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LOCAL SCOUR AT STRAIGHT GUIDE BANKS IN PLAIN RIVERS

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Abstract. The local scour at abutments, elliptical and straight guide banks in plain rivers was studied. The flow pattern and the scour hole parameters at abutments, elliptical and straight guide banks are different. Some researchers believe that the guide banks can be used to protect the abutments, namely to remove the scour hole from the abutment. But the scour hole does not disappear; it is developing at the head of a straight guide bank and is of a greater size than that at abutments. The scour near the straight guide banks has not yet been studied. A streamline concentration, a local increase in flow velocity, vortex and eddy structures, flow separation, an additional flow contraction by a separation zone, and a scour hole were observed at the head of the straight guide banks. The differential equation of equilibrium for the bed sediment movement in clear water is used, and a new method for computing the scour development in floods at straight guide banks is elaborated. The method is confirmed by experimental data. This method can be used for predicting in advance the scour development at straight guide banks with the flow and riverbed parameters varying during floods of different probability, sequence, frequency, and duration.

Keywords: scour, straight guide banks, floods, abutments

1. Introduction

The scour development in floods at abutments [1], elliptical guide banks [2, 3], and straight guide banks was studied. According to the tests and methods proposed, the scour depth at the straight guide banks is greater than that at the elliptical guide banks and abutments with equal time, hydraulic, and riverbed parameters.

The concentration of streamlines, a local increase in flow velocity, vortex and eddy structures, flow separation, an additional flow contraction by a separation zone at the alignment of bridge crossing, and the development of a scour hole were observed at the upstream head of the straight guide bank.

The size, shape, length, and other parameters of guide banks were studied by different authors [4–13], and others. According to some studies, the guide banks can be used to protect the abutments. However, the scour hole does not disappear, it is developing at the head of the straight guide banks and has a greater size than that at the abutments.

The straight guide banks considerably change the flow pattern. An additional contraction of the flow by a separation zone reduces the flow area at the opening of the bridge crossing and increases the backwater value, slopes, flow velocities, and non-uniformity of the flow velocities and scour at the alignment of the bridge.

The length of a separation zone depends on the contraction of the flow by the bridge crossing.

The differential equation of equilibrium for the bed sediment movement in clear water is used, and a new method for computing the scour development at the straight guide banks during multiple floods is elaborated. The method is confirmed by experimental data. By using this method, the scour development at the head of the straight guide banks during floods can be computed in advance at the stage of design or in the maintenance period.

2. Experimental setup

Tests were carried out in a flume 3.5 m wide and 21 m long.

Experimental data for the open flow conditions are presented in Table 1. The dimension of the upper part of a straight guide bank, namely the length, was the same as that calculated for an elliptical one according to the Latishenkov method [14] and was found to be dependent on the flow contraction rate and the main channel width. The length of the lower part of the straight guide bank was assumed to be half of the upper part.

Table 1. Experimental data for open flow conditions in flume

Tests	L	h_f	V	Q	Fr	Re_c	Re_f
	cm	cm	cm/s	l/s			
L1	350	7	6.47	16.60	0.0780	7500	4390
L2	350	7	8.58	22.70	0.0103	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 discharge distribution between the channel and the floodplain was studied under open flow conditions.

The rigid bed tests were performed for different flow contraction rates, so that to investigate the flow velocity, the flow separation, and the changes in water level in the vicinity of the straight guide bank.

The aim of the sand bed tests was to study the scour processes, the changes in the flow velocity with time, the effect of hydraulic parameters, the flow contraction rate, the grain size of the bed material, the scour development in time, the bed level changes along the straight guide bank, and the size of the flow separation zone.

The openings of the bridge model were 50, 80, 120, and 200 cm. The flow contraction rate Q/Q_b (where Q is the flow discharge and Q_b is the discharge in the bridge opening under open flow conditions) varied from 1.56 to 5.69 for the depth of floodplain of 7 and 13 cm. The Froude number varied from 0.0665 to 0.1339. The slope of the flume was 0.0012.

The tests with a sand bed were carried out in the conditions of clear water.

The sand was placed 1 m up and down the contraction of the flume. The mean grain size was 0.24 mm with a standard deviation. The conditions 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 with time scale 7. With respect to the real conditions, the test time was equal to 2 days. This was the mean duration of time steps into which the flood hydrograph should be divided.

3. Method

The differential equation of equilibrium bed sediment movement in the conditions of clear water has the form

$$dw / dt = Q_s \qquad (1)$$

where t = time; w = volume of scour hole; Q_s = sediment discharge out of the scour hole.

According to laboratory tests, the scour hole volume at the straight guide banks was $w = 1/6\ \pi m^2 h_s^3$.
The left-hand part of Eq. (1) can be written as

$$\frac{dw}{dt} = \frac{1}{2}\pi m^2 h_s^2 \frac{dh_s}{dt} = a h_s^2 \frac{dh_s}{dt} \qquad (2)$$

where h_s = scour depth; m = steepness of the scour hole; and $a = ½\ \pi m^2$.
The sediment discharge is determined by the Levi [15] formula

$$Q_s = A \cdot B \cdot V_l^4 \qquad (3)$$

where $B = mh_s$ = width of the scour hole; V_l = local velocity at the head of the straight guide bank; and A = parameter in the Levi formula [15].

The sediment discharge upon development of the scour is

$$Q_s = A \cdot mh_s \cdot V_l^4 = b \frac{h_s}{k_{str}\left(1 + \frac{h_s}{2h_f}\right)^4} \qquad (4)$$

where $b = AmV_l^4$; k_{str} = coefficient of changes in the discharge due to scour.

The hydraulic characteristics, the flow contraction rate, the velocities V_0 and V_l, the grain size in different bed layers, the sediment discharge, and the depth and width of the scour hole varied during the flood.
Upon development of the scour, we have

Here, γ = specific weight of sediments; β = coefficient of reduction in V_0 due to the vortex and eddy systems; V_0 = velocity required to start the sediment movement; d = mean grain size of the bed material; and h_f = depth of water in floodplain.

$$A = \frac{5.62}{\gamma} \cdot \left[1 - \frac{\beta V_0}{V_l} \left(1 + \frac{h_s}{2h_f} \right)^{1.25} \right] \cdot \frac{1}{d^{0.25} h_f^{0.25} \left(1 + \frac{h_s}{2h_f} \right)^{0.25}} \quad (5)$$

Taking into account Eqs. (2) and (4), differential Eq. (1) can be presented as

$$a h_s^2 \frac{dh_s}{dt} = b \frac{h_s}{k_{str} \left(1 + \frac{h_s}{2h_f} \right)^4} \quad (6)$$

or

$$D_i \cdot h_s \left(1 + \frac{h_s}{2h_f} \right)^4 dh_s = dt \quad (7)$$

where D = a/b.

After integration, we have

$$t = D_i \int_{x_1}^{x_2} h_s \left(1 + \frac{h_s}{2h_f} \right)^4 dh_s \quad (8)$$

It was assumed that D was constant inside the time interval.

After integration with new variables, $x = 1+ +h_s/2h_f$, $h_s = 2h_f(x-1)$, and $dh_s = 2h_f dx$, we have

$$N_i = \frac{t_i}{4 D_i h_f^2} + N_{i-1} \quad (9)$$

where $N_i = 1/6x_i^6 - 1/5x_i^5$ and t_i = time interval.

Using the graph N = *f* (x) or the data of Table 2 for the calculated N_i, we find x_i and the scour depth at the end of time interval:

$$h_s = 2h_f (x-1) \quad (10)$$

The scour depth depends on the side-wall slope of the straight guide bank and the angle of flow crossing:

$$h_s = 2h_f (x-1) k_m k_\alpha \quad (11)$$

where k_m = coefficient depending on the side-wall slope of the guide bank [16]; and k_α = coefficient depending on the angle of flow crossing [10].

To determine the scour depth development during the flood, the hydrograph was divided into time steps with duration of 1 or 2 days, and each time step was divided into time intervals up to several hours (Fig. 1). In the laboratory tests, the time steps were divided into 20 time intervals. For each time step, the following parameters must be determined: h_f – water depth in the floodplain; Q/Q_b – flow contraction rate; Δh – maximum backwater (after computing the general scour development in time by Rotenburg method [17]; d – grain size; H – thickness of the bed layer with d_i; and γ – specific weight of the bed material.

As a result, we have V_l, V_0, A, D, N_i, N_{i-1}, and h_s at the end of time intervals and finally at the end of the time step. For the next time steps, the flow parameters change under the action of the flood because of the general and local scour developed during the previous time steps

Table 2. The value of N_i as a function of x_i

x_i	1.0	1.2	1.4	1.6	1.8
N_i	-0.033	0.0002	0.18	0.70	1.90
x_i	2.0	2.2	2.4	2.6	2.8
N_i	4.29	8.62	15.98	27.20	46.07

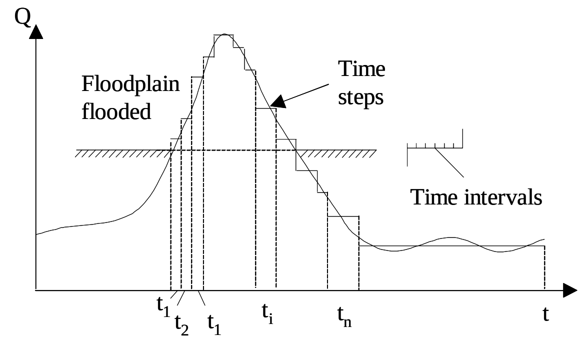

Fig. 1. Hydrograph divided into time steps and time intervals of the hydrograph.

The depth of the local scour at the head of the straight guide banks depends on the general scour at the opening of the bridge crossing.

4. Results

The contraction of the river by bridge embankments with straight guide banks considerably alters the flow pattern. The streamlines become curved; the concentration of streamlines, increased 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 streamline and the straight guide bank) are observed (Fig. 2). The flow is redirected by the straight guide bank to the opposite riverbank in the case of a one-side contraction or to the center of bridge opening in the case of a two-side contraction. The additional contraction of the flow by the separation zone significantly increases the flow velocities and the scour non-uniformity at the opening of the bridge crossing.

Approaching the bridge-crossing model, the longitudinal flow velocity along the extreme streamline reduces and, not far from the straight guide bank, becomes almost zero. At the head of the guide bank, the flow velocity is sharply increasing, the water level shows a sharp drop, and the development of the scour hole is observed.

According to the tests, the length of the flow separation zone at the alignment of the model bridge crossing depends on the initial flow contraction rate (Fig. 3).

The local velocity is changing with the flow contraction rate, the length of the separation zone, and the Froude number of open-flow conditions. The local velocity was found according to the formula

$$V_l = \varphi_{str}\sqrt{2g \cdot \Delta h_{str}} \qquad (12)$$

where φ_{str} = velocity coefficient for the straight guide banks; g = gravitational acceleration; and Δh_{str} = maximum backwater determined by the Rotenburg (1969) formula.

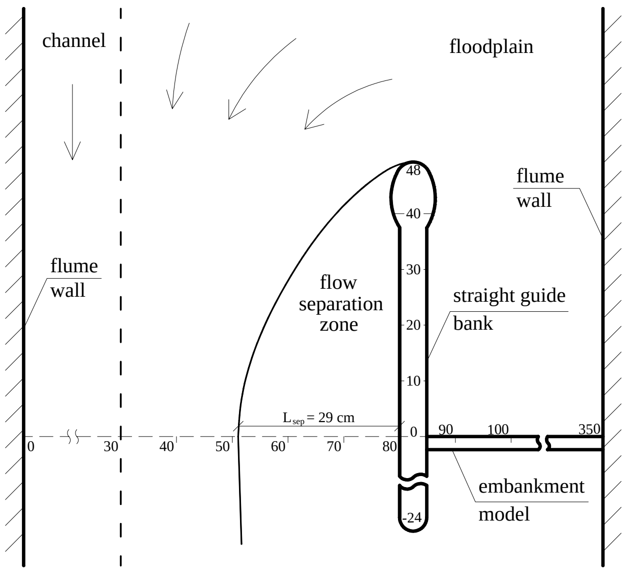

Fig. 2. Section of the flow separation zone near the straight guide bank (test ST29)

In the rigid bed conditions, the changes in the local velocity and water level were measured for different flow contraction rates, and the values of φ_{str} were found. Figure 4 shows the velocity coefficient φ_{str} as a function of the flow contraction rate. With increasing flow contraction rate, the velocity coefficient φ_{str} decreases.

The velocity coefficient depends on the shape of the guide banks; at elliptical guide banks, the value of φ_{el} is higher than that of φ_{str} at the straight guide banks.

The hydraulic losses at the straight guide banks are higher than those at elliptical guide banks, and consequently the value of φ_{str} is smaller than φ_{el}.

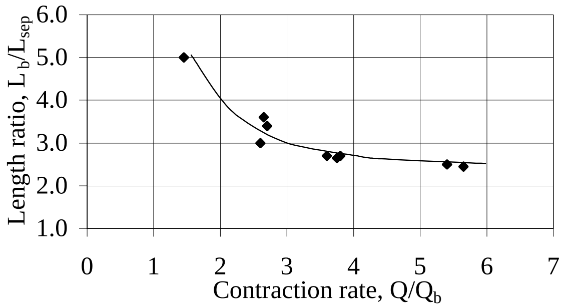

Fig. 3. Ratio between the bridge opening length and the flow separation zone length versus the flow contraction rate

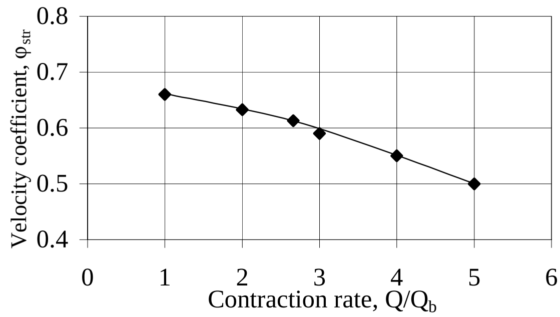

Fig. 4. Velocity coefficient φ_{str} versus the flow contraction rate for straight guide banks

Table 3. Comparison between the experimental and calculated data for local velocities at the straight guide banks

Tests	Δh cm	Q/Q_b	$V_{l.exp}$ cm/s	$V_{l.calc}$ cm/s	$V_{l.calc}$ / $V_{l.exp}$
ST26	6.29	5.69	50.00	50.90	0.9823
ST27	2.88	5.27	41.05	36.10	1.1371
ST28	5.82	5.69	49.00	48.90	1.0020
ST29	2.26	3.66	38.00	37.70	1.0080
ST30	3.67	3.87	44.50	47.10	0.9448
ST31	3.95	3.78	59.70	49.30	1.2110
ST32	1.11	2.60	26.70	28.00	0.9536
ST33	1.656	2.69	34.00	34.90	0.9742
ST34	1.098	2.65	41.20	39.30	1.0483
ST35	0.422	1.56	18.60	18.60	1.0000
ST36	0.575	1.66	20.30	21.60	0.9398
ST37	0.77	1.67	25.60	25.00	1.0240

A comparison between the experimental and calculated data for local velocities at the straight guide banks is presented in Table 3.

With the development of scour hole, the local velocity decreases in the time step of the hydrograph under steady flow conditions. The discharge across the width of a scour hole also changes: $Q_s = k_{str}Q_{se}$, where Q_f = flow discharge across the width of the scour hole with a plain bed; Q_{se} = flow discharge across the width of the scour hole with scour depth h_s; and k_{str} = coefficient of changes in the discharge due to scour at the straight guide banks (Fig. 5). The coefficient k_{str} depends on the flow contraction rate Q/Q_b. The local velocity at any time step of hydrograph and at any depth of the scour hole is found by the following formula:

$$V_{lt} = \frac{V_l}{k_{str}\left(1+\frac{h_s}{2h_f}\right)} = \frac{\varphi_{str}\sqrt{2g \cdot \Delta h_{str}}}{k_{str}\left(1+\frac{h_s}{2h_f}\right)} \quad (13)$$

Using Eq. (13), we can calculate the changes in the local velocity with scour development under steady or unsteady flow conditions.

Part of the bed materials removed from the scour hole gets deposited along the extreme streamline, while another part of sediments is transferred away and gets deposited inside the separation zone. Along the straight guide bank, the bed level increases (Fig. 6).

The straight guide banks help to remove the scour from the abutments, but at the same time increase the flow contraction rate, the non-uniform distribution of the flow velocities, and the scour at the opening of the bridge, the backwater value and slopes, as well as the depth of scour. The conditions of the flow passage through the bridge opening with straight guide bank become worse than in the case of the abutment alone. A considerable scour hole is developing at the heads of the straight guide banks and is greater in size than at the abutments and elliptical guide banks. Consequently, the straight guide banks cannot be used for abutment protection.

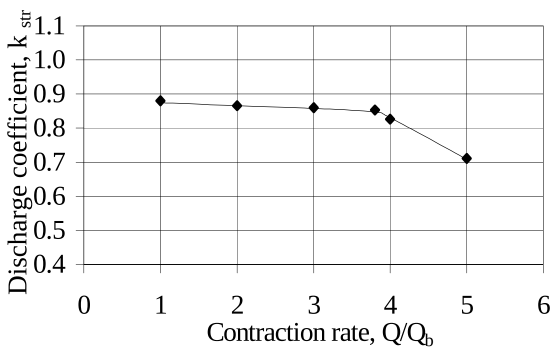

Fig. 5. Coefficient k_{str} versus the flow contraction rate Q/Q_b

A comparison between the experimental and calculated volumes of a scour hole at the straight guide banks is presented in Table 4. The results obtained showed an acceptable agreement.

The shape of the scour hole at the straight guide banks was not changing with time during the tests. The scheme of a scour hole at the head of the straight guide bank of test ST26 with bridge opening L_b = 50 cm and flow contraction rate Q/Q_b = 5.69 is presented in Fig 7.

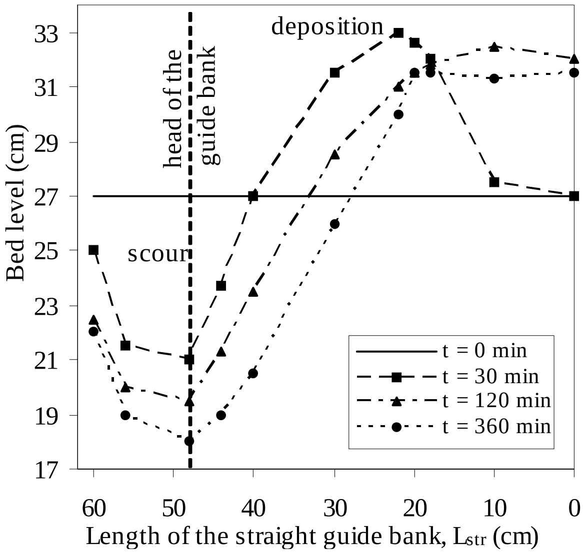

Fig. 6. Bed-level changes in time at the upstream part of the straight guide bank (test ST33)

Table 4. Comparison of the experimental and calculated volumes of the scour hole at the straight guide banks

Tests	Time min	h_s cm	W_{exp} cm^3	W_{calc} cm^3	W_{exp} / W_{calc}
ST27	220	14.60	4912.0	4760.0	1.0319
ST26	40	13.10	3519.7	3498.0	1.0062
ST26	70	15.20	5660.9	5800.0	0.9760
ST26	90	16.00	6901.0	7520.0	0.9177
ST26	300	19.30	11722.4	11950.0	0.9810
ST29	20	5.40	419.0	535.0	0.7832
ST30	80	10.10	3072.0	3045.0	1.0089
ST33	120	7.40	1240.9	1255.0	0.9888
ST33	240	7.90	2003.3	1820.0	1.1007
ST34	270	11.50	3165.6	3465.0	0.9136

Comparisons between the experimental and calculated scour depth development in time for different flow parameters and flow contraction rates in tests ST32 and ST34 are illustrated in Figs. 8 and 9.

The development of the scour depth measured in tests and calculated by the method suggested is similar, namely the rapid development at the initial stage of the process is gradually reduced with time (Figs. 8 and 9). A comparison between the experimental and calculated scour depths at the straight guide banks after 7 hours from the start of tests is presented in Table 5. According to the data obtained, the results are acceptable.

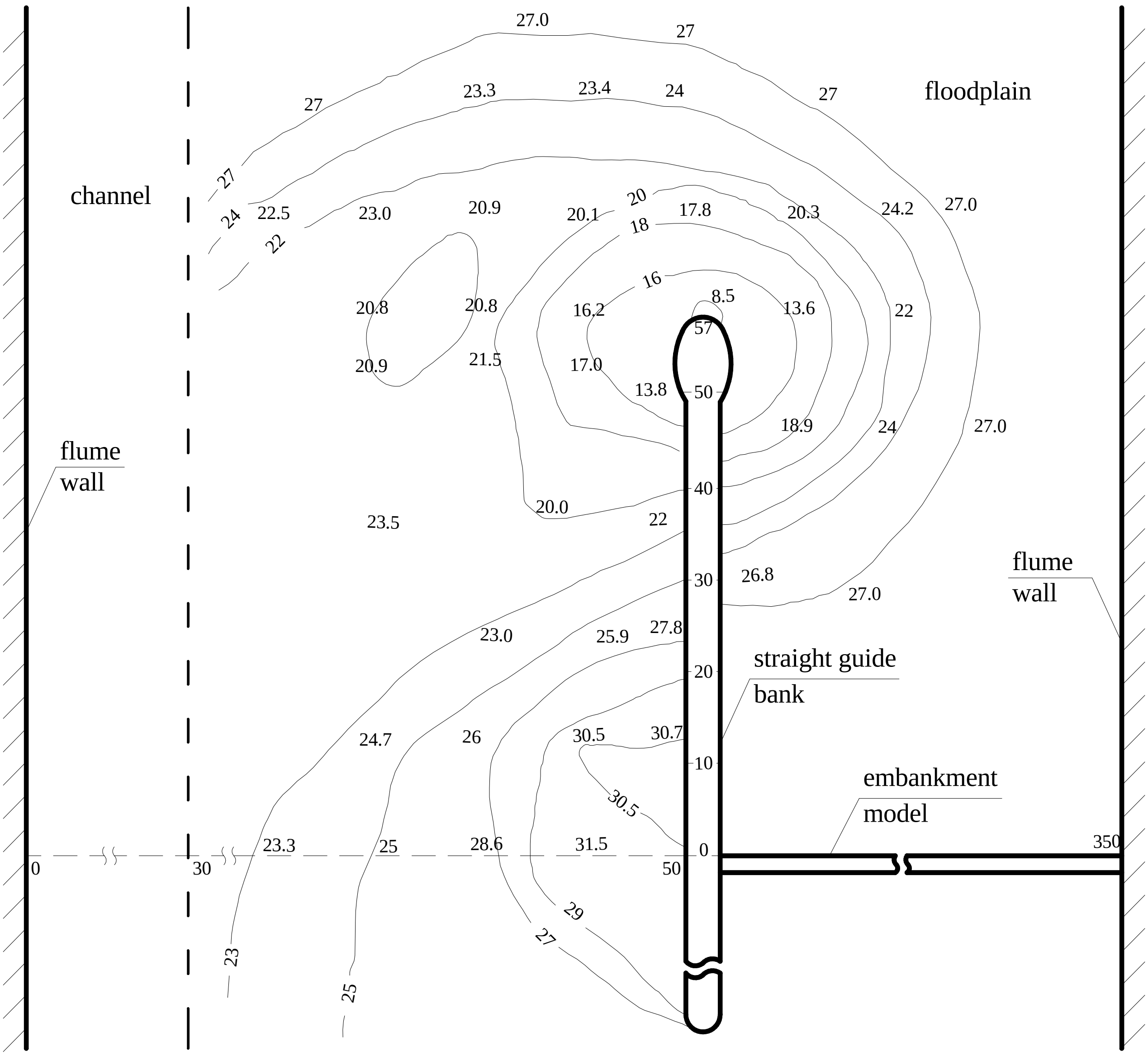

Fig. 7. Scheme of a scour hole athe straight guide bank (test ST26)

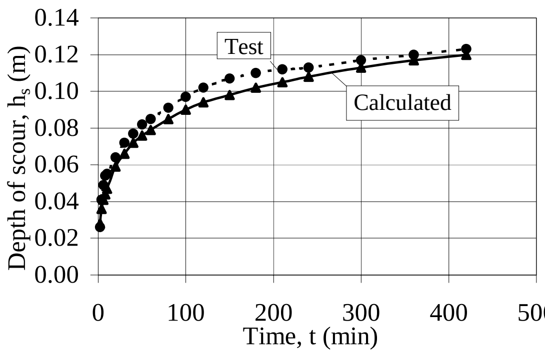

Fig. 8. Scour development in time at the head of the straight guide bank (test ST34)

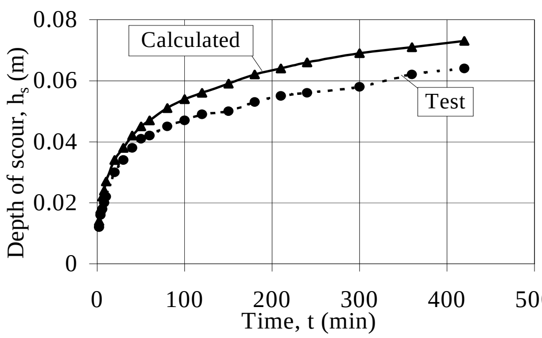

Fig. 9. Scour development in time at the head of the straight guide bank (test ST32)

Table 5. Comparison of the experimental and calculated depths of scour at the straight guide banks

Tests	Q l/s	Q/Q_b	h_f cm	L_b cm	d mm	V_l cm/s	$h_{s.exp}$ cm	$h_{s.calc}$ cm	$h_{s.exp}/h_{s.calc}$
ST26	22.7	5.69	7	50	0.24	50.9	19.9	23.6	0.8432
ST27	16.55	5.27	7	50	0.24	36.1	16.6	14.6	1.1370
ST28	22.7	5.69	7	50	0.24	48.9	20.8	22.7	0.9163
ST29	16.55	3.66	7	80	0.24	37.7	10.4	11.5	0.9043
ST30	22.7	3.87	7	80	0.24	47.1	14.2	15.7	0.9045
ST31	27.14	3.78	7	80	0.24	49.3	18.3	16.4	1.1159
ST32	16.55	2.60	7	120	0.24	28.0	6.4	7.3	0.8767
ST33	22.7	2.69	7	120	0.24	34.9	8.7	10.1	0.8614
ST34	27.14	2.65	7	120	0.24	39.3	12.3	12.0	1.0250

The order of calculating the dimensions of the scour hole at the straight guide banks is as follows.

1. The hydrograph of the design flood should be divided into time steps. Each time step in turn should be divided into time intervals.
2. The values of water depths and flow velocities at each time interval under open-flow conditions should be calculated.
3. Grain sizes of the bed materials and depths of the bed layers with different grain sizes should be found.
4. The general scour depth is calculated at each time step of the flood hydrograph by the Rotenburg (1969) method. As a result, we determine the flow contraction rate and the maximum backwater value.
5. Using the method suggested, we determine the development in time of depth, width, and volume of the scour hole at the straight guide banks with different probability, sequence, frequency, and duration of flood hydrograph.

5. Conclusions

In the tests and by the methods suggested, it was found that the dimensions of scour at the bridge crossing structures – abutments, elliptical and straight guide banks – are different.

The tests at the head of straight guide banks showed the presence of a streamline concentration, a local increase in the flow velocities 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 flow velocities and scour depths in the opening of the bridge crossing. The conditions of the flow passage through the bridge opening with the straight guide bank become worse than in the case of the abutment alone.

The scour hole developing at the head of the straight guide banks is greater in size than that at the abutments and elliptical guide banks.

Because of the flow-pattern changes, non-uniform velocities and scour distribution at the bridge opening, as well as a considerable scour at the head of straight guide banks, the straight guide banks cannot be used as abutment protection measures; they work only in special cases when it is necessary to redirect the flow from the abutment.

In the present study, the differential equation of the bed sediment movement under clear-water conditions was used, and a method for calculating the scour development at the head of the straight guide banks during floods was elaborated and confirmed by experimental data. The method suggested can be used for predicting in advance the scour development at the head of straight guide banks at the stage of design or in the maintenance period.

References

1. Gjunsburgs, B. and Neilands, 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, 2004. vol. 1: 443-448.
2. Gjunsburgs, B., Neilands, R.R., and Govsha, E. Local Scour at Elliptical Guide Banks in Plain Rivers. *Proc. of River Flow 2006*, Lisbon, Portugal, in Ferreira, Alves, Lead, and Cordoso (eds), London: Taylor & Francis Group, 2006. vol. 2: 1649-1655.
3. Gjunsburgs, B., Neilands, R.R., and Govsha, E. Scour Development at Elliptical Guide Banks During Multiple Floods. *Proc. of 32nd Congress of IAHR*, Corila, Venice, Italy, 2007. vol.2, p. 598 (on cd – 10 pages).
4. Rotenburg, I.S. *Shape of the Downstream Part of the Guide Banks.* Proc. of Saratov Road Construction Institute 1940. (in Russian).
5. Rotenburg, I.S., Poljakov, M.P., Zolotarev, I.V. and Lavrovskij, V.A. *Bridge Crossing Design.* Moscow: Vysshaya Shkola 1965. (in Russian).
6. Latishenkov, A.M. *Guide Banks*. Materials of VODGEO Water Research Institute, Laboratory of Hydraulics, Informative materials No.1 1956. (in Russian).
7. Neill, C.R. *Guide to Bridge Hydraulics.* Roads and Transportation Association of Canada, Press of University of Toronto, Toronto, Canada. 1973.
8. Richardson, E.V. and Simons, D.B. Use of Spurs and Guide Banks for Highway Crossing. *Proc. of Transportation Research Record, 2nd Bridge Engineering Conf.*, 1984. vol. 2.
9. Bradley, J.N. *Hydraulics of Bridge Waterways*. Hydraulic Design Series No. 1, U.S. Dept. of Transportation, Federal Highway Administration, 2nd Ed., Washington D.C. 1978.

10. Richardson, E.V. and Davis, S.R. *Evaluating Scour at Bridges*. 3rd ed. of Hydraulic Engineering Circular, No. 18, U.S. Department of Transportation, Federal Highway Administration, Washington D.C. 1995.
11. Lagasse, P.F., Schall, J.D., Johnson, F., Richardson, E.V., and Chang, F. *Stream Stability at Highway Structures.* Report No. FHWA IP-90-014, HEC-20. 1995.
12. Lagasse, P.F., Richardson, E.V., and Zevenbergen, L.W. *Design of Guide Banks for Bridge Abutment Protection.* Stream Stability and Scour at Highway Bridges. Reston, VA: ASCE, 0-7844-0407-0. 1999.
13. Lagasse, P.F., Zevenbergen, L.W., Schall, J.D., and Clopper, P.E. *Bridge Scour and Stream Instability Countermeasures.* Publication No. FHWA NHI 01-003, Hydraulic Engineering Circular No.23, U.S. Department of Transportation, Federal Highway Administration. 2001.
14. Latishenkov, A.M. *Questions of Artificially Contracted Flow*. Moscow: Gostroizdat 1960. (in Russian).
15. Levi, I.I. *Dynamics of River Flow*. Moscow: Gidrometeoizdat 1969. (in Russian).
16. Yaroslavcev, I.A. *Calculation of Local Scour at Bridge Piers*. Moscow: Bulletin of TCNIIS N80, Moscow 1956. (in Russian).
17. Rotenburg, I.S. and Volnov, V.S. *Project Examples of Bridge Crossing*. Moscow: Vysshaya Shkola 1969. (in Russian).