Equilibrium depth of scour at straight guide banks

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Abstract: The equilibrium stage of scour at the head of straight guide banks with a uniform and stratified bed conditions have been studied. The contraction of the river by bridge crossing with straight guide banks considerably alters the flow pattern. The streamlines become curve and the concentration of streamlines, longitudinal and transverse slopes of the water surface, a local increase in velocity, vortex and eddy structures, and the origin of a flow separation zone between the extreme streamlines and the guide bank are observed and local scour is developing at the head of the straight guide banks. New formulae for calculation of equilibrium depth of scour at straight guide banks at uniform and stratified river bed is elaborated and confirmed by tests and computer modelling results.

1. Introduction

The aim of the present study is to elucidate the influence of the uniform stratified river bed on the equilibrium scour depth at straight guide banks for clear water conditions on the low-land rivers. Equilibrium stage of scour at uniform and stratified river bed at the head of the straight guide banks is not studied yet. The straight guide banks considerably change the flow pattern. At the head of the straight guide band there is local increase in velocity, flow separation, increased vortexes and scour hole. An additional contraction of the flow by a separation zone reduces the flow area at the alignment of the bridge crossing and increases the backwater value, slope, flow velocity, and non-uniformity of the scour at the alignment of the bridge crossing.

The length of a separation zone depends on the contraction of the flow by the bridge crossing. With equal time, hydraulic, and riverbed parameters, the scour depth at the straight guide banks is greater than that at the elliptical guide banks and abutments.

New formulae for calculation of equilibrium depth of scour at straight guide banks at uniform and stratified river bed is elaborated and confirmed by tests and computer modelling results. The size, shape, length, and other parameters of guide banks were studied by different authors: Rotenburg (1969), Latishenkov (1960), Neil (1973), Bradley (1978), Richardson and Simons (1984), Richardson and Davis (1995), Lagasse et al. (2001), and others.

The influence of the river bed stratification 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), Melvile & Coleman (2000), Gjunsburgs (2006, 2010) and the others, but at present time there are no

methods or formulas to calculate equilibrium depth of scour at straight guide banks at complex geological river bed conditions.

The equilibrium depth of scour considerably increases or reduces - depending on sequence, thickness of layers with different grain sizes. For example, the depth of scour is always greater when a fine - sand layer is under a coarse-sand layer(s) compare with the depth of scour obtained in coarse - sand layer with mean grain size, which is on the top of the river bed. Calculation of the depth of scour at the bridge foundations in the flow and taking into account only the grain size diameter in the upper layer of the river bed, as it excepted now, and neglecting stratification will lead to wrong results and finally to considerable damages and losses.

2. 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 - channel flow conditions. The rigid - bed tests were performed for different flow contractions and Froude numbers with the purpose of investigating the changes in velocity and water level near the embankment, along it, and near the modelled elliptical guide bank.

Table 1. Experimental data for free flow conditions in a flume.

Test	L (cm)	h_f (cm)	V (cm/s)	Q (l/s)	Fr	Re_c	Re_f
L1	350	7	6.47	16.60	0.780	7500	4390
L2	350	7	8.58	22.70	0.010	10010	6060
L4	350	7	8.16	20.81	0.098	10270	5590/5660
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
L8	350	13	8.74	41.38	0.076	16010	11395
L9	350	13	9.90	47.10	0.088	14300	14300

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, and with additional contraction by separated zone from 2.08 to 6.84, for the floodplain depth h_f = 7 or 13 cm; the Froude numbers varied from 0.078 to 0.134, R_c — from 7500 to 16010, and R_f — from 4390 to 14300, where R_c and R_f are the Reynolds numbers for the channel and floodplain, respectively; the slope of the flume was 0.0012. The sand was placed 1 m up and down the contraction point of the flume. The grain sizes were 0.24 and 0.67 mm, and the tests were performed with a uniform layer or with two layers of different thicknesses and grain sizes.

The dimension of the upper part of the straight guide bank, namely the length, calculated according to the Latishenkov (1960) method, as for elliptical guide banks, and was found to be dependent on the flow contraction rate and the main channel width. The length of the lower part of the guide bank was assumed to be half of the upper part.

3. Methods. Calculation equilibrium depth of scour at uniform and stratified river bed

Civil engineers should know the equilibrium depth of scour as important parameter for appointment the depth for bridge foundation. It is essential for engineers to have no uncertainty in determination of safe depth of burial of footing and selection of scour countermeasures.

In the approach of bridge contraction, the streamlines are bended and after that goes parallel to embankment. The flow velocities along the extreme streamline dropped down to almost zero, then gradually increases and reach its maximum at the head of the straight bank, the local velocity with vortex structures forms scour holes.

The Bernoulli equation for two cross sections for unit streamline was used and the local velocity V_l at the straight guide bank can be found:

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

where φ – velocity coefficient depending on flow contraction rate, g – gravitational acceleration, and Δh – maximum backwater (Rotenburg et al. 1965). Local flow modification at the head of the straight guide bank is forming scour hole.

Based on the flow - continuity relation, the discharge across the width of a scour hole before and after the scour can be defined as:

$$Q_f = k \cdot Q_{sc}, \tag{2}$$

where Q_f – the discharge across the width of the scour hole with a plain bed, Q_{sc} – the discharge of the scour hole with a scour depth h_s, and k – a coefficient depending on the contraction rate of the flow.

The equation (2) can be written as follows:

$$mh_s \cdot h_f V_l = k(mh_s h_f + \frac{mh_s}{2} \cdot h_s)\cdot V_{lt}, \tag{3}$$

where m – the slope of the scour hole wall, h_s – the depth of the scour hole, h_f – the water depth in floodplain, V_l – local flow velocity, and V_{lt} – local flow velocity after time t at a scour depth h_s.

Local flow velocity at any depth of scour h_s is:

$$V_{lt} = \frac{V_l}{k\left(1+\dfrac{h_s}{2h_f}\right)} = \frac{\varphi\sqrt{2g\Delta h}}{k\left(1+\dfrac{h_s}{2h_f}\right)}, \tag{4}$$

The critical velocity of the beginning of sediment movement V_0 can be found from the formulae (Studenitcnikov 1964):

$$V_0 = 3.6d^{0.25}h_f^{0.25}, \tag{5}$$

where d – the grain size of the bed material in the layer Hd.

The critical velocity of the beginning of sediment movement V_{0t} at any depth of scour h_s, is given by:

$$V_{0t} = \beta \cdot V_0\left(1+\frac{h_s}{2h_f}\right)^{0.25}, \tag{6}$$

where b – a coefficient of velocity V_0 reduction because of flow vortex structures.

The local flow velocity V_{lt} is decreasing and velocity V_{0t} is increasing with development of the scour hole. The clear - water scour reaches the equilibrium and ceases when V_{lt} becomes equal to V_{0t}:

$$\frac{V_l}{k\left(1+\dfrac{h_{equil.}}{2h_f}\right)} = \beta V_0 \cdot \left(1+\frac{h_{equil.}}{2h_f}\right)^{0.25} , \qquad (7)$$

The equilibrium depth of scour for uniform river bed can be determined from (7) as follows:

$$h_{equil} = 2h_f\left[\left(\frac{V_l}{k\beta V_o}\right)^{0.8} - 1\right] \cdot k_m \cdot k_\alpha , \qquad (8)$$

where h_f – the water depth in floodplain, V_l – local flow velocity, k – a coefficient depending on the contraction rate of the flow, b – a coefficient of the critical velocity V_0 reduction, because of flow vortex structures, V_0 – velocity of the beginning of sediment movement, k_m – a coefficient depending on the side - wall slope of the guide bank [27], and k_α – a coefficient depending on the angle of flow crossing.

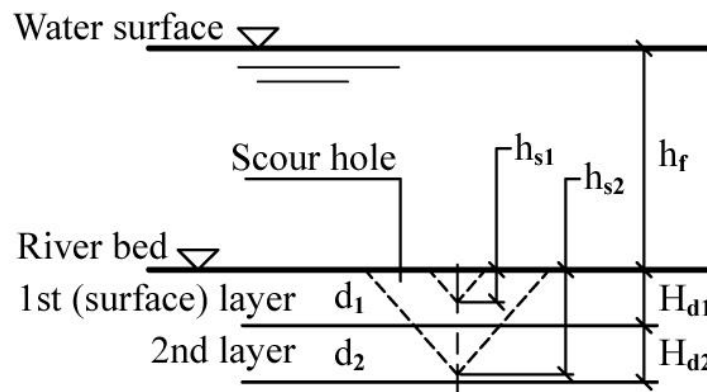The geology of the river bed is complicate and usually is formed by layers with different thickness and grain sizes.

Figure 1. Scour hole at two layers Hd1 and Hd2 with different grain sizes d1/d2 or d2/d1.

For computing equilibrium depth of scour necessary to know new local and critical velocities on the top of the second layer, because at those velocities depth of scour is developing in the second layer. The local velocity on the surface of the second layer is found by the formula:

$$V_{lt1} = \frac{V_{l.}}{k\left(1+\dfrac{H_{d1}}{2h_f}\right)} , \qquad (9)$$

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

The critical velocity on the top of second layer is determined using 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:

$$V_{01} = \beta 3.6 \cdot d_2^{0.25} h_f^{0.25} \left(1+\frac{H_{d1}}{2h_f}\right), \tag{10}$$

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.

Then, the scour depth in the second layer is determined as:

$$h_{s2} = 2h_m\left[\left(\frac{V_{lt1}}{V_{01}}\right)^{0.8} -1\right]\cdot k_\alpha \cdot k_m, \tag{11}$$

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

$$h_{equil} = H_{d1} + h_{s2}, \tag{12}$$

If $h_{s2}>H_{d2}$, the calculation could be continued using Eq. (11,12).

4. Results

Depth of scour measured in time for seven hours during the tests were compared with depth of scour calculated in time early preposed method (Gjunsburgs et al.2008) for stratified river model bed with grain size d1=0.24mm and d2=0.67mm. The good agreement with calculation data allow to make computer modeling and prolong the scour depth development in time till to equilibrium stage and compare with equilibriun depth of scour calculated by Eq.8,11,12 .

When the scour depth is less than thickness of the first layer $h_{equil}<H_{d1}$, equation (8) can be used for depth of scour calculation at the head of the straight guide bank; however, when equilibrium depth of scour is greater than thickness of the first layer: $h_{equil}>H_{d1}$, the scour develops in the second layer with a grain size d_2. If $h_{equil}>H_{d1} + H_{d2}$, the scour develops in the third layer with a grain size d_3, and so on.
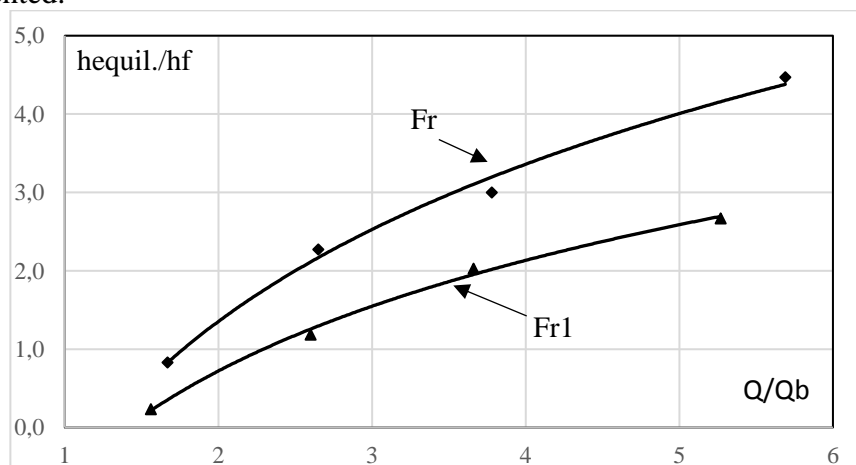
Future, using method for calculation of scour development in time and computer program Robo, depth of scour was calculated till equilibrium stage and compared with depth of scour calculaed with formula (8) for uniform river bed and with formula (11) at stratified river bed conditions.

In Table 2 are presented comparison test at steady flow conditions with calculation results with contraction rate of the flow Q/Qb from 5.69 to 2.60, with thicknes of the first layer Hd1 from 0.1 m to 0.04m. The depth of scour in the second layer hs2 is calculated by formula (11), and equilibrium depth of scour was sum the of the thickness of the first layer and depth of scour at the second layer hs2 (12). The equilibrium depth (11,12) of scour is comared with equilibrium depth of scour computed by method presented early (Gjunsburgs et al.2010) and results are in good agreement (Table 2).

Table 2. Comparison equilibrium depth of scour at river bed layering.

Test	Q/Qb	Hd	hs2	hs equil.	hst.equil	hs/hst	hs2	hs equi	hst	hs/hs
		m	m	m	m	m	m	m	m	m
			d1/d2				d2/d1		0.24/0.67	d2/d1
				d1/d2	d1/d2	d1/d2		d2/d1		
				Robo					Robo	
ST22	5.690	0.100	0.214	0.314	0.307	1.021	0.129	0.229	0.223	1.025
ST24	5.270	0.100	0.087	0.187	0.183	1.023	0.026	0.126	0.124	1.015
ST25	5.690	0.100	0.203	0.303	0.292	1.037	0.118	0.218	0.210	1.036
ST26	3.660	0.070	0.072	0.142	0.138	1.033	0.020	0.090	0.096	0.934
ST27	3.870	0.070	0.132	0.202	0.198	1.019	0.068	0.138	0.135	1.021
ST28	3.780	0.070	0.138	0.208	0.206	1.010	0.075	0.145	0.143	1.016
ST29	2.600	0.040	0.032	0.072	0.080	0.897	0.002	0.042	0.042	1.006
ST30	2.690	0.040	0.077	0.117	0.115	1.019	0.032	0.072	0.075	0.966
ST31	2.650	0.040	0.109	0.149	0.156	0.953	0.064	0.104	0.102	1.016

In Figure 2 the relative equilibrium depth of scour dependence on contraction rate of the flow is presented.

Figure 2. Relative equilibrium depth of scour dependence on contraction rate of the flow.

As show tests and calculated results with increase of the contraction rate of the flow the relative equilibrium depth is increasing (see Figure 2).

5. Conclusion

The tests of the development of a scour hole at the head of the straight guide banks showed the presence of a streamline concentration, a local increase in the flow velocity and backwater value, the origin of vortex and eddy systems, the flow separation, an additional flow contraction by the separation zone, and an increase in the non-uniformity of distribution of flow velocities and scour depth in the alignment of the bridge crossing.

Presented method for calculation equilibrium depth of scour at straight guide banks at uniform and stratified river bed. The equilibrium depth of scour considerably increases or reduces - depending on sequence, thickness of layers with different grain sizes. Most dangerous condition for stricture is when layer with fine sand is under the coarse sand layer.

When the scour depth is less than thickness of the first layer $h_{equil}<H_{d1}$, Eq. (8) can be used, when equilibrium depth of scour is greater than thickness of the first layer: $h_{equil}>H_{d1}$, Eq. (8,11,12). The formulas suggested can be used for predicting the equilibrium depth of scour at the stage of design or maintenance of the straight guide banks.

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