

**EQUILIBRIUM SCOUR DEPTH AT WATER INTAKE STRUCTURES****MAKSIMĀLAIS IZSKALOJUMA DZIĻUMS PIE ŪDENS NEMŠANAS BŪVĒM****Roberts Neilands**

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**Introduction**

Water intake structures in common with other river engineering structures, as bridge abutments, piers, guide banks, spurs, and others, are exposed to flow hence risk of local scouring at structures in floods should be considered as one of the significant causes of possible failures, because obstructed structures considerably disturbs flow regime, inducing flow contraction and local flow conditions. Local scour can expose foundation of intakes and can lead to substantial adverse economical, sanitary, and environmental consequences.

Local scour at water intakes in rivers has not been studied yet. Calculation method for equilibrium scour depth estimation at water intakes is needed to ensure the reliability of structure in floods, because engineers should design hydraulic structures to withstand the effect of scour from the design flood and super-flood (flood with the magnitude of 100-year flood and 500-years flood, respectively) with little risk of failing [1].

Because of the similarity of the shape, location, and consequently of similarity in influence on flow conditions by river intakes and other hydraulic structures, it is accepted that methods designed for scour estimation at structures with vertical walls can be used for equilibrium scour depth calculation at water intakes, abutments, as well as, at similar hydraulic structures.

The equilibrium scour depth under clear-water conditions at abutments were studied and different empirical and non-empirical equations were proposed by Liu et al. [2], Gill [3], Laursen [4], Froehlich [5], Richardson et al. [6], Sturm & Janjua [7], Lim [8], Young et al. [9], Chang & Davis [10], Melville [11], Richardson & Davis [1, 12], Kothyari & Ranga Raju [13], Rahman & Haque [14], Sturm [15], Benedict et al. [16], Gjunsburgs et al. [17], and others. An analysis of the methods available in literature showed that many authors do not

take into account the flow discharge contraction, local increase in velocity, and stratification of the riverbed.

The objective of the research was to develop new equilibrium clear-water scour depth calculation method for water intakes by combining into methodology following: flow discharge contraction effect instead of geometric contraction or abutment length; backwater effect induced by contraction; local flow velocity, which together with vortex structures forms scour hole at abutment; stratified riverbed conditions; as well as, other hydraulic and riverbed parameters already researched in literature.

## 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 scour at abutments. The experimental setup and data for the open-flow conditions were published earlier by Gjunsburgs & Neilands [18, 19], and Gjunsburgs et al. [20, 21].

## Equilibrium scour depth calculation method

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 increase and reaches maximum at the corner of abutment [18]. As found from the tests, the local velocity with vortex structures forms scour hole at abutments [19].

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

$$Q_f = k \cdot Q_{sc} \quad (1)$$

where  $Q_f$  – discharge across the width of the scour hole with a plain bed,  $Q_{sc}$  – discharge of the scour hole with a scour depth  $h_s$ , and  $k$  – coefficient depending on the contraction rate of the flow (according to experimental data by Gjunsburgs & Neilands [19]).

The equation (1) can be written as follows:

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

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  $h_s$ .

Local flow velocity at any depth of scour  $h_s$  is:

$$V_{lt} = \frac{V_l}{k \left( 1 + \frac{h_s}{2h_f} \right)} = \frac{\varphi \sqrt{2g\Delta h}}{k \left( 1 + \frac{h_s}{2h_f} \right)} \quad (3)$$

where  $\varphi$  – velocity coefficient (according to experimental data by Gjunburgs & Neilands [19]),  $g$  – gravitational acceleration, and  $\Delta h$  – maximum backwater determined by Rotenburg & Volnov formula [22].

The critical velocity of the beginning of sediment movement  $V_0$  can be found by Stutenitnikov formulae [23], and critical velocity  $V_{0t}$  at any depth of scour  $h_s$ , is given by:

$$V_{0t} = \beta \cdot V_0 \left( 1 + \frac{h_s}{2h_f} \right)^{0.25} \quad (4)$$

where  $\beta$  – coefficient of reduction in the critical velocity due to vortex structures.

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

$$\frac{V_l}{k \left( 1 + \frac{h_{equil.}}{2h_f} \right)} = \beta V_0 \cdot \left( 1 + \frac{h_{equil.}}{2h_f} \right)^{0.25} \quad (5)$$

The equilibrium depth of scour at abutments can be determined from (5) as follows:

$$h_{equil} = 2h_f \left[ \left( \frac{V_l}{k\beta V_0} \right)^{0.8} - 1 \right] \cdot k_m \cdot k_s \cdot k_\alpha \quad (6)$$

where  $h_f$  – water depth in floodplain,  $V_l$  – local flow velocity,  $k$  – coefficient depending on the contraction rate of the flow,  $\beta$  – coefficient of velocity  $V_0$  reduction because of flow vortex structures,  $V_0$  – velocity of the beginning of sediment movement,  $k_m$  – coefficient depending on the side-wall slope of the abutment (after Yaroslavcev [24]),  $k_s$  – coefficient depending on the abutment shape (after Richardson & Davis [1]), and  $k_\alpha$  – coefficient depending on the angle of flow crossing (after Richardson & Davis [1]).

Because of the similarity in shape, location, and influence on flow conditions of water intakes and abutment-like structures, presented methodology for abutment scour depth estimation can be used for equilibrium scour depth calculation at water intakes, e.g., for rectangular water intake structures shape coefficient  $k_s = 1$  and side-wall slope coefficient  $k_m = 1$  should be used, as it is for vertical-wall abutments.

### Verification of the method

The laboratory experimental data and calculation method of scour development at abutments in time during multiple floods by Gjunburgs & Neilands [18, 19] were used for computer program “RoBo” development. Program “RoBo” were used for computer modeling of the scour depth development in time. By using computer modeling, the duration of laboratory SL tests of 7 hours were prolonged. Computer simulation of the scour depth development under steady flow conditions with time intervals 1 minute was performed for each of the SL test (Fig. 1). The aim of the simulation of scour depth development was to find

the equilibrium stage at which the scour development stopped. By using computer modeling the duration of the simulations is not restricted, therefore the only question was to find a criterion, which limits the changes of scour depth in time to find the equilibrium stage for each of the experimental tests.

Coleman et al. [25] method were used which stated that time to achieve equilibrium conditions, for scouring from a plane bed, is time required for the rate of scouring reducing to 5% of the smaller of the flow depth in the succeeding 24 hours period. Thus, when scour depth changes were smaller than 0.0035 m in succeeding 24 hours period, experimental equilibrium scour depth and equilibrium time values were derived for each of SL tests (Fig. 1). Obtained and accepted equilibrium time values were 0.16 – 2.25 days for SL tests. Experimental equilibrium depth values were compared to calculated values by the suggested method (Table 1). However, the computer modeling of SL tests showed that scour development did not stopped at experimentally obtained equilibrium time, in fact, it continued for several days, but with insignificant increase in scour depth.

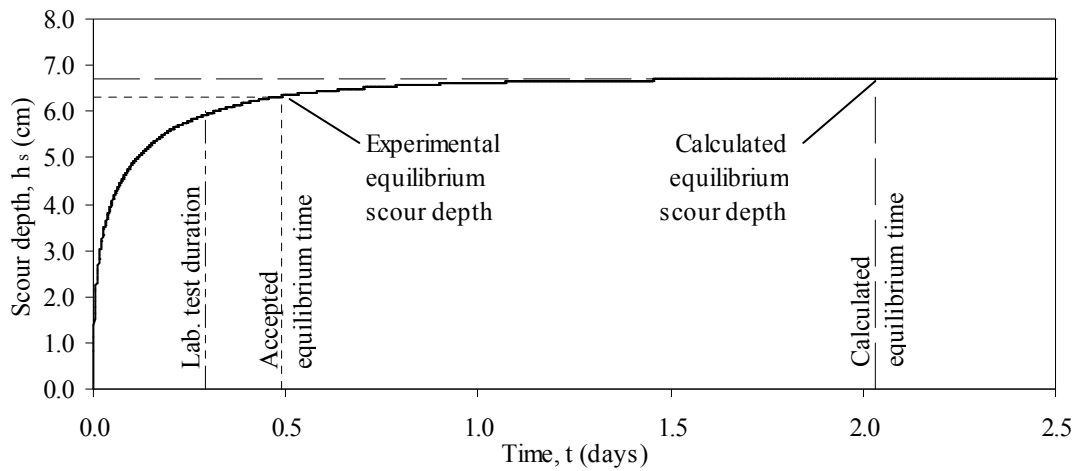


Fig. 1. Scour depth development in time for test SL7

Table 1. Updated calculated and experimental equilibrium scour depth values

Tests	$Q/Q_b$	$t_{\text{equil EXP}}$ (days)	$h_{\text{equil EXP}}$ (cm)	$h_{\text{equil CALC}}$ (cm)	$\epsilon_{\text{equil}}$ (%)
SL1	5.27	1.53	15.67	16.19	3.34
SL2	5.69	2.16	20.67	21.25	2.84
SL3	5.55	2.25	22.45	23.12	3.02
SL4	3.66	1.05	11.38	11.82	3.82
SL5	3.87	1.56	15.78	16.30	3.30
SL6	3.78	1.99	19.27	19.83	2.91
SL7	2.60	0.48	6.33	6.70	5.89
SL8	2.69	0.96	10.63	11.05	4.00
SL9	2.65	1.27	13.41	13.88	3.52
SL10	1.56	0.16	2.86	3.22	12.39
SL11	1.66	0.27	4.10	4.46	8.74
SL12	1.67	0.39	5.34	5.71	6.84
SL16	3.66	0.25	6.67	7.02	5.33
SL17	3.87	0.46	10.31	10.68	3.51
SL18	3.78	0.64	13.18	13.55	2.84

The calculated values of equilibrium scour depth at abutments showed good agreement with experimentally derived equilibrium scour depth values (Fig. 2). An percent relative error was calculated for each of the SL tests:  $\varepsilon_{equil} = (h_{equil.CALC} - h_{equil.EXP}) / h_{equil.EXP}$  (Table 1). The error frequency was found for the presented Eq. (6); 71% of all data set have less than 5 % error, with average error 4.82 % for all SL tests (Fig. 3).

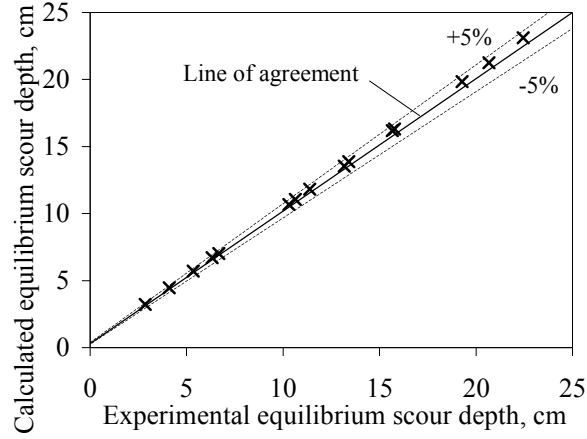


Fig. 2. Comparison of calculated and experimental equilibrium scour depths

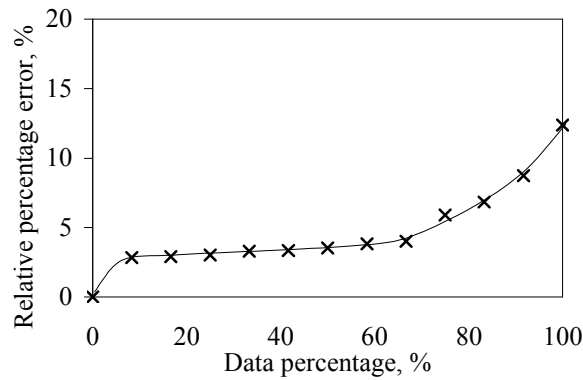


Fig. 3. Error frequency of suggested equation

### Analyze of the equilibrium scour depth calculation method

To analyze the method, Eq. (6) is transformed to a form that shows clearly that equation contain dimensionless parameters and characteristics of the flow and riverbed:

$$h_{equil.} = 2h_f \left[ \left( \frac{\varphi \sqrt{2g\Delta h}}{3.6 \cdot k \cdot \beta \cdot d^{0.25} h_f^{0.25}} \right)^{0.8} - 1 \right] \cdot k_m \cdot k_s \cdot k_\alpha \quad (7)$$

Rotenburg and Volnov [22] has found that the relative maximum backwater is a function of the following parameters:

$$\frac{\Delta h}{h_f} = f \left( \frac{Q}{Q_b}; P_K; P_{Kb}; \frac{Fr}{i_0}; \frac{h}{h_f} \right) \quad (8)$$

where  $Q/Q_b$  = flow contraction rate,  $P_K$  = kinetic parameter of the open flow,  $P_{Kb}$  = kinetic parameter of the flow under the bridge,  $Fr/i_0$  = ratio of the Froude number to the river slope,  $h/h_f$  = relative flow depth,  $h$  = average depth of the flow, and  $h_f$  = water depth in the floodplain.

Using the equation of Rotenburg and Volnov [22], Eq. (7) can be written as:

$$h_{equil} = 2h_f \left[ \frac{\left( \varphi \sqrt{2g \left\{ \frac{P_K}{2} \left[ \left( \frac{Q}{Q_b} \right)^2 - 1 \right] + \frac{P_{Kb}}{2} \sqrt{\frac{1}{Fr/i_0} \left[ \left( \frac{Q}{Q_b} \right)^2 + 1 \right] + P_{Kb}} \right\}} \right)^{0.8}}{3.6 \cdot k \cdot \beta \cdot d^{0.25} h_f^{0.25}} - 1 \right] \cdot k_m \cdot k_s \cdot k_\alpha \quad (9)$$

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

$$\frac{h_{equil}}{h_f} = f \left( \frac{Q}{Q_b}; P_K; P_{Kb}; \frac{Fr}{i_0}; \frac{h}{h_f}; \frac{d_i}{h_f}; H_{strat}; \frac{V_l}{k\beta V_0}; k_m; k_s; k_\alpha \right) \quad (10)$$

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

### Comparison of equilibrium scour depth calculation methods

Clear-water scour depth calculation methods available in literature were used to compare computed scour depth values with laboratory SL test data. Following methods were applied: Liu et al. (1961) [2], Gill (1972) [3], Laursen (1980) [4], original Froehlich clear-water equation (1989) [5], modified Froehlich live-bed equation (1989) [5], modified HIRE equation [1], Sturm & Janjua (1994) [7], Lim (1997) [8], Young et al. (1998) [9], Chang & Davis (1999) [10], Melville (1992-2000) [11], Kothyari & Ranga Raju (2001) [13], Rahman & Haque (2003) [14], Sturm (2004) [15], and modified Young equation [16]. Moreover, selected equations were analyzed by main hydraulic and riverbed variables – scour control parameters used in scour depth calculations at abutments (Table 2).

Analyze of the scour calculation methods showed that there is no unified opinion which flow velocity forms scour hole at abutment; either average approach flow velocity, approach flow velocity in obstructed area by embankment and abutment or local flow velocity were used in methodology; while presence of maximum (local) velocity near abutments was confirmed by Latishenkov [26] in laboratory tests, Ahmed & Rajaratnam [27] observed increased local flow pattern in detailed laboratory flow field study around abutment, Young et al. [9] defined local flow velocity as a resultant velocity at abutment due to contraction, which depended on average uniform flow velocity and geometric contraction, Sturm [15] presented a

relationship between approach flow velocity and maximum resultant (local) flow velocity near upstream corner of abutment by correlating laboratory data, but did not suggested to use it in scour depth estimation, because of difficult estimation of local flow velocity through numerical models, moreover, Gjunsburgs & Neilands [18, 19] by using laboratory tests concluded that local velocity with vortex structure was forming scour hole at abutments and was depending on characteristics of the flow, backwater value, rate of contraction by bridge crossings, and depth of scour.

Table 2. Analyze of the equilibrium scour depth calculation methods

Main variables in proposed methods: Scour calculation methods:	Discharge contraction	Geometric contraction	Abutment length	Flow depth	Local flow velocity	Average approach flow velocity	Flow velocity in obstructed area	Average flow velocity	Critical velocity	Froude number	Grain size of sediments	Abutment shape	Abutment side wall slope	Abutment alignment
Liu et al. (1961)		X	X	X				X		X				
Gill (1972)		X	X	X					X		X			
Laursen (1980)			X	X					X		X	X		
Froehlich clear-water eq. (1989) HIRE			X	X			X			X	X	X		X
Sturm & Janjua (1994)	X		X	X		X			X		X			
Lim (1997)			X	X		X			X	X	X	X		
Young et al. (1998)		X	X	X	X				X		X			
Chang & Davis (1999)	X		X	X			X		X	X	X	X		X
Melville & Coleman (2000)			X	X		X			X		X	X	X	X
HEC-18 (2001) modified Froehlich live-bed eq.			X	X			X			X		X		X
HEC-18 (2001) modified HIRE eq.			X	X			X			X		X		X
Kothyari & Ranga Raju (2001)		X	X	X				X	X		X	X	X	
Rahman & Haque (2003) modified Lacey eq.			X	X					X		X			
Sturm (2004)	X		X	X			X		X		X	X		
Benedict et al. (2006) modified Young eq.		X	X	X	X			X	X		X	X		X
Proposed eq.	X		X	X	X		X		X	X	X	X	X	X

Early scour calculation methods were derived from laboratory experiments in rectangular flumes under steady flow conditions, where abutment length or geometric contraction rate were used as one of the primary variables affecting scour, otherwise it is in nature, in plain rivers, where distribution of the flow discharge between channel and floodplain exists that should be considered. Abutment length is important control parameter, however the same abutment length may result in different scour depths depending on the approach flow distribution in the compound channel and its redistribution as it flows through bridge opening [15], therefore discharge contraction factor rather than abutment length should be used as appropriate variable to compute local scour depth. Rotenburg & Volnov [22] and Bradley [28] studied flow contraction and backwater effects; Sturm & Janjua [7], and Sturm [15] proposed equilibrium clear-water scour depth calculation equations, where dimensionless discharge contraction ratio (ratio of discharge over bridge opening length upstream to the total discharge) were used; Chang & Davis [10] used dimensionless velocity adjustment factor,

which depended on the ratio of flow rate per unit width in the approach section to that in contracted section; while Gjunsburghs & Neilands [20] used discharge contraction rate for local flow velocity calculation and scour depth development at abutments in floods.

As a rule, in natural conditions riverbed is not homogeneous, but with stratified bed which is composed of layers with different grain sizes, while most of scour calculation equations considers uniform sediments. To account sediment non-uniformity some authors like Froehlich [5], Lim [8], Melville & Coleman [11], and others, considers sediment size distribution, but also stratified riverbed conditions should be considered. Gjunsburghs et al. [17] used methodology to calculate critical velocity by taking into account stratification of riverbed, and it was found that equilibrium scour value at the abutment with homogeneous bed is greater than scour value calculated with stratified bed with layers of different grain sizes  $d$ .

It should be accented primary that most of scour calculation methods selected above do not take into account both – flow discharge contraction and local flow velocity, leading to over-estimated results.

## Conclusions

The shape, location and influence on flow conditions of water intakes in rivers are similar to abutments-like structures. Because local scour at water intakes has not been studied yet, it is proposed to use abutment scour methods as a base for equilibrium scour depth estimation at water intakes. New method for equilibrium scour depth calculation at water intakes was presented and verified by experimental data.

Suggested method in comparison with other earlier published equilibrium scour depth calculation methods, beside primary hydraulic and riverbed parameters, also considers such parameters as flow discharge contraction rate, local flow velocity, and stratified riverbed conditions, which were not accounted into most of the formulas available in literature. The lack of understanding of complex flow conditions, application of empirical calculation methods, and simplification of scour process leads to inadequacy in results and over-estimated scour depth values.

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 under the bridge, ratio of the Froude number to the river slope, relative flow depth, dimensionless grain size, stratified riverbed conditions, ratio of the local velocity to the critical velocity at which the sediment movement starts, side-wall slope of the structure, structure shape, and angle of flow crossing.

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**Neilands R., Gjunsburgs B. Maksimālais izskalojuma dziļums pie ūdens ņemšanas būvēm.**

*Ūdens ņemšanas būves līdzīgi kā citas upju hidrotehniskās būves, kā krasta balsti, balsti, plūsmas novirzošie dambji, krasta aizsardzības dambji, u.c., ir pakļautas plūsmas iedarbībai plūdu laikā, veidojot vietējo izskalojumu pie pamatiem un iespējamus šo būvju bojājumus. Maksimālā izskalojuma dziļuma aprēķināšana pie hidrotehniskajām būvēm nodrošina to izturību plūdu laikā un novērš būtiskas nelabvēlīgas ekonomiskās un apkārtējās vides sekas. Vietējais izskalojums pie ūdens ņemšanas būvēm līdz šim nav vēl pētīts. Dēļ tā, ka ūdens ņemšanas būvēm un citām hidrotehniskajām būvēm ir līdzīga forma, novietojums, un sekojoši līdzīga ietekme uz plūsmas stāvokli, ir pieņemts, ka metodes, kuras ir domātas izskalojuma aprēķināšanai pie būvēm ar vertikālam sienām, var tikt izmantotas maksimālā izskalojuma dziļuma aprēķināšanai pie ūdens ņemšanas būvēm un citām hidrotehniskām būvēm, piemēram, pie tiltu krasta balstiem. Ir piedāvāta jauna maksimālā izskalojuma dziļuma aprēķina metode ūdens ņemšanas būvēm un pārbaudīta ar eksperimentālajiem datiem. Tika noskaidrota galveno hidraulisko un upes grunts parametru ietekme uz vietējo izskalojumu un tika konstatēts, ka citi parametri kā - vietējais plūsmas ātrums, plūsmas saspišana pakāpe, un noslāņotas grunts apstākļi, kurus vairums agrāk publicēto izskalojuma aprēķinu metožu neņem vērā, arī ietekmē izskalojuma dziļumu, un tika ņemti vērā piedāvātajā metodē.*

**Neilands R., Gjunsburgs B. Equilibrium scour depth at water intake structures.**

*Water intake structures in common with other river hydraulic structures, as abutments, piers, guide banks, spurs, and others, are exposed to flow in floods, leading to local scour at foundations and possible failures of these structures. Calculation of the equilibrium scour depth at the hydraulic structures ensures the reliability of the structures in floods and prevents from substantial adverse economical and environmental consequences. Local scour at water intakes in rivers has not been studied yet. Because of the similarity of the shape, location, and consequently of similarity in influence on flow conditions by river intakes and other hydraulic structures, it is accepted that methods designed for scour estimation at structures with vertical walls can be used for equilibrium scour depth estimation at water intakes and other hydraulic structures, e.g., at bridge abutments. New equilibrium scour depth calculation method for water intakes was presented and verified by experimental data. The influence of main hydraulic and riverbed parameters on local scour were established and it was found that other parameters like – local flow velocity, flow contraction, and stratified bed conditions, which were not accounted in most of the earlier published scour calculation methods, have also influence on scour depth and were considered in proposed method.*

***Neilands R., Gjunsburgs B. Максимальная глубина размыва у водозаборных сооружений.***

*Водозаборные сооружения как и другие гидротехнические сооружения: устои, опоры, струенаправляющие дамбы, траверсы, и другие, подвергаются воздействию потока в период паводка, что приводит к образованию местного размыва у фундаментов и к возможному разрушению этих сооружений. Определение максимальной глубины воронки местного размыва у гидротехнических сооружений позволяет обеспечить их устойчивость и избежать значительных экономических и экологических потерь. Местный размыв у водозаборных сооружений до настоящего времени не был исследован. В виду того, что форма, положение и воздействие на поток водозаборных и других гидротехнических сооружений с вертикальной стенкой сходно, то нами установлено, что при определении максимальной глубины размыва возможно использовать методы применившие как для водозаборных сооружений, так и других гидротехнических сооружений, например, у устоев мостов. В статье представлен новый метод расчета максимальной глубины размыва у водозаборных сооружений и подтвержден экспериментальными данными. Установлено влияние основных гидравлических параметров потока и его дна на величину местного размыва и выяснено что другие параметры как - местная скорость, стеснение и слоистое строение дна потока, которые не учитываются многими ранее опубликованными методами по расчету размыва, также влияют на глубину размыва, и учтено в предложенном нами методе.*