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RIGA TECHNICAL UNIVERSITY

EQUILIBRIUM TIME OF SCOUR NEAR WATER ENGINEERING STRUCTURES ON RIVER FLOODPLAINS

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Introduction

- River flooding is identified as one of the most important natural hazards in the EU in terms of economic loss;
- Flood occurrence is projected to increase even further with climate change. Main reason – general increase in winter precipitation;
- 1997 floods in Poland and Czech Republic were responsible for losses of about EUR 5.2 billion;
- Next three decades Extreme floods are likely to double with triple the expected damage (at least EUR 4 billion per year);
- Despite the significant investment of researchers, hydraulic structures still fail due to scouring processes;
- Water engineering structures change the natural flow:
  - Contracted flow;
  - Streamline concentration;
  - water level change at the structure;
  - Increased local flow velocity & vortex system.

Literature review

Since the scouring process at hydraulic structures is never ending, threshold criteria are used for equilibrium time of scour evaluation:

- Scour increase in 24 hours:
  - < 5 % of pier diameter [Melville and Chiew, 1999];
  - < 5 % of flow depth / abutments length [Coleman et al., 2003];
  - < 5 % of 1/3 of pier diameter [Grimaldi et al., 2006];
- The proposed threshold criteria are only depending on the size of the hydraulic structure, and not on hydraulic parameters of the flow.

Literature review

Parameters used	Parameters avoided
Approach flow depth; Approach flow velocity and critical flow velocity; Abutments length / pier diameter; Froude number; Median sand grain size and density.	Flow contraction; Local flow velocity; Bed stratification; Flood duration, sequence, probability and frequency.

Computation of sediment discharge in rivers: the contributions by Levi and Studenitcnikov revisited. S. Evangelista, J. Govsha, M. Greco, B. Gjunsburgs. – *Journal of Hydraulic research*, 2017.

Method

The differential equation of equilibrium for the bed sediment movement under clear-water conditions was used (Levi's formula for sediment discharge):

$$(1-p)\frac{dW}{dt} = Q_s$$

$$(1-p)\frac{dW}{dt} = a h_s^2 \frac{dh_s}{dt}$$

$$Q_s = AB \cdot V_1^4$$

Levi (1969)

p – porosity of riverbed material, %;

W – volume of the scour hole, m^3;

t – time, s;

Q_s – sediment discharge out of the scour hole;

a - equal to $3/5\,\pi m^2$ where m - steepness of the scour hole;

h_s – scour depth, m;

A – parameter in Levi (1969) formula, $A = f(\gamma, V_0, V_l, d_i, h_f)$;

B – width of the scour hole, equal to mh_s, m.

Method

Local flow velocity at the structure for any depth of scour:

$$V_{lt} = \frac{V_l}{1 + \frac{h_s}{2h_f}}$$

V_l – local flow velocity at the structure, m/s;

h_f – water depth in the floodplain, m.

Critical flow velocity at the structure can be determined by the Studenicnikov (1964) formula:

$$V_0 = 1{,}15\sqrt{g}\, d_i^{0{,}25} h_f^{0{,}25}$$

g – acceleration due to gravity, m/s^2;

d_i – grain size of the bed material, m.

Method

The critical flow velocity V_{0t} at the structure for any depth of scour h_s is:

$$V_{0t} = \beta \cdot 3{,}6 \cdot d_i^{0{,}25} \cdot h_f^{0{,}25} \left(1 + \frac{h_s}{2h_f}\right)^{0{,}25}$$

β - coefficient of critical flow velocity reduction near the structure (after Rozovskij, 1956).

At a plain riverbed the formula for A is:

$$A = \frac{5{,}62}{\gamma}\left(1 - \frac{\beta V_0}{V_l}\right)\frac{1}{d_i^{0{,}25} \cdot h_f^{0{,}25}}$$

At any depth of scour:

$$A_i = \frac{5{,}62}{\gamma}\left[1 - \frac{\beta V_0}{V_l}\left(1 + \frac{h_s}{2h_f}\right)^{1{,}25}\right]\frac{1}{d_i^{0{,}25} \cdot h_f^{0{,}25}\left(1 + \frac{h_s}{2h_f}\right)^{0{,}25}}$$

$$\frac{\beta V_{0t}}{V_{lt}} = \frac{\beta V_0}{V_l}\left(1 + \frac{h_s}{2h_f}\right)^{1{,}25}$$

Method

Then V_l is replaced with V_{lt} and parameter A with A_i:

$$Q_s = A_i \cdot m h_s \cdot V_{lt}^4 = b \frac{h_s}{\left(1 + \frac{h_s}{2h_f}\right)^4} \rightarrow b = A_i m V_l^4$$

After separating the variables and integrating:

$$D_i = \frac{a}{b} = \frac{3}{5} \frac{\pi \cdot m}{A_i \cdot V_l^4} \rightarrow D_{equil} = \frac{3}{5} \frac{\pi \cdot m}{A_{equil} \cdot V_l^4}$$

D_i – constant parameter in short time interval.

$$t = 4D_i \cdot h_f^2 \left(N_i - N_0\right) \rightarrow t_{equil} = 4D_{equil} \cdot h_f^2 \left(N_{equil} - N_0\right)$$

$$N_{equil} = \frac{1}{6} x_{equil}^6 - \frac{1}{5} x_{equil}^5$$

$$x_{equil} = 1 + \frac{h_{equil}}{2h_f}$$

N_0 = - 0,033 – constant to calculate scour in the previous time step;

h_{equil} – equilibrium scour depth, m.

Threshold condition

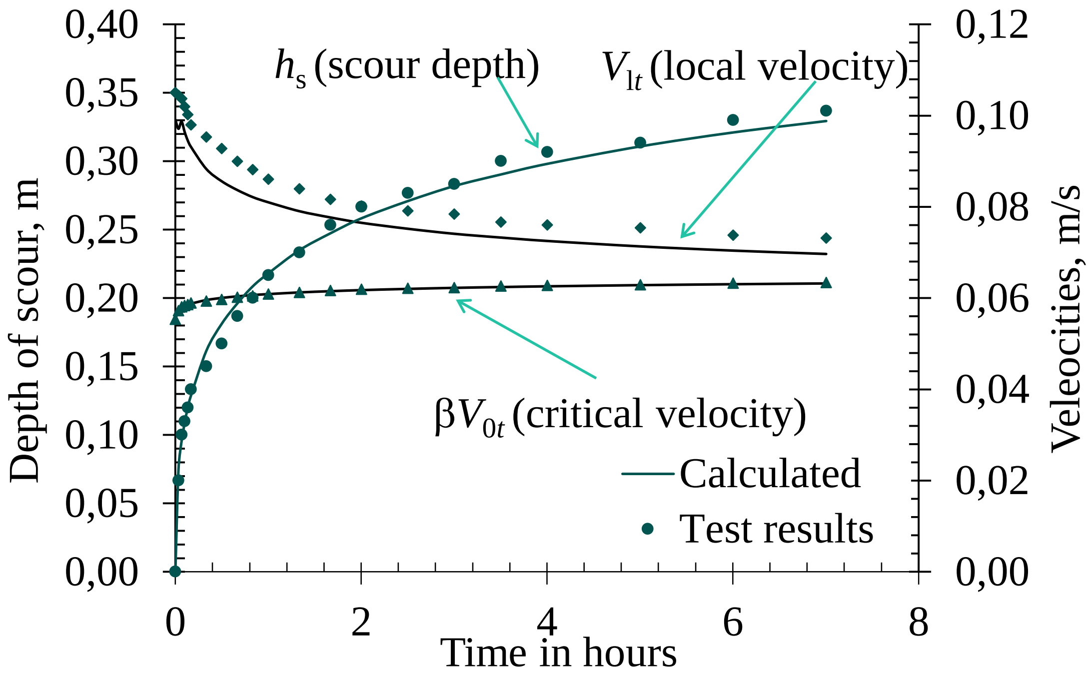
Ratio of critical flow velocity to the local one at the structure is accepted as the point of equilibrium;

$$\beta V_{0t} = V_{\mathrm{l}t} \rightarrow \frac{\beta V_{0t}}{V_{\mathrm{l}t}} = 1 \rightarrow t_{\mathrm{equil}} = \infty$$

The threshold criterion for the equilibrium time of scour calculation checked and accepted is equal to:

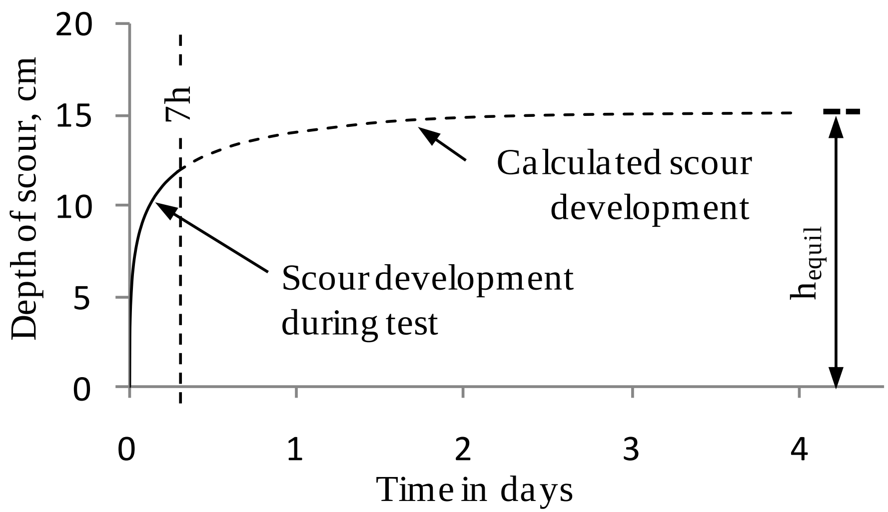
$$\frac{\beta V_{0t}}{V_{\mathrm{l}t}} = \frac{\beta V_{0}}{V_{\mathrm{l}}} \left(1 + \frac{h_{\mathrm{equil}}}{2 h_{\mathrm{f}}} \right)^{1,25} = 0,985$$

Data computer-modelling



2 experiment campaigns;
4 contraction rates;
3 flow intensities;
2 sand types;
24 test runs.

Test duration of 7 hours was prolonged until equilibrium was reached.



Computer-modelling results

TEST	Q/Q_b	*Fr*	t_{comp} (h)	t_{form} (h)	ε (%)
AL1	5,27	0,078	99,00	95,93	-3,10
AL2	5,69	0,103	190,00	183,66	-3,34
AL3	5,55	0,124	228,00	238,78	4,73
AL4	3,66	0,078	103,00	119,10	15,63
AL5	3,87	0,103	144,00	152,02	5,57
AL6	3,78	0,124	172,00	158,37	-7,92
AL7	2,60	0,078	48,00	46,85	-2,40
AL8	2,69	0,103	93,00	103,12	10,88
AL9	2,65	0,124	100,80	95,63	-5,13
AL10	1,56	0,078	12,40	11,42	-7,90
AL12	1,67	0,124	36,00	32,26	-10,39

Increase in flow contraction rate leads to equilibrium time of scour increase.

Increase in flow intensity results in equilibrium time of scour increase.

Average (n=11) percent relative error is 7,0 %;

For d_2=0,67 mm → 7,4 % (n=11).

Theoretical analysis

Processing of experimental data and theoretical analysis of the method showed that equilibrium time of scour depends on

$$t_{\mathrm{equil}} = f\left(\frac{Q}{Q_{\mathrm{b}}}; P_{\mathrm{k}}; P_{\mathrm{kb}}; \frac{Fr}{i}; \frac{d}{h_{\mathrm{f}}}; \frac{\beta V_0}{V_{\mathrm{l}}}; \frac{h}{h_{\mathrm{f}}}; \frac{h_{\mathrm{equil}}}{h_{\mathrm{f}}}\right)$$

Q/Q_{b} – flow contraction rate;

P_{k} and P_{kb} – kinetic parameters of the flow;

Fr/i – ratio of the Froude number to the river slope;

d/h_{f} – dimensionless sand grain size;

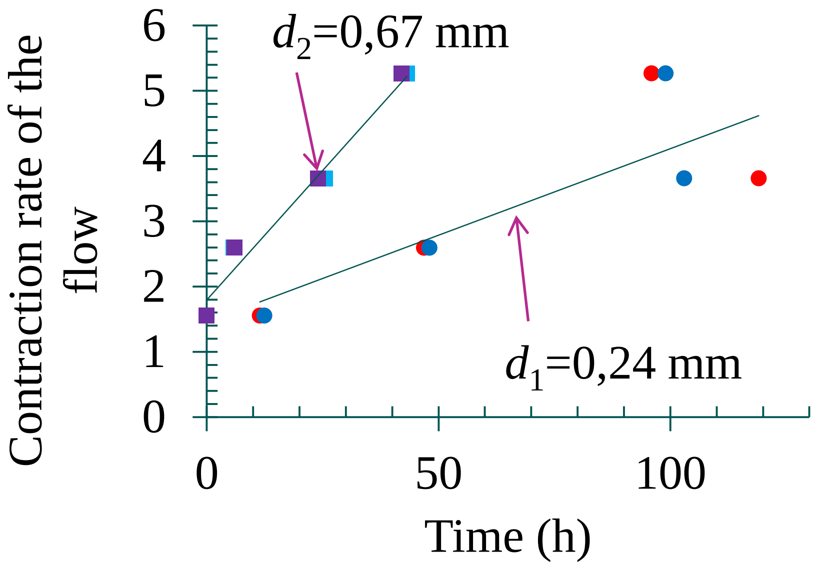
$\beta V_0/V_{\mathrm{l}}$ – ratio of the recalculated critical flow velocity to the local flow velocity;

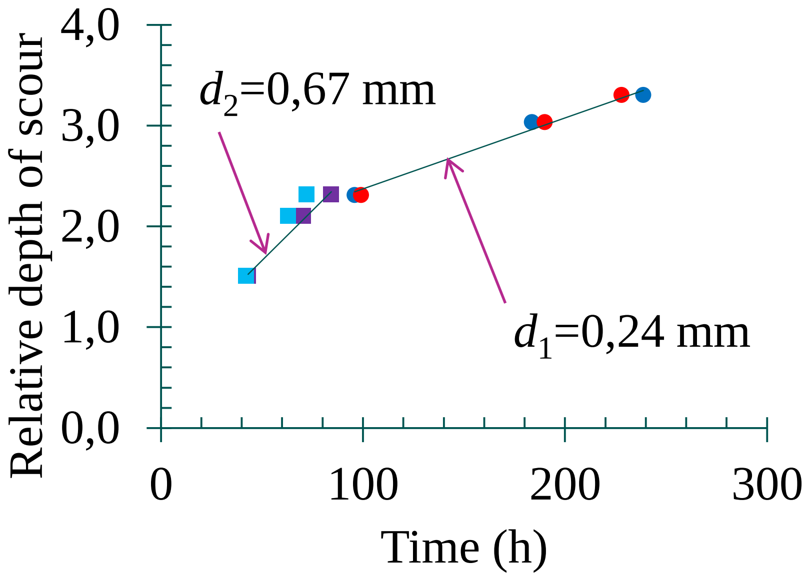
h/h_{f} – relative flow depth;

$h_{\mathrm{equil}}/h_{\mathrm{f}}$ – relative scour depth.

Graphical analysis

A graphical analysis of the processed data showed equilibrium time of scour dependence from the following parameters:



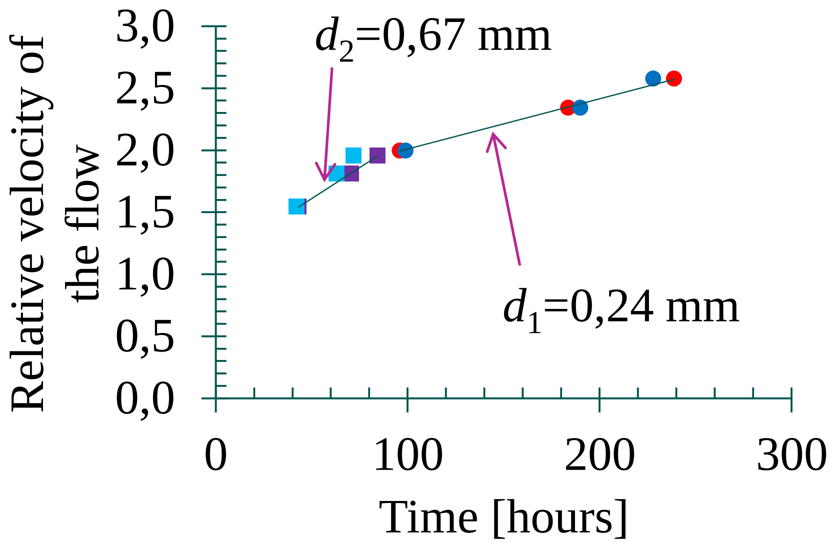


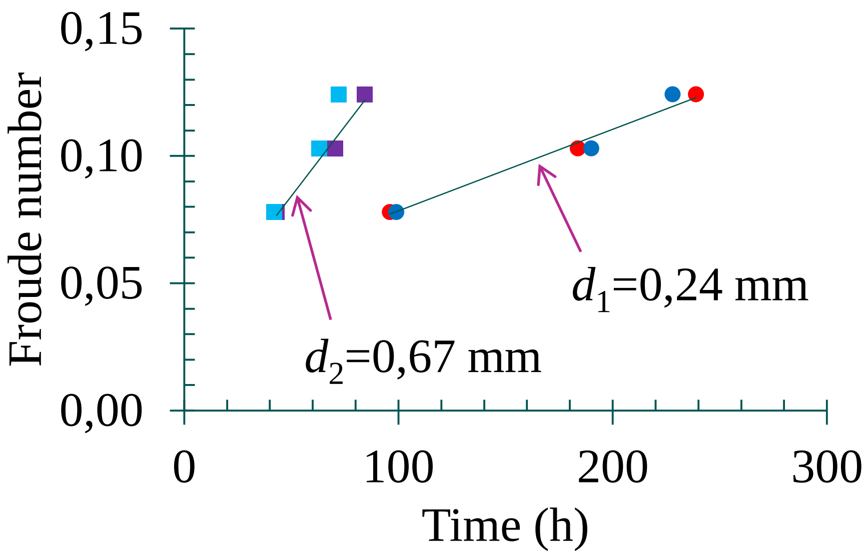
Time of scour increases by increase in flow contraction.

As relative depth of scour increases, time of scour increases as well;

Graphical analysis

Time of scour increases by increase in relative velocity of the flow;





Time of scour increases by increase in Froude number;

Conclusions

1. Proposed threshold criteria depend on physical parameters;
2. Differential equation of the bed sediment movement in clear-water conditions was used and a new method was worked out;
3. New hydraulic threshold criterion was proposed - $\beta V_{0t}/V_{1t}$=0,985;
4. Processed data revealed that with an increase in flow contraction and approach flow Froude number, time of scour increases as well;
5. Theoretical and graphical analysis of the method showed that equilibrium time of scour depends on flow contraction, kinetic parameters of the flow, relative depth of scour, Froude number and relative velocity of the flow.

Thank you!