bed tests was to study the scour process at the head of elliptical guide bank, the changes in the local velocity, the effect of different flow parameters, the contraction rate, and the grain size of bed material on the scour near vertical abutment wall.

The openings of the bridge model were 50, 80, 120, and 200 cm. The flow contraction rate $Q/Q_b$ varied respectively from 1.56 to 5.69 for a floodplain depth of 7 and 13 cm, and the Froude numbers varied from 0.078 to 0.134 (Table 1); the slope of the flume was 0.0012.

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 at the bridge crossing introduction, 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). Thickness of the layers with different grain size 0.24 mm and 0.67 mm with standard deviation was equal 4, 7 and 10 cm. The Froude number at open-flow conditions varied from 0.078 to 0.1243, densiometric Froude numbers – from 0.62 to 1.65, 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, one side contraction of the flow.

Computer modelling was made to study impact of discharge redistribution between channel and floodplain on depth of scour.

3. Results
Results of the impact hydraulic contraction rate of the flow $Q/Q_b$ (where $Q$ is the flow discharge and $Q_b$ is the discharge in the bridge opening under free surface flow conditions): the relative local scour $h_s/h_f$ (where $h_s$ is the depth of scour and $h_f$ is the depth of water in the floodplain), the backwater value $\Delta h/h_f$ (where $\Delta h$ is the backwater value at the head of elliptical guide bank), relative local velocity $V_l/\beta V_0$ (where $V_l$ is the local velocity at the head of elliptical guide bank and $\beta V_0$ is the critical velocity) and the local velocity $V_l/V_{ap}$ (where $V_l$ is the local velocity and $V_{ap}$ is the approach flow velocity); the effect of the $Fr$ number of the flow on the scour development in time at the same contraction rate of the flow at the head of elliptical guide bank in clear water conditions are presented. Discharge distribution between the channel $Q_c$ and the floodplain $Q_f$ undergoes changes during the flood and because of that the contraction rate of the flow is changing in time. The computer modelling shows that the hydraulic contraction rate of the flow due to discharge redistribution between the channel and floodplain impact significantly on the depth of scour value.

With increase in the contraction rate of the flow, the local velocity, backwater values, and scour depth increase. At the same contraction rate, but at a different $Fr$ number of the flow, the depth of scour is different: an increase in the $Fr$ number leads to an increase in the local velocity, backwater, scour depth, width, and volume.

![Figure 1. Scour depth $h_s$, local velocity $V_l$, and critical velocity $\beta V_0$ development in time (Test EL4)](image-url)
With increase depth of scour in time the local velocity is reducing and critical velocity is increasing at steady flow conditions (Figure 1). The geometrical contraction of the flow — the ratio between the channel width and length of the abutment $L_a/L_c$, upon different values of discharge distribution between the channel and floodplain and different $Fr$ numbers in floods, is a constant value and cannot be used for a step-by-step calculation of the scour depth developed in time at the abutments during floods. All the results obtained are confirmed by the tests and calculated data and are presented in figures and tables.

Figure 2. Depth of scour development in time at different contraction rates of the flow $Q/Q_b$.

With increase of the hydraulic contraction rate $Q/Q_b$ the depth of scour is increasing as it confirmed in tests and theoretically (Figures 2, 3).

Figure 3. Relative depth of scour versus contraction rate of the flow

With increase of Froude number of the flow the relative backwater value is increasing (Figure 4).

Figure 4. Relative backwater value versus contraction rate of the flow at different $Fr$ number
At different contraction rate of the flow, $Fr$ number relative local velocity $V_l/\beta V_0$ is increasing (Figure 5).

![Figure 5](image)

**Figure 5.** Relative local velocity $V_l/\beta V_0$ versus contraction rate of the flow at different $Fr$ number

Relative local velocity $V/V_{ap}$ is increasing with increase of the contraction rate of the flow (Figure 6). The modified flow with increased local velocities near elliptical guide banks is forming the scour hole at the structures, but not the mean velocity as accepted by different authors.

![Figure 6](image)

**Figure 6.** Relative local velocity $V/V_{ap}$, versus contraction rate of the flow $Q/Q_b$.

![Figure 7](image)

**Figure 7.** Flow rates and depth distribution in the river Nemunas in the outflow Atmata at the cross-section Rusne (S.Vaikasas data).

More rapid increase of discharge in floodplain (Figure 7) leads to increase of the hydraulic contraction during the flood. Table 2 presents computer modelling results of changes in the contraction rate because discharge $Q$ distribution between channel $Q_c$ and floodplain $Q_f$ and impact of this distribution on the depth of scour. With increase of the floodplain discharge $Q_f$ the depth of scour is increasing.
Table 2. Impact discharge distribution between the channel and floodplain on the scour depth

| $Q_C$% | $Q_F$% | $L_a$ (cm) | $Q$ (l/s) | $Q/Q_b$ | $\Delta h$ (cm) | $V_l$ (cm/s) | $h_s(7\, h)$ (cm) | $h_{equil}$ (cm) | $L_a/b$ |
|-------|-------|------------|-----------|----------|----------------|-------------|------------------|-----------------|--------|
| 5%    | 85%   | 300        | 27.14     | 5.55     | 5.00          | 52.44       | 20.30           | 26.80           | 6      |
| 20%   | 80%   | 300        | 27.14     | 4.00     | 3.18          | 52.12       | 18.32           | 24.05           | 6      |
| 30%   | 70%   | 300        | 27.14     | 2.91     | 2.30          | 49.79       | 15.72           | 20.26           | 6      |
| 40%   | 60%   | 300        | 27.14     | 2.29     | 1.85          | 47.61       | 14.55           | 18.60           | 6      |
| 50%   | 50%   | 300        | 27.14     | 1.88     | 1.55          | 44.24       | 13.05           | 16.40           | 6      |
| 60%   | 40%   | 300        | 27.14     | 1.60     | 1.30          | 40.80       | 11.48           | 14.18           | 6      |
| 80%   | 20%   | 300        | 27.14     | 1.23     | 0.83          | 32.90       | 7.98            | 9.38            | 6      |

At stratified bed conditions when the first layer is scoured and the depth of scour $h_s > H_{d1}$ (where $H_{d1}$ the depth of the first layer with grain size $d_1$), scour continues in the second layer with grain size $d_2$ with another local and critical velocities on the top of the second layer (Figures 8, 9). 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.

Figure 8. Depth of scour, local and critical velocities development in time at stratified bed conditions, with $d_1 = 0.24 \text{ mm}$ in the first and $d_2 = 0.67 \text{ mm}$ in the second layer (Test AUL 6).

In Figures 8 and 9 depth of scour, local $V_l$ and critical $V_{0t}$ velocities development in time because of scour with different sequence of the layers are presented – fine on the top of the coarse grain size 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 $V_l$ 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 size $d_1/d_2$ or $d_2/d_1$ at the border of two layers changes its intensity – rapid development, when the first coarse sand layer is scoured and scour is continued in the fine.

It was found that the most critical conditions for structures take place when a fine-sand layer occurs under a coarse-sand layer. As soon as the coarse 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. Using the mean grain size on the top of the river bed for the depth of scour calculation, as it is accepted now by different authors and neglecting layering of the river bed can lead to the collapse of the structure.
Figure 9. 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 (TestAUL5).

4. Conclusions

The results obtained in tests, by the method for calculation of scour development in time (Gjunsburgs et al. 2006) and computer modelling results confirmed that the hydraulic contraction rate of the flow considerably affects the depth, width, and volume of a scour hole at the elliptical guide banks. The results of investigation are presented in Figures 1-9. An increase in the contraction rate of the flow, the relative local depth of scour \( h_s/h_f \) (Figure 3), relative backwater \( \Delta h/h_f \) (Figure 4), relative local velocity \( V_l/bV_0 \) (Figure 5) and ratio between local and approach flow velocities \( V_l/V_{ap} \) (Figure 6) leads to increase the depth of the scour hole. Increase of discharge distribution between the channel and floodplain, an increase of the discharge in floodplain leads to increase of the contraction rate of the flow and as well depth of scour. The increased \( Fr \) number of the flow (at the same contraction rate) leads to increases the depth of the scour hole. In the river bed layering the most critical condition arises when a fine-sand layer occurs under a coarse-sand layer (Figures 8, 9).

The geometrical contraction of the flow, i.e., the ratio of the channel width to the length of the abutment \( L_a/L_c \), at different discharge distributions between the channel and flood plain and different \( Fr \) number in floods has a constant value and cannot be used for a step-by-step calculation of the scour depth developed in time during floods at the elliptical guide banks. Acceptance of the geometrical contraction of the flow, approach velocity and top sand layer of the river bed for scour depth calculation as accepted now, may be the reason of the structures failure and human life losses.

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