

On local scouring below small water structures (#46700)

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On local scouring below small water structures

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Background. In the aim of water discharge quantity regulation hydraulic structures are used, such as weirs or checks, frequently equipped with gates. Water discharge can pass under, over the gate or simultaneously over and under the gate. The diversification of hydraulic gradient, as an effect of damming up the river by the structure, and the resulting shear stresses at the bed, exceeding the critical value, invokes the local scouring in the lower stage of the structure, as one of erosion types often met in the case of alluvial streams. This phenomenon has been studied in laboratory and field conditions for many years, however, researchers still disagree on the parameters that influence its size and intensity. There are also no universal methods for estimating its magnitude. The need to study this phenomenon results from the prevalence of hydrotechnical structures equipped with gates (from the small gated checks to great dams) and from potential damage that may be associated with excessive development of local erosion downstream, including washing of foundations and, consequently, loss of stability of the structure.

Methods. Paper verifies empirical formulas used for years to estimate the geometry parameters of the scour hole, on a laboratory model of the structure, where water is conducted below the gate, equipped with bottom reinforcements of various roughness. A specially designed remote-controlled measuring device, equipped with laser scanner, was applied to describe the shape of the sandy bottom. Then formula optimization is conducted, using Monte Carlo sampling method, followed by verification of field conditions.

Results. The suitability of a specially designed device, equipped with laser scanner, for measuring the bottom shape in laboratory conditions has been demonstrated. Simple formula describing local scour geometry in laboratory conditions has been derived, basing on Straube formula. Optimized formula was verified for the real object, giving very good comparison result, therefore could be considered in engineering and designing practice.

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Abstract

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Introduction

Damming up the river by hydraulic structures unavoidable influences the river channel course and valley morphology. Upstream the structure, due to water surface level increment and, therefore, stream velocity reduction, sediment accumulation occurs. Simultaneously erosion is intensified downstream the structure. The effect of strengthened erosion taking place directly below the structure, is primarily local scour and the gradual downgrading of the bottom, permanently involving an increasingly long reach of a river.

The increased erosion of a riverbed is an unfavorable and undesirable phenomenon not only due to the slow degradation of the riverbed. It is commonly assumed that the most intensive transformation of riverbeds takes place during catastrophic flooding when basic hydrodynamic parameters of the stream increase many times. Excessive development of the scour hole directly behind the structure, such as weir or sluice, poses a threat to its safety, as it may lead to washing away the foundation, embankments damages and loss of stability (Bajkowski et al. 2002). Removing and repairing these undesirable effects is troublesome and expensive. Therefore,

technical solutions are sought in the aim to reduce the scour hole dimensions. At the design stage, it is important to develop a reliable forecast of the size, shape and position of the local scour, both in a case of dams and small hydraulic structures, such as gated checks, weirs or sluices.

Gated checks are often used in channels where water level adjustment is required more frequently or where the higher cost, compared to stop-logs is justified (e.g. saving of labour).

There structures are usually equipped with hand-operated slide gates various types, from simple wooden shutters to hand-wheel operated adjustable orifice type gates (Kraatz & Mahajan 1975).

Most of attempts of recognition laws ruling the process of local scouring below the structures was carried out in the laboratory conditions. Despite many experiments carried out in various structures construction conditions and a wide range of variability of hydraulic conditions, the universal principles of calculating the dimensions of local scour hole its transfer to natural conditions are still unknown. Moreover, amidst this, designers find it difficult to choose those that give reliable results. Due to the diversity of applied constructions of structures and the variability of hydraulic conditions, it is difficult to generalize derived formulas (Graf, 1998; Ślizowski & Radecki-Pawlik, 2003; Ben Meftah & Mossa, 2006).

Additionally, the results of tests carried out in the laboratory are difficult to translate directly into field conditions due to the scale effect (Farhoudi & Smith, 1985). On the other hand, in field tests problems result mainly from the lack of knowledge of the initial conditions, i.e. the shape of the bottom before disturbing the existing dynamic balance in the channel (Lenzi, Marion & Comiti, 2003; Pagliara et al., 2016).

The estimation of the maximal scour hole depth and the channel reach infested by extensive erosion allows for the proper design of the lower stage of hydraulic structure, ensuring safety and stability, as well as reducing the construction and subsequent operation cost. Therefore, the estimation of the geometry of forecasted scour should be an integral part of the design stage of hydrotechnical structures (Brandimarte, Paron & Di Baldassarre, 2012; Prendergast & Gavin, 2014).

Difficulties of local scouring investigations result primarily from the multitude of factors influencing its shape and dimensions. The following factors can be mentioned among them (Dąbkowski et al., 1982):

- related to the flume or channel geometry (e.g. Shalash and Franke, Müller, Tajarmovič formula);
- related to the type and geometry of the structure (e.g. Rossinski formula);
- related to water flow conditions, such as flow rate, average speed or flow resistance);
- water physical properties;
- related to the bed material (e.g. Straube method).

Present paper comprises the verification and optimization of chosen empirical formulas to estimate the scour dimensions in the case of local scour process forming due to damming up the flume by the gate, equipped with lower stage embankment. For formula optimization, Monte

Carlo sampling method was applied. Laboratory research was performed as a first part of the studies, then the formula best describing flume experiment was verified in the field conditions.

Materials & Methods

Laboratory studies were conducted in a 11-m long flume with 0.58-m width and with no bed inclination downstream. Research basically comes down to bed shape measurements during local scouring formation, both using pin gauge as well as laser scanning of the surface, and water surface level examination in presumed hydraulic conditions.

Two gated check models assumed slide gate introduction, which was constantly raised to 5 cm of height to ensure invariable flow area of 0.029 m² (Fig. 1 a, b). In the vicinity of the damming structure, the bottom was non-washable on the length of $L_1 = 0.30$ m upstream the gate and $L_2 = 0.80$ m downstream. The reinforcement downstream the check was made of plain slab working as a reinforcement in I model of flume development (Fig 2a, 3a) (4), whereas II model assumed stone riprap reinforcement made of rocks (8), which medium height was 1.5 cm (Fig. 2b, 3b). Scour hole formed inside sandy part below the check with a length L_3 of 2.20 m (2).

A pin water gauges were used in order to measure the water surface elevation at the intake part and along the flume (1). Water surface level was regulated with an outlet gate (6). The level of sandy bottom was measured with laser scanner device (7) and with a moving disc probe as a helping device (1). Bottom shape was investigated at all flume length.

Flume side walls were made of glass with a roughness coefficient $n_w = 0.010$ m^{-1/3}/s. The soil used during the studies was uniform coarse sand with medium diameter $d_{50} = 0.91$ and $d_{95} = 1.2$ mm and roughness coefficient $n_b = 0.028$ m^{-1/3}/s. Experiments were performed in the scope of steady water flow discharge within the following range $Q_w = 0.010 - 0.045$ m³/s, water depth downstream the structure $h = 0.05 - 0.26$ m and Froude number $Fr < 1.29$ measurement series were performed, each lasting 8 hours (9 measurement series on model I and 20 on model II). Bed shape was measured in presumed time steps (0.5 – 2 h of interval) (Tab. I, II).

No sediment feeding system was adopted. Bedload transport conditions were assured by specific set of hydraulic conditions, that invokes particle movement from upstream towards lower stand of the structure. Therefore, experiment was carried out in ‘live-bed’ conditions, where soil leaving the scour hole is substituted by approaching load from the upstream.

Due to flow resistance increment along the whole flume, resulting from varied roughness of solid and sandy bottom, the hydraulic gradient increases causing the intensification of shear stress at the bottom. After exceeding the critical shear stress, the motion of sediment grains starts, followed by gradual scouring of the bed. Maximal scour depth z_{max} , scour length L_s and the distance between the deepest point of the hole and the end of reinforcement L_e were examined (Fig. 4) during each measurement.

In the aim to investigate the scour shape both device equipped with laser scanner and disc probe were applied as a helping device. Prototype A1 of device was engineered in 2016 by Marta Kiraga and Matvey Razumnik within the university grant for young researchers “The influence of small hydraulic structures on sediment transport conditions” (Kiraga et al. 2018).

Prototype A1 (Fig. 5) is equipped with a laser rangefinder and automatic movement system embedded on guides along the flume, scanning the bottom area with a demanded grid (every 1 mm in the case of present experiments). Grid density alteration possibility gives a far greater accuracy of measurement than the disc probe. The use of the device ensures data transmission directly in digital form, so that the coordinates can be easily processed to obtain the desired scour hole geometrical parameters.

Laser scanning, also known as LiDAR (Light Detection and Ranging) is an active tele-detection method, which uses the electromagnetic waves sent by the emitter. The result is point cloud with coordinates (x, y, z) . The measuring system (LiDAR) consists mainly of a transmitter, i.e. a module generating laser light (diodes), an optical telescope focusing the returning reflected radiation, and a detector converting light energy into an impulse recorded in the module recording the acquired data (Fig. 6).

LiDAR technology application in scour shape and its volume in flume experiments is based on the introduction of an automatic measuring module, which, placed above the bottom on a specially prepared controllable system of guides, describes its shape creating a point cloud.

The prototype's supporting elements are made of polylactide (PLA) and are printed on a 3D printer. Used polylactide is a polymer belonging to the group of aliphatic polyesters, obtained from renewable natural resources such as corn meal being simultaneously fully biodegradable.

Using Raspberry Pi microcomputer allows simultaneous computations and data collecting by the beam. The device is fully automated, what was executed using single board computer, dedicated software and the set of stepper motors, what results in measurements repeatability, constant accuracy on demand and fast execution of results. Obtained coordinates mesh is characterized by high resolution – therefore bottom shape is described very precisely, both in numerical form and also as a graphical tracing. Numerical cloud could be easily transformed, thence scour hole dimensions could be estimated, such as length or depth.

Deriving from the statement that scouring process stops when stream velocity v is equal to non-scouring velocity v_n Rossinski (Dąbkowski et al., 1982) stated that water depth above the local scour could be calculated as:

$$H = z_{max} + h = k_1^{1.2} \sqrt{q/v_{n1}} \quad (1)$$

where z_{max} is local scour depth, [m]; h is water depth before scour formation (See fig. 4), [m]; k_1 is a non-dimensional coefficient, describing intensified turbulence of the stream below the structure, [-]; q is unit discharge, [$m^3 \cdot s^{-1}/m$]; v_{n1} is non-scouring velocity for water depth of 1 m, depending to soil properties, [$m^2 \cdot s^{-1}$] calculated as following:

$$v_{n1} = \sqrt{2g(\gamma_r - \gamma_w)/1.75\gamma_w d_{50} \log(8.8/d_{95})} \quad (2)$$

in which g is gravity acceleration, $g = 9.81 \text{ m/s}^2$; γ_r and γ_w are specific weights, sediment and water, respectively, [N/m^3]; d_{50} and d_{95} are diameters that correspond to 50% and 95% of particles under the reported particle size.

The k_1 value in the formula (1) is empirical coefficient, dependent on lower stage development conditions. Basing on practice experiences k_1 is assumed to be 1.70 in the case when the reinforcement downstream the gate is not deepened and sheet piling, palisade or other vertical protection element is additional protection. Due to stream energy in the region of the gate outlet without any energy dissipating device local scouring process is intensified. In the case when transverse trench is applied below the reinforcement, deep equally to the expected depth of the scour; and the slope of this is no more than 1:4, $k_1 = 1.05$ should be assumed (Fig. 7 a, b).

Experimental case is referred to the conditions when coarse sandy bed is preceded by deepened reinforcement at the lower stand (Fig. 7 c), therefore empirical studies on k_1 parameter were needed.

The difficulty of explaining and presenting the impact the factors influencing local scouring process in the case of the large scale hydraulic structures with the lack of perspectives for establishing relations between the complicated flow system and the sediment transport, induce to apply in practice simple, intuitive relations allowing for the determination of the depth of scour holes. Scour length L_s and the distance between the deepest point of the hole and the end of reinforcement L_e for the cases where the stream comes out from under the gate were determined by several authors:

--According to Shalash and Franke (Dąbkowski et al., 1982):

$$L_s, L_e = f(z_{max}) \quad (3)$$

$$L_s = 11 \cdot z_{max} \quad (4)$$

$$L_e = 6.6 \cdot z_{max} \quad (5)$$

--According to Müller (Dąbkowski et al., 1982):

$$L_s, L_e = f(z_{max}) \quad (6)$$

$$L_s = (9.9 \div 0.8) \cdot z_{max} \quad (7)$$

$$L_e = (4.9 \div 0.5) \cdot z_{max} \quad (8)$$

$$\text{or} \quad L_s, L_e = f(z_{max}, h) \quad (9)$$

$$L_s = (6.0 \div 1.22) \cdot (z_{max} + h) \quad (10)$$

$$L_e = (2.94 \div 0.59) \cdot (z_{max} + h) \quad (11)$$

--According to Straube (Dąbkowski et al., 1982):

$$L_s = f(z_{max}, q, h, d_{50}) \quad (12)$$

$$L_s = 8.0q^{0.36}(z_{max} + h)d_{50}^{-0.14}h^{-0.40} \quad (13)$$

$$L_e = f(L_s, h, d_{50}) \quad (14)$$

$$L_e = 0.39L_sd_{50}^{0.12}h^{-0.12} \quad (15)$$

The formulas (3-15) are recommended for systems in which the stream flows out of the closure directly onto an unreinforced ground. For constructions equipped with reinforcement Tajarmovič formula is recommended (Dąbkowski et al., 1982):

$$L_s = f(z_{max}) \quad (16)$$

$$L_e = 12.75z_{max}^{0.5} \quad (17)$$

The basis of Monte Carlo method is the random sampling of the solution space to solve the considered issue. In the investigated case, the parameters of the function, best describing geometric parameters of local scour, were searched in presumed value ranges for giving the most accurate fit of the formula to the results of laboratory results.

The key to the accuracy and correctness of the Monte Carlo method is a random number generator. Method presents a solution to a problem as a parameter of a hypothetical population. Using a sequence of random numbers, it creates a population sample from which the estimated values of the sought parameters can be obtained (Niederreiter 1992).

Results

Basic geometric parameters of observed scour during 29 measurement series, each characterized by unit discharge q (9 on Model I and 20 on model II) were set in Table III and IV. Non-washable velocity for water depth of 1 m v_{n1} in the case of presumed grain conditions was equal to 0.502 m/s. Maximal scour depth was ranging from 1 to 10 cm. The criterion for the reach infested by the scour is bed level, i.e. scour is recognized within the area in which the depth of the bottom after the 8-hours measurement series exceeds 10% of the maximum hole depth.

Rossinski formula (1) was optimized for investigated test stand (Fig. 7 c) due to lack of the present gate check structure construction analyses so far. Optimization was performed on the basis of mean relative error δ between observed scour depth and calculations results. k_1 was investigated within the range of 0,00 to 2,00 and it was recognized to be equal to 1.10 in the aim to diminish the error δ ranging from 100 to 15 % in presumed k_1 range (Fig. 8).

Formulas 4,5; 7,8; 10,11; 13; 15 and 17 was verified for two models of gated check development. Calculated parameters of observed scour were examined in the comparison with measured ones. The criterion of comparison evaluation was mean relative error of each scour parameter estimation δ (Tab. V) calculated for each group of 29 measurements.

The limitation in determining the range of the scour hole was the length of the washable part (bottom edge) L_3 , which was 2.20 m. Formulas that depend only on the local scour hole depth z_{max} (Shalash and Franke – Eq. 4, 5; Müller – Eq. 7, 8) or on the local scour hole depth z_{max} and the depth of the water above the unwashed bottom h (Müller – Eq. 10, 11) demonstrated mean relative error of 56.9-72.8% in the scope of total scour length L_s and 38.3-57.0% for the distance between the deepest point of scour and the end of reinforcement L_e . The Tajarmovič equation indicate a 392.7% error. Calculations using the formula, involving not only local scour hole depth z_{max} and the depth of the water above the unwashed bottom h , but also grain characteristics, represented by d_{50} diameter and hydraulic parameter, i.e. unit water discharge q (Straube formula – Eq. 13, 15) provides the best fit to the measurement data. The relative error was 34.2 % for total scour length and 32.1% for the distance between the deepest point of scour and the end of reinforcement (Fig. 9, 10).

In order to achieve a better data explanation, a Monte Carlo sampling procedure for the parameters of Straube formula was performed. Straube equations could be described generally in following forms:

$$L_s = a q^b (z_{max} + h) d_{50}^c h^d \quad (18)$$

$$L_e = k L_s d_{50}^m h^p \quad (19)$$

where a, b, c, d, k, m, p are function parameters, which were sampled in following ranges:

-- $a \in \langle 5.0, 8.0 \rangle$;

-- $b \in \langle 0.24, 0.40 \rangle$;

-- $c \in \langle 0.10, 0.20 \rangle$;

-- $d \in \langle 0.35, 0.45 \rangle$;

-- $k \in \langle 0.30, 0.60 \rangle$;

-- $m \in \langle 0.01, 0.13 \rangle$;

-- $p \in \langle 0.01, 0.20 \rangle$

in 6000 combinations.

The best data explanation for laboratory database of I and II model was achieved in the case of the following parameters values: $a = 7.41$; $b = 0.38$; $c = 0.10$; $d = 0.45$; $k = 0.34$; $m = 0.01$; $p = 0.01$, thence optimized formulas, could be described as:

$$L_s = 7.41 q^{0.38} (z_{max} + h) d_{50}^{0.10} h^{0.45} \quad (20)$$

$$L_e = 0.34 L_s d_{50}^{0.01} h^{0.01} \quad (21)$$

Optimization revealed a diminished error, both in the case of total scour length L_s (10.1%) and for the distance between the deepest point of scour and the end of reinforcement L_e (18.2%).

Discussion

Optimized Straube formula demonstrated very accurate laboratory dataset description, whereas remaining equation analysis shown the relative error ranging up to more than 390%. The Straube's equations forms, which have been optimized for the laboratory workstation, have been checked for field data. Zagożdżonka river in Czarna (Poland) was built in the fifties of the last century as a concrete hydraulic structure to store up the water and to use its energy to drive the mill wheel. The total width of the spill is divided by I-beam guides into 3 clear spans: 1.16 m wide outermost spans and 1.22 m center span (Fig. 11 a, b). In the guides, a measuring sharp-crested triangular weir was installed. The height and shape of the weir edges were developed in the aim to ensure non-submergence weir working conditions at the highest possible flow rates.

The lower stage of the structure consists on 8.80 m long concrete reinforcement with a longitudinal slope of 1%, followed by a 0.60 m drop, so it could be recognized as similar to laboratory condition test models. The river bed, directly below the drop, is partially covered with a stone riprap over on a reach of about 1.0 m, and in a further section it is scourable, made of sand, with d_{50} diameter of 0.42 mm and d_{90} diameter of 0.74 mm.

On June 11, in 2013, a flood occurred. Flow rate in the hydrograph peak reached $5.06 \text{ m}^3\text{s}^{-1}$. This event resulted in local scour formation below the weir, which dimensions were measured, analyzed

and published by Urbański and Hejduk (14). Field measurements performed the following local scour dimensions:

-- the water depth above the deepest scour point $H_{max} = z_{max} + h = 2.43\text{m}$;

-- local scour length $L_s = 13.8\text{ m}$;

-- the distance between the deepest point of scour and the end of reinforcement $L_e = 5.20\text{ m}$.

In the case of water depth H_{max} calculations an error of 39.5% was achieved using Rossinski formula with a k_1 parameter equal to 1.70 (Eq.1) (Tab. VI). The best fit of the measurement and calculations was obtained for Müller equations, where measured scour length and the distance between the deepest point of scour from the end of reinforcement rare within the ranges described in Equations no 8 and 10 (an error of 0%). In the case of default form of Straube equations, 57.2 % of an error was achieved for scour length L_s analysis and 7.7 % for the L_e distance.

An optimized form of Straube equations (20), (21) were checked on the field measurements. Calculations using Straube's optimized formula showed excellent adherence for the measured and calculated value of the local bottom scour length (an error equal to 0.2%). However, the distance of the maximum hole depth from the end of the reinforcement was underestimated and the underestimation amounted to 16.6% of this value. A common observation for laboratory and field tests is the overestimation of both parameters using the Tajarmović formula.

Conclusions

Two gated check models have been investigated, in water discharge conducting from underneath the gate, characterized by different roughness of the lower stage reinforcement, followed by scourable bed. 29 measurement series were performed in total, each lasting 8 hours. The basic geometrical parameters of local scour hole, resulting from the disturbance of hydrodynamic balance of the system were examined using autonomic remote-controlled measuring unit. The construction of the tested models was chosen due to the prevalence of such solutions among real objects.

10 computational formulas, used for many years in the water engineering practice, were verified for laboratory data. It was stated that functions based only on one (z_{max}) or two (z_{max} , h) parameters provide weaker adjustment between calculations results and laboratory measurements. Straube's formula, assuming that geometric parameters follow up on not only maximal scour depth and water level, but also from granulometric parameters, represented by medium grain diameter d_{50} and hydraulic properties of experiment, such as unit discharge q was distinguished as the best description of laboratory test results.

The Straube function demonstrated the mean relative error of 34.2% in the case of comparing the measurement and calculation result of the local scour depth and an error of 32.1% for the distance of the deepest point from the end of the reinforcement, while medium error for all the rest of formulas was 67% for L_s and 133% for L_e .

The Monte Carlo sampling procedure resulted in a much better match between the calculation results and the dimensions measured in the laboratory: the Straube function optimized in this way demonstrated an error of 10.1% in the case of comparing the measurement and the calculation of

the local scour length and an error of 18.2% for the distance of the deepest point from the end of the reinforcement.

The optimized for laboratory measurements equation was checked for the real object, which was selected on the basis of the similarity of the lower stand reinforcement, and of the data availability. It should be emphasized that field measurements of the bottom shape after the formation of local scour hole are often difficult to access due to the imperfection of measuring instruments and lack of data before the formation of local scour. Optimization led to obtain an error of 0.2% for scour length and an error of 16.6% for the distance of the deepest point from the end of the reinforcement.

The extension of the optimized Straube formula verification to other hydro-technical field objects is necessary to applicability investigation, however it has to be stated that very high degree of adjustment of calculation results to field data (especially local scour length) provide an encouraging premise for further investigations.

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Figure 1

Gated check details: (a) – model I (gated check without additional roughness downstream); (b) – model II (gated check with additional roughness downstream).

(a) – model I (gated check without additional roughness downstream); (b) – model II (gated check with additional roughness downstream).

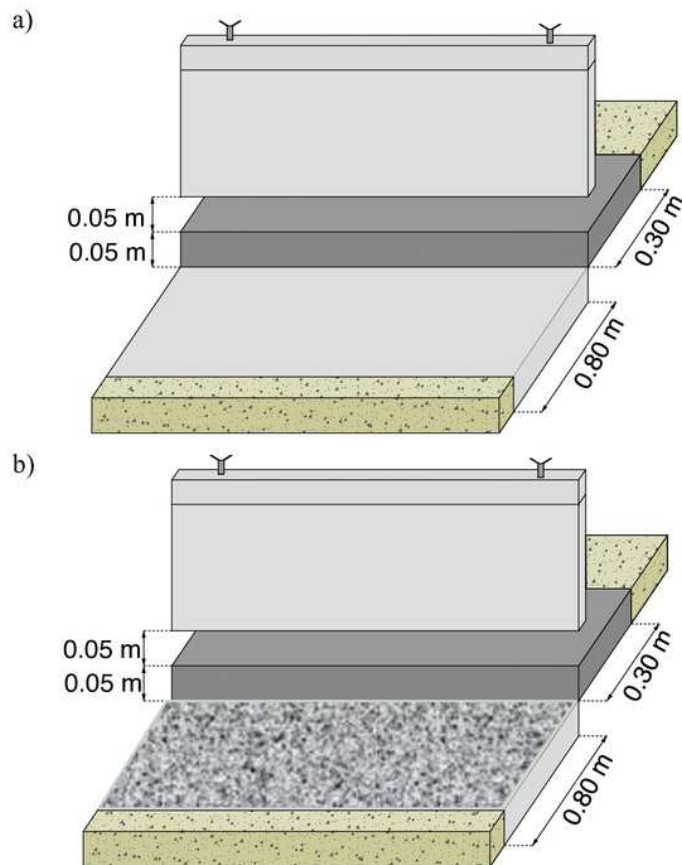


Figure 2

Laboratory test stand

(a) - model I (gated check without additional roughness); (b) - model II (gated check with additional roughness), where: 1 - movable pin gauge equipped with disc probe; 2 - sandy bed; 3 - gate; 4 - reinforcement; 5 - drainage; 6 - outlet gate; 7 - laser scanner; 8 - reinforcement with additional roughness.

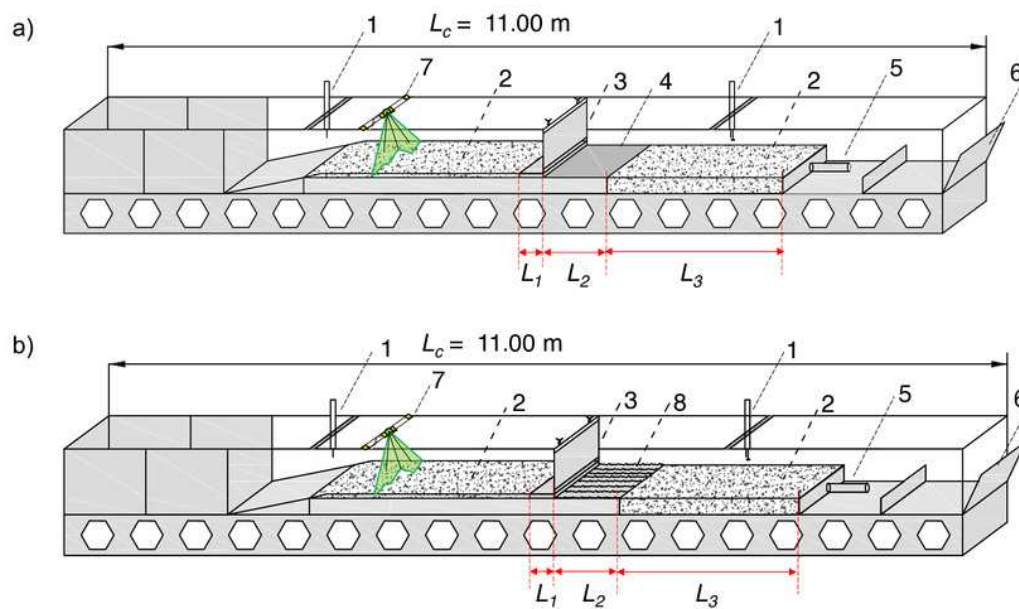


Figure 3

Photography of laboratory model

(a) - model I; (b) - model II.

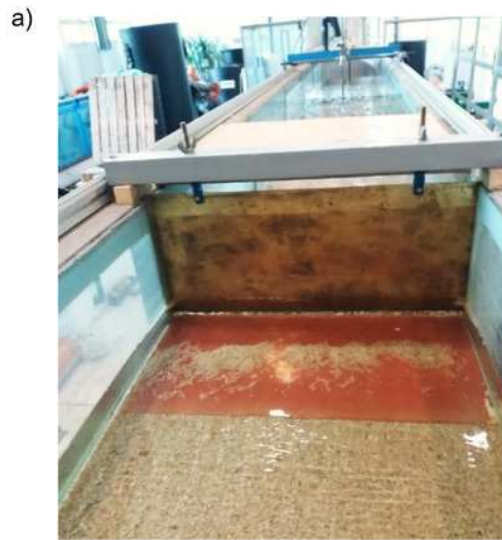


Figure 4

Local scour geometrical parameters

z_{max} – maximal scour depth; h – water depth before scour formation; L_s – scour length; L_e – the distance between the deepest point of the hole and the end of reinforcement

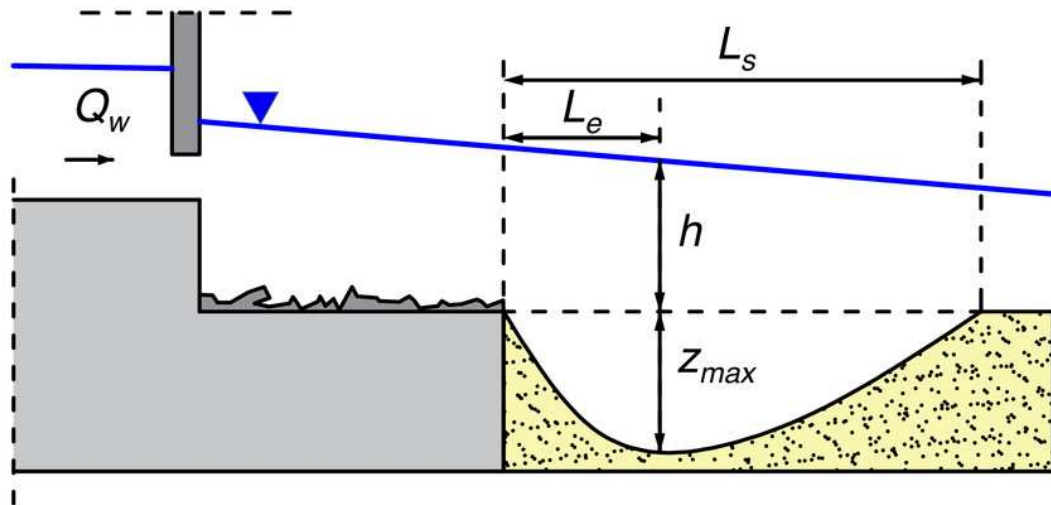


Figure 5

Prototype A1 during laboratory measurements.

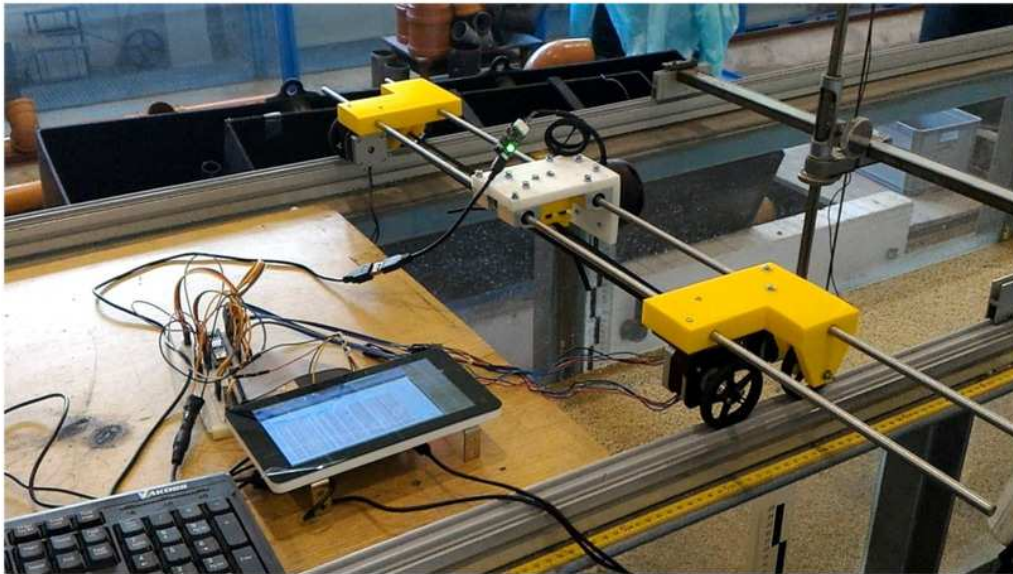


Figure 6

The measuring system (LiDAR)

1 - supporting guides; 2 - power supply unit; 3 - measuring module; 4 -remote connection.

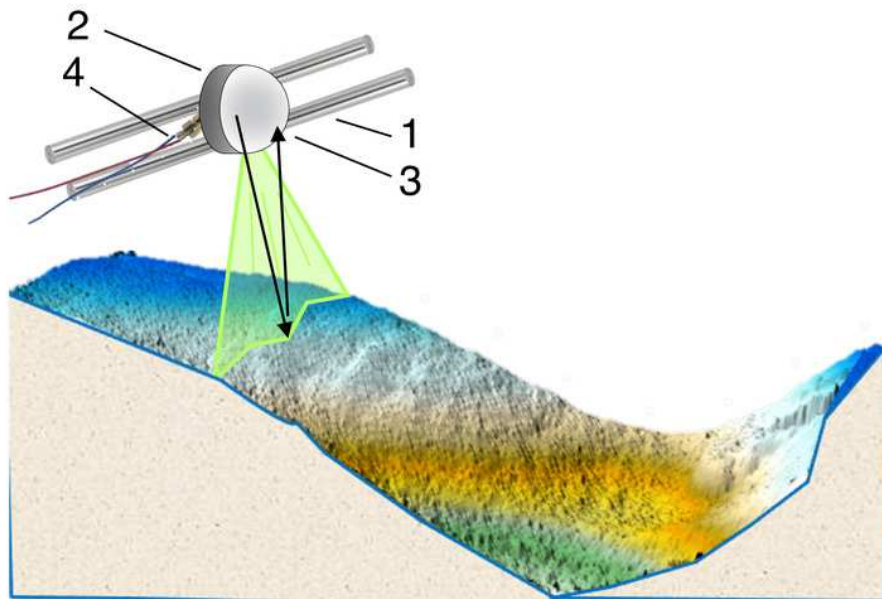


Figure 7

Various types of lower stage of gated check construction

a) reinforcement equipped with sheet piling, b) reinforcement followed by transversal trench, c) sandy bed following reinforcement with lowered bottom, where: 1 – gate; 2 – solid bottom; 3 – stone reinforcement; 4 – sandy bed; 5 – sheet piling or palisade; 6 – bank reinforcement; 7 – transverse trench with stone bottom; 8 – lowered reinforcement.

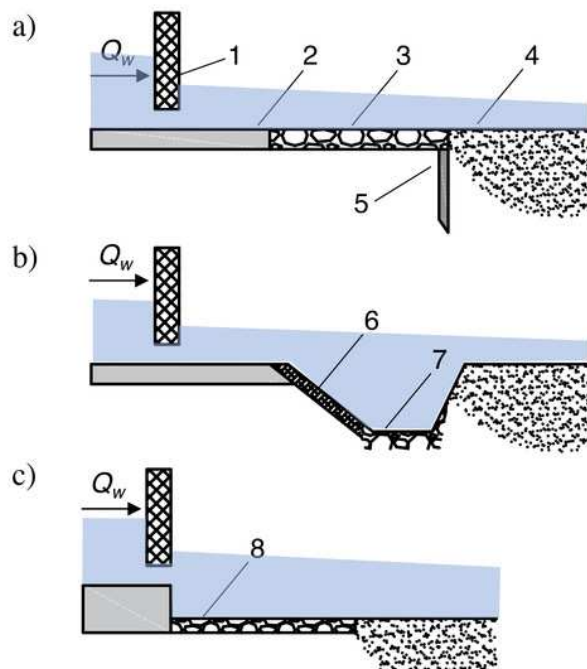


Figure 8

k_1 coefficient impact on the mean relative error of calculations using Rossinski formula
(1)

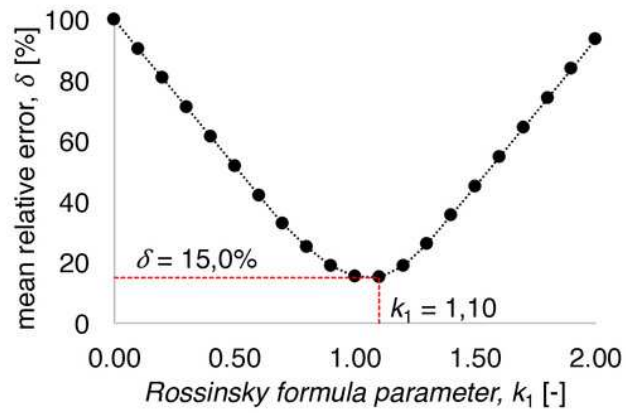


Figure 9

Local scour length L_s measurements and calculations results

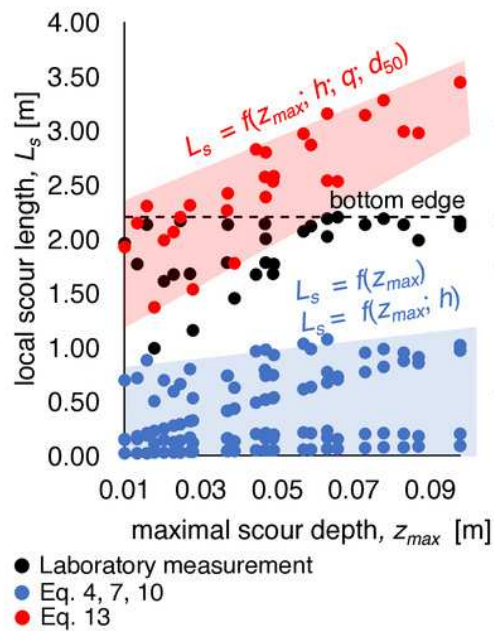


Figure 10

The distance between the deepest scour point and the end of reinforcement L_e measurements and calculations results

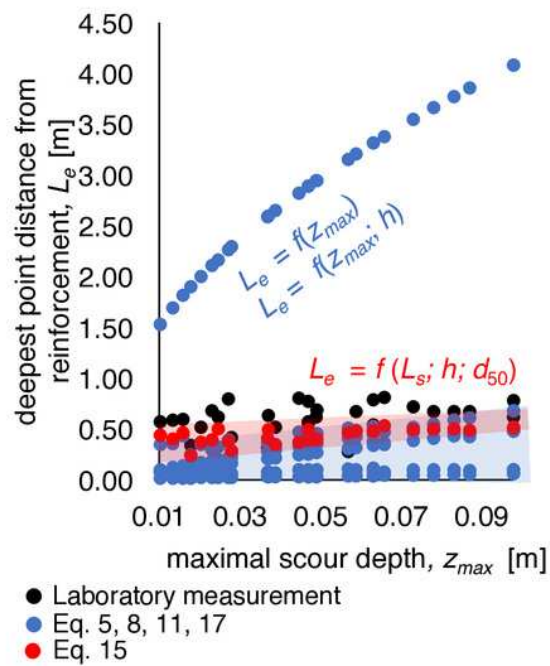


Figure 11

Weir in Czarna schematic

(a) - side view; (b) - the view from the upper stage of the weir (own elaboration after Urbański and Hejduk 2014).

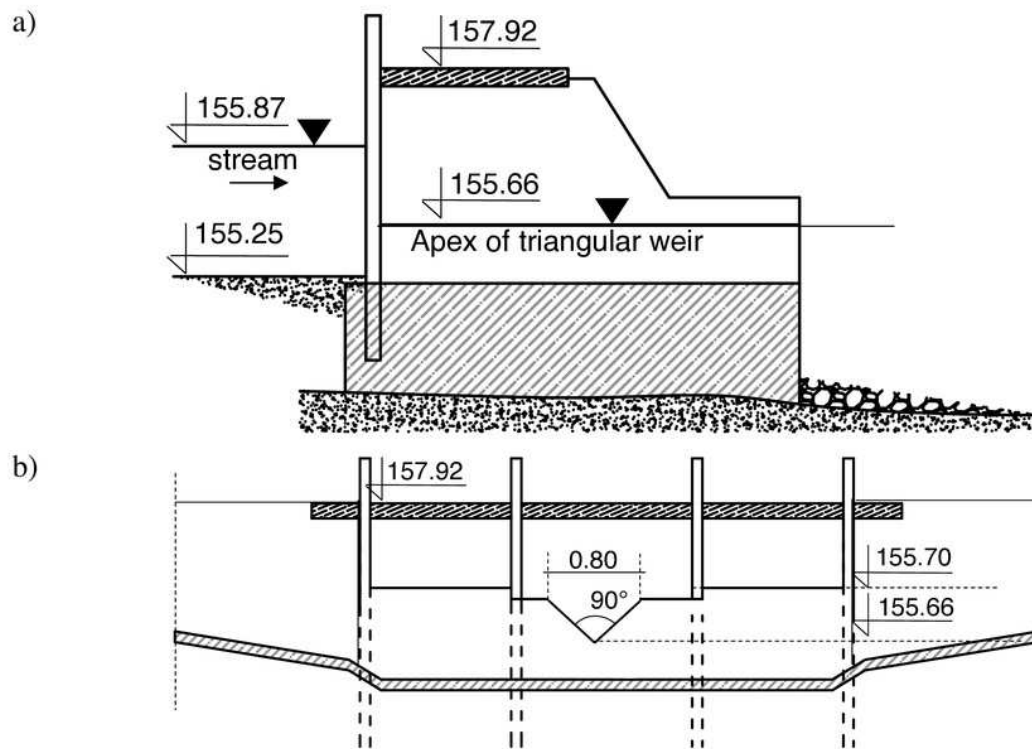


Table 1(on next page)

Model I – measurement series summary table

Where: Q_w – water flow discharge; h – initial water depth in control profile; T – measurement duration; Fr – Froude number.

Table I: Model I – measurement series summary table

No of measurement series	Q_w [m ³ /s]	h [m]	T [s]	Fr [-]
1	0.025	0.13	28800	0.31
2	0.020	0.05	28800	0.98
3	0.023	0.10	28800	0.40
4	0.030	0.08	28800	0.73
5	0.025	0.05	28800	0.99
6	0.030	0.11	28800	0.45
7	0.028	0.11	28800	0.42
8	0.026	0.10	28800	0.45
9	0.029	0.08	28800	0.71

Where: Q_w – water flow discharge; h – initial water depth in control profile; T – measurement duration; Fr – Froude number.

Table 2 (on next page)

Model II – measurement series summary table

Where: Q_w – water flow discharge; h – initial water depth in control profile; T – measurement duration; Fr – Froude number.

Table II: Model II – measurement series summary table

No of measurement series	Q_w [m ³ /s]	h [m]	T [s]	Fr [-]
1	0.020	0.05	28800	0.98
2	0.023	0.10	28800	0.40
3	0.030	0.08	28800	0.73
4	0.025	0.06	28800	0.99
5	0.030	0.11	28800	0.45
6	0.028	0.11	28800	0.42
7	0.026	0.10	28800	0.45
8	0.029	0.08	28800	0.71
9	0.024	0.08	28800	0.58
10	0.029	0.10	28800	0.50
11	0.013	0.06	28800	0.48
12	0.013	0.06	28800	0.57
13	0.014	0.06	28800	0.52
14	0.021	0.06	28800	0.78
15	0.022	0.09	28800	0.46
16	0.022	0.07	28800	0.65
17	0.027	0.07	28800	0.80
18	0.028	0.08	28800	0.67
19	0.024	0.07	28800	0.72
20	0.030	0.07	28800	0.88

Where: Q_w – water flow discharge; h – initial water depth in control profile; T – measurement duration; Fr – Froude number.

Table 3(on next page)

Model I – scour geometry parameters summary table

Where: q – unit water flow discharge; z_{max} – maximal scour depth; L_e – the distance between the deepest point of the hole and the end of reinforcement; L_s – scour length.

Table III: Model I – scour geometry parameters summary table

No of measurement series	q [m ³ ·s ⁻¹ /m]	$z_{\max}$ [m]	$H_{\max}$ [m]	L_e [m]	L_s [m]
1	0.0431	0.0201	0.1451	0.59	2.10
2	0.0345	0.0911	0.1411	0.66	2.10
3	0.0397	0.0532	0.1532	0.68	2.20
4	0.0517	0.0821	0.1621	0.67	2.18
5	0.0431	0.1020	0.1600	0.78	2.01
6	0.0517	0.0672	0.1772	0.78	2.18
7	0.0483	0.0511	0.1611	0.76	2.20
8	0.0448	0.0630	0.1630	0.66	2.20
9	0.0500	0.0772	0.1572	0.71	2.20

Where: q – unit water flow discharge; $z_{\max}$ – maximal scour depth; L_e – the distance between the deepest point of the hole and the end of reinforcement; L_s – scour length.

Table 4(on next page)

Model II – scour geometry parameters summary table

Where: q – unit water flow discharge; z_{max} – maximal scour depth; L_e – the distance between the deepest point of the hole and the end of reinforcement; L_s – scour length.

Table IV: Model II – scour geometry parameters summary table

No of measurement series	q [m ³ ·s ⁻¹ /m]	$z_{\max}$ [m]	$H_{\max}$ [m]	L_e [m]	L_s [m]
1	0.0345	0.0700	0.1200	0.80	2.19
2	0.0397	0.0143	0.1143	0.56	2.20
3	0.0517	0.0287	0.1087	0.61	2.20
4	0.0431	0.1020	0.1600	0.61	2.20
5	0.0517	0.0487	0.1587	0.79	2.20
6	0.0483	0.0610	0.1710	0.27	2.20
7	0.0448	0.0313	0.1313	0.79	2.20
8	0.0500	0.0412	0.1212	0.63	2.20
9	0.0414	0.0410	0.1210	0.31	1.77
10	0.0500	0.0175	0.1175	0.58	2.20
11	0.0220	0.0220	0.0820	0.33	1.00
12	0.0231	0.0321	0.0871	0.41	1.10
13	0.0240	0.0430	0.1030	0.51	1.50
14	0.0360	0.0673	0.1273	0.53	1.98
15	0.0385	0.0244	0.1144	0.51	1.60
16	0.0375	0.0873	0.1573	0.66	2.20
17	0.0465	0.0530	0.1230	0.61	2.20
18	0.0475	0.0510	0.1310	0.56	2.13
19	0.0415	0.0511	0.1211	0.55	2.01
20	0.0510	0.0271	0.0971	0.67	1.70

Where: q – unit water flow discharge; $z_{\max}$ – maximal scour depth; L_e – the distance between the deepest point of the hole and the end of reinforcement; L_s – scour length.

Table 5 (on next page)

Formulas verification summary table

Where: (1 - 17) - number of formula; d_{Hmax} - an error of the depth of the water above the deepest point of the scour calculation; ; d_{Ls} - an error of the scour length calculation; d_{Le} - an error of the distance between the deepest point of the scour and the end of reinforcement calculation.

Table V: Formulas verification summary table

Author's Name	δ_{Hmax} [%]	δ_{Ls} [%]	δ_{Le} [%]
Rossinski	(1) 15.0 %		
Shalash & Franke		(4) 69.8 %	(5) 45.2 %
Müller		(7) 72.8 %	(8) 57.0 %
Müller		(10) 56.9 %	(11) 38.3 %
Straube		(13) 34.2 %	(15) 32.1 %
(Optimized) Straube		(20) 10.1 %	(21) 18.2 %
Tajarmovič			(17) 392.7 %

Where: (1 - 17) – number of formula; δ_{Hmax} – an error of the depth of the water above the deepest point of the scour calculation; δ_{Ls} – an error of the scour length calculation; δ_{Le} – an error of the distance between the deepest point of the scour and the end of reinforcement calculation.

Table 6(on next page)

Field measurements and calculations results summary table – Czarna Gauge

$z_{\max}$ – maximal scour depth; h – water depth before scour formation; L_s – scour length; L_e – the distance between the deepest point of the hole and the end of reinforcement

Table VI: Field measurements and calculations results summary table – Czarna Gauge

	Geometric scour parameters		
	$H_{max} = z_{max} + h$ [m]	L_s [m]	L_e [m]
Field measurements	2.43	13.8	5.2
Author:	Calculations results using Eqs. (1), (7)-(21) (error %)		
Rossinski	(1) 3.39 (39.5 %)		
Müller		(7) 10.3 - 12.1 (12.3%)	(8) 5.0-6.1 (0%)
Müller		(10) 11.6 – 17.5 (0%)	(11) 5.7-8.6 (9.6%)
Straube		(13) 21.7 (57.2%)	(15) 4.8 (7.7%)
(Optimized) Straube		(20) 13.8 (0.2%)	(21) 4.3 (16.6%)
Tajarmovič			(17) 4.8 (159.6%)