EQUILIBRIUM SCOUR STAGE AT THE STRAIGHT GUIDE BANKS IN PLAIN RIVERS

Roberts Neilands[1], Boriss Gjunsburgs[2], Jelena Govsha[3], Romans Neilands[4]

Abstract

The guide banks can be used to protect bridge abutments by redirecting stream flow through a bridge opening, and transfer scour away from abutment to prevent scour potential damage. But scour hole does not disappear, it is developing at the head of a straight guide bank and according to some studies can be greater in size than that at abutment. According to experimental data 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 equilibrium scour at the straight guide banks was studied and new method for equilibrium depth of scour calculation was elaborated and verified by experimental data. Hybrid modelling of scour depth development in time and experimental data were used for validation of the method. Equilibrium scour depth reflects the maximum value of the local scour hole that can be reached at the guide bank at a certain flood probability. Equilibrium scour depth should be calculated at the straight guide banks for design and extreme flood events to ensure the reliability of the structure for a lifetime.

Key words

Equilibrium, floods, local scour depth, modelling, straight guide banks.

To cite this paper: *R. Neilands, B. Gjunsburgs, J. Govsha, R. Neilands. Equilibrium Scour Stage at the Straight Guide Banks in Plain Rivers, In Proceedings of International Scientific Conference People, Buildings and Environment 2012, Vol .2, pp. 580-590, ISSN: 1805-6784.*

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1 INTRODUCTION

Such bridge structures, as abutments, are exposed to the flow in floods, inducing flow contraction, reducing effective bridge opening and leading to the local scour at abutment foundations and possible failures of these structures.

The guide banks, formerly known as spur dikes, can be used in these cases to protect abutment by redirecting stream flow through a bridge opening, and removing scour away from abutments to prevent damage caused by scour. The two major enhancements guide banks bring to bridge design are (1) reduce the separation of flow at the upstream abutment face and thereby maximize the use of the total bridge waterway area, and (2) reduce the abutment local scour due to lessening turbulence at the abutment face [1], [2]. Guide banks are also used to protect highway embankments.

However, scour hole does not disappear, it is developing at the head of the straight guide bank and has a greater size than that at the abutment [3].

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.

The shape, upstream and downstream length, elevation, orientation to the bridge opening, control of bridge scour, and other factors of the guide banks were studied by different authors like Rotenburg [4], [5], Latishenkov [6], [7], Apmann and Ali [8], Neill [9], Bradley [10], Richardson and Simons [11], Lagasse et al. [1], [12], [2], and others.

There are 3 main shapes of the guide banks available in literature: straight, elliptical, and straight with aligned head. According to tests and methods proposed by Gjunsburgs et al. [3], the scour depth at the straight guide banks was found greater than that at the elliptical guide banks and abutments with equal time, hydraulic, and river 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 [3].

Estimation of the equilibrium scour depth at the head of guide bank is critical to successful design of the bridge opening to ensure the reliability of the whole bridge structure in flood events. Equilibrium scour depth reflects maximum value of the scour hole that can or cannot be reached at the guide bank at a certain flood probability. Equilibrium scour depth should be calculated at the straight guide banks for design and extreme flood events to ensure safety of structure for a lifetime. Thus, substantial adverse structural, economical and environmental consequences can be prevented in advance.

Based on previous studies on local scour development in time at abutments [13], [14], elliptical guide banks [15], [16], straight guide banks [3], and equilibrium scour studies at abutments [17], the equilibrium scour stage at straight guide banks in floodplain was studied and results are presented in this paper.

The method of scour depth development estimation at the straight guide banks in time (in flood events) and experimental data by Gjunsburgs et al. [3] were used in hybrid modelling of the local scour depth development and validation of new method for calculation of the equilibrium scour depth at the straight guide banks in plain rivers.

For bridge structures with guide banks, the potential scour depth development in floods with different probability, sequence, frequency, duration, and equilibrium scour depth should be evaluated at the straight guide banks to ensure safety of the engineering structure.

2 EXPERIMENTAL DATA

The tests were carried out at the Transport Research Institute (Russia) in a flume 3.5 m wide and 21 m long. The tests were carried out with rigid bed and sand bed under open flow conditions studying local flow velocity, flow contraction, flow separation, changes in water level in the vicinity of the guide bank, and clear-water scour development in time at the straight guide banks.

The experimental setup, data for the open-flow conditions, and investigation results of the local scour development in time at the straight guide banks were published earlier by Gjunsburgs et al. [3].

According to setup the dimensions of the upper part of a straight guide bank, namely length, was calculated according to Latishenkov method [7] 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.

3 EQUILIBRIUM SCOUR DEPTH CALCULATION METHOD

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) can be observed. The flow is redirected by the straight guide bank to the opposite riverbank in the case of a one-side contraction or to the centre 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 scour hole is developing.

With development of the scour hole at the straight guide bank, the local flow velocity decreases. The discharge across the width of a scour hole also changes.

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

$$Q_f = k_{str} \cdot Q_{sc} \tag{1}$$

where Q_f – discharge across the width of the scour hole with a plain bed, Q_{sc} – discharge of he scour hole with a scour depth h_s, and k_{str} – coefficient of changes in the discharge due to scour at the straight guide bank (Fig.1).

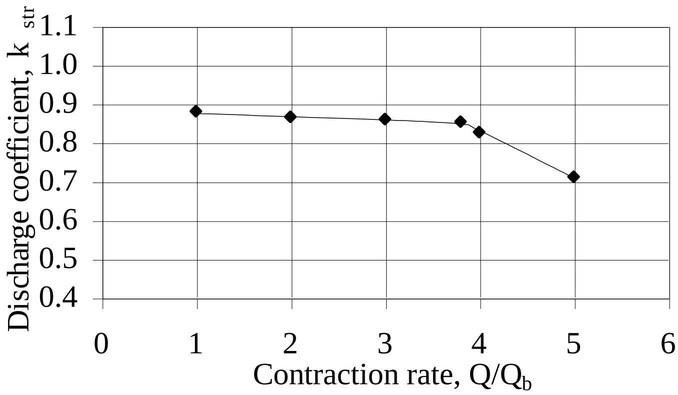

Fig. 1) Coefficient kstr versus the flow contraction rate Q/Qb

The coefficient k_{str} depends on the flow contraction rate Q/Q_b (Fig.1) according to experimental data by Gjunsburgs et al. [3], where Q – total flow discharge, and Q_b – flow discharge in the bridge opening in open-flow conditions.

The equation (1) can be written as follows, assuming cone-shaped scour hole geometry:

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

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

It was found in tests that the local flow velocity is changing with the flow contraction rate, the length of the separation zone, and the Froude number of open-flow conditions [3]. The local velocity at the head of the straight guide bank was found according to the formula:

$$V_l = \varphi_{str} \sqrt{2g \cdot \Delta h_{str}} \tag{3}$$

where φ_{str} – velocity coefficient for the straight guide banks; g – gravitational acceleration; and Δh_{str} – maximum backwater determined by the Rotenburg and Volnov [18].

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 2 shows the velocity coefficient φ_{str} as a function of the flow contraction rate Q/Q_b [3]. With increasing flow contraction rate, the velocity coefficient φ_{str} decreases.

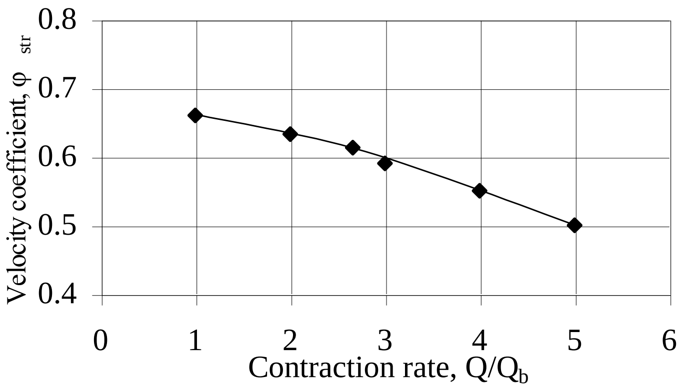

Fig. 2) Velocity coefficient φstr versus the flow contraction rate Q/Qb

The velocity coefficient φ depends on the shape of the guide banks; at the elliptical guide banks, the value of φ_{el} was found higher than that of φ_{str} at the straight guide banks [3]. The hydraulic losses at the straight guide banks are higher than those at the elliptical guide banks, and consequently the value of φ_{str} is smaller than φ_{el}.

Maximum backwater level at the straight guide banks can be found according to Rotenburg and Volnov [18]:

$$\Delta h_{str} = \frac{V_K^2}{2g}\left[\left(\frac{Q}{Q_b}\right)^2 - 1\right] + \frac{Li_0}{2}\sqrt{\frac{Fr}{i_0}}\left[\left(\frac{Q}{Q_b}\right)^2 + 1\right] + \frac{V^2}{g} \tag{4}$$

where V_K – average flow velocity in bridge opening in open-flow conditions, Q – total discharge of the flow, Q_b – flow discharge in the bridge opening in open-flow conditions, L – river width, i_0 – river slope, Fr – Froude number, V – average flow velocity in open-flow conditions.

Local flow velocity at any depth of scour h_s then can be found from equation (2):

$$V_{lt} = \frac{V_l}{k_{str}\left(1 + \frac{h_s}{2h_f}\right)} = \frac{\varphi_{str}\sqrt{2g\Delta h_{str}}}{k_{str}\left(1 + \frac{h_s}{2h_f}\right)} \tag{5}$$

For clear-water scour initial phase the critical flow velocity of the beginning of sediment movement V_0 can be found by Studenitcnikov formula [19]:

$$V_0 = 3.6 d_i^{0.25} h^{0.25} \tag{6}$$

where d_i – median grain size of the bed material, and h – average flow depth. Average flow depth over scour hole in floodplain can be expressed: $h = h_f\,(1 + h_s/2h_f)$.

Thereafter critical flow velocity V_{0t} at any depth of scour h_s, is given by:

$$V_{0t} = \beta \cdot V_0 \left(1 + \frac{h_s}{2h_f}\right)^{0.25} \tag{7}$$

where β – coefficient of reduction in the critical flow velocity due to vortex structures.

According to investigation by Rozovskij [20] on circulation of curved river flow, it was found that curved flow streamlines induces flow turbulence and vortex structures near protruding obstacle, and flow velocity, which is necessary for sediment motion, reduces because of turbulence (coefficient β depends on the Reynolds number). It was assumed that coefficient β = 1.0 for laboratory flume, and β = 0.8 for natural river conditions [20].

The local flow velocity V_{lt} is decreasing and velocity V_{0t} is increasing with development of the scour hole and increasing scour depth h_s. The clear-water scour reaches the equilibrium $(h_s = h_{equil})$ and ceases when V_{lt} becomes equal to V_{0t}. The relation between local velocity and critical velocity at which initiates sediment motion can be expressed as follows, by using Eqs. (5) and (7):

$$\frac{V_l}{k_{str}\left(1 + \dfrac{h_{equil}}{2h_f}\right)} = \beta V_0 \cdot \left(1 + \frac{h_{equil}}{2h_f}\right)^{0.25} \tag{8}$$

The equilibrium depth of scour at the straight guide banks can be determined from (8) as follows:

$$h_{equil} = 2h_f \left[\left(\frac{V_l}{k_{str}\beta V_o}\right)^{0.8} - 1\right] \tag{9}$$

where h_f – water depth in floodplain, V_l – local flow velocity, k_{str} – coefficient of changes in the discharge due to scour at the straight guide bank, β – coefficient of velocity V_0 reduction because of flow vortex structures, V_0 – critical flow velocity of the beginning of sediment movement.

To analyze the method, Eq. (9) is transformed to a form that shows clearly that equation contain dimensionless parameters and characteristics of the flow and riverbed:

$$h_{equil} = 2h_f \left[\left(\frac{\varphi_{str}\sqrt{2g\left\{\dfrac{V_K^2}{2g}\left[\left(\dfrac{Q}{Q_b}\right)^2 - 1\right] + \dfrac{Li_0}{2}\sqrt{\dfrac{Fr}{i_0}}\left[\left(\dfrac{Q}{Q_b}\right)^2 + 1\right] + \dfrac{V^2}{g}\right\}}}{3.6 \cdot k_{str} \cdot \beta \cdot 3.d_i^{0.25} h_f^{0.25}}\right)^{0.8} - 1\right] \tag{10}$$

In the general form, the relative equilibrium depth of scour is a function of the following parameters:

$$\frac{h_{equil}}{h_f} = f\left(\frac{Q}{Q_b}; P_K; P_{Kb}; \frac{Fr}{i_0}; \frac{h}{h_f}; \frac{d_i}{h_f}; H_{strat}; \frac{V_l}{k_{str}\beta V_0}; k_m; k_s; k_\alpha\right) \quad (11)$$

where Q/Q_b – flow contraction rate, P_K – kinetic parameter of the open flow, P_{Kb} – kinetic parameter of the flow in bridge opening in open-flow conditions, Fr/i_0 – ratio of the Froude number to the river slope, h/h_f – relative flow depth, d_i/h_f – dimensionless grain size, $V_l/k_{str}\beta V_0$ – ratio of the local velocity to the critical velocity at which the sediment movement starts, k_{str} – coefficient depending on the flow contraction rate, β – coefficient of reduction in the critical velocity due to vortex structures, and according to other studies H_{strat} – stratified riverbed conditions, k_m – coefficient depending on the side-wall slope of the structure, k_s – coefficient depending on the structure shape, and k_α – coefficient depending on the angle of flow crossing.

4 COMPARISON OF CALCULATED AND EXPERIMENTAL EQUILIBRIUM SCOUR DEPTH VALUES

To verify presented calculation method of equilibrium scour depth at the straight guide banks, calculated equilibrium scour depth values were compared to experimental values and relative error was estimated.

Hybrid modelling of scour depth development in time and definition of equilibrium stage were used to estimate experimental values of equilibrium scour depth and time as follows.

4.1 Computer modelling of the scour depth development in time

The experimental data and method for estimation of scour development in floods at the straight guide banks by Gjunsburgs et al. [3] were used for computer modelling of the scour depth development in time. Method for estimation of scour development in time during floods was confirmed by experimental data of laboratory tests with duration of 7 hours. By using computer modelling, the duration of laboratory ST tests of 7 hours were prolonged until rapid scour depth development stopped and equilibrium stage could be defined (Fig.3).

According to the method by Gjunsburgs et al. [3], the flood hydrograph is divided into time intervals and time steps. The hydraulic characteristics, the backwater value, the flow contraction rate, the flow velocities V_o and V_l, the grain size in different layers of the bed, the sediment discharge, as well as the depth and width of the scour hole varies during floods. 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, d_i – median grain size, H – height of the bed layer with d_i, and γ – specific weight of the bed material. As a result, we have flow velocities: V_{lt}, V_{0t}, parameters: A_i, D_i, N_i, N_{i-1}, and scour depth h_s at the end of time intervals and finally at the end of the time step. For the next time step, the flow and bed parameters were changed because of the flood and the scour developed in the previous time step.

In our case - the duration of each steady state simulation ST test was divided into time intervals of constant duration of 1 minute. At the end of each time interval there is a change in local flow velocity and in velocity at which the sediment movement starts, because of changes of scour hole in previous time interval. It means that with increase of scour depth at the end of each time interval, current cross section increases, decreasing local flow velocity V_{lt}, on the other hand, velocity at which sediment movement starts V_{0t} increases because of increase of total flow depth (sum of initial flow depth and scour depth developed in previous time interval).

By using computer modelling, the number of time intervals and duration of the simulations are not restricted. The key consideration here is to determine an appropriate criterion, which defines the equilibrium stage for each of the experimental tests.

4.2 Experimental equilibrium scour depth

The equilibrium depth of scour can be reached in equilibrium time. Duration of the clear-water scour development in time can be very long because small grains of the bed material are removed continuously from scour hole. The question is when to stop and accept the equilibrium stage of scour, and which criteria to use for the estimation.

The literature studies shows that different criteria are proposed for the estimation of the equilibrium stage of the scour at abutments by Cardoso et al. [21], Grimaldi et al. [22], Coleman et al. [23], and other authors. Definition of equilibrium stage is important problem because it is directly bounded to the test duration. In general, three different criteria are proposed: (a) – in tests with different duration by measurement confirmation, (b) – of the pattern of time development of the scour depth, and (c) – estimation of scour increase in succeeding 24 hours in tests have been proposed [22].

According to Coleman et al. [23], it was accepted that if the variation of the scour depth in following 24 hours $\Delta h_{s,24h} \leq 0.05 \cdot h_f$, where h_f – flow depth in floodplain, then it is assumed that equilibrium stage is reached. Since computer modelling of scour depth development in time were used, it was possible to find equilibrium stage – equilibrium time and depth at most precise scour depth changes in time.

Computer modelling of scour depth development at straight guide banks were done for 12 ST tests (Table 1). Example of scour depth development modelling results and definition of equilibrium scour stage of test ST26 is showed in Fig.3.

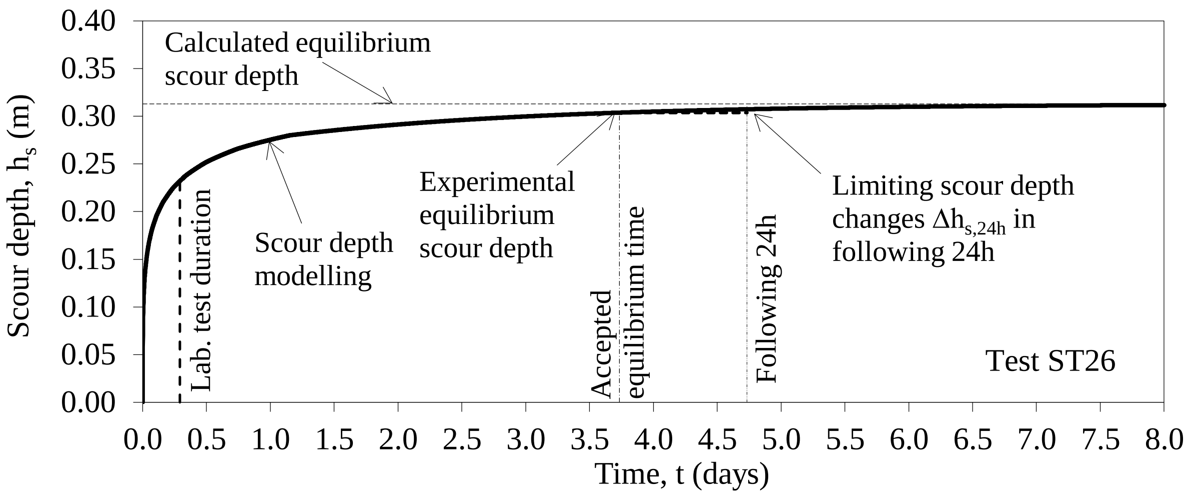

Fig. 3) Scour depth modelling for test ST26

The development of a scour depth is inherent with a rapid scour depth development at the beginning with followed slow development stage until equilibrium stage is reached.

The computer modelling of ST tests showed that scour development did not stop at experimentally obtained equilibrium time, in fact, it continued up to several days, but with insignificant increase in scour depth. For practical purposes it was assumed that such accuracy as $\Delta h_{s,24h} = 0.05 \cdot h_f = 0.0035m$ are acceptable for given tests, because in spite of relevant increase in time, insignificant increase in scour depth was observed until scour development stops, and in nature duration of the floods is restricted.

4.3 Validation of the method

To verify suggested equilibrium depth of scour calculation method, the calculated scour depth values were compared to the experimentally obtained equilibrium scour depth values, as showed in Table 1. Results show close agreement.

A percent relative error was calculated for each of the tests:

$$\varepsilon_{equil}(\%) = \frac{\left(h_{equil.Calc} - h_{equil.Exp}\right)}{h_{equil.Exp}} \cdot 100 \qquad (10)$$

where $h_{equil.Calc}$ – equilibrium depth of scour calculated by the suggested method, and $h_{equil.Exp}$ – equilibrium depth of scour obtained experimentally.

Relative error varied from 2.9 to 6.7 percent for most part of tests, which is acceptable (Table 1). The average relative error for these tests is 3.9 percent.

Tab. 1) Comparison of the experimental and calculated data for equilibrium scour stage

Tests	**Δh (cm)**	**Q/Qb**	**tequil.Exp (days)**	**hequil.Exp (cm)**	**hequil.Calc (cm)**	**εequil (%)**
ST26	6.290	5.69	3.73	30.374	31.281	3.0
ST27	2.880	5.27	1.76	18.109	18.688	3.2
ST28	5.820	5.69	3.22	28.903	29.896	3.4
ST29	2.260	3.66	1.30	13.728	14.211	3.5
ST30	3.670	3.87	1.91	19.533	20.143	3.1
ST31	3.950	3.78	2.14	20.456	21.042	2.9
ST32	1.110	2.60	0.67	7.949	8.335	4.9
ST33	1.656	2.69	1.07	11.671	12.115	3.8
ST34	1.098	2.65	0.65	7.806	8.193	5.0
ST35	0.422	1.56	0.05	1.288	1.640	27.3
ST36	0.575	1.66	0.20	3.296	3.653	10.8
ST37	0.770	1.67	0.40	5.467	5.834	6.7

The exceptions are tests ST35 and ST36, where calculated relative error was 27.3 and 10.8 percent, respectively. It is explainable with setup of these tests - hydraulic conditions with smallest contraction rate and smallest backwater level, resulting in smallest calculated scour depth and equilibrium stage, and consequent shortest time of scour development – 0.05 and 0.20 days, respectively. Because of these conditions, the scour development was still at the end of the rapid development phase for defined experimental equilibrium stage, resulting in biggest differences of calculated and experimental equilibrium scour depth because of defined $\Delta h_{s,24h}$.

5 CONCLUSIONS

The equilibrium scour at the straight guide banks was studied and new method for equilibrium depth of scour estimation was elaborated and verified by experimental data. The equilibrium stage of a scour hole is achieved when the local flow velocity at the head of the straight guide bank calculated at the flood peak becomes equal to the velocity of the beginning of sediment movement.

To verify presented calculation method of equilibrium scour depth at the straight guide banks, calculated equilibrium scour depth values were compared to experimental values and relative error was estimated. Results are acceptable.

Theoretical analysis of the suggested method was presented and showed that relative equilibrium scour depth depends on: flow contraction rate, kinetic parameter of the open flow and flow in the bridge opening, ratio of the Froude number to the river slope, relative flow depth, dimensionless grain size, ratio of the local velocity to the critical velocity at which the sediment movement starts, stratified riverbed conditions, side-wall slope of the structure, structure shape, and angle of flow crossing.

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ACKNOWLEDGEMENT

The travel costs and participation fee to conference was supported by the European Regional Development Fund project «Development of international cooperation projects and capacity in science and technology Riga Technical University», Nr. 2DP/2.1.1.2.0/10/APIA/VIAA/003.