LOCAL SCOUR MODELLING ON THE BASIS OF FLUME EXPERIMENTS

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ABSTRACT

The paper presents the verification of sediment transport formulas present in the HEC-RAS framework using flume data. The study includes Ackers–White, Laursen, and Meyer-Peter–Müller functions. The analysis consists of three parts. In the first part functions were used with their default parameter values, established by their authors for a specific set of geometric and hydraulic properties. Later, functions parameters were calculated using empirical equations. The third part comprises Monte Carlo sampling technique in the scope of choosing the parameters set, that lead to the best model fit. The subject of the comparison was local scour volume and medium local scour depth. Scour hole was formed laboratory flume with partially sandy bed, preceded by solid bottom, as a result of energy gradient increment due to bed roughness variability.

Key words: sediment transport, HEC-RAS, erosion, empirical formulas, hydraulic modelling, Monte Carlo sampling

INTRODUCTION

Damming up a river reduces its dynamic stability and intensifies morphogenetic processes. Upstream the structure, such as weir or dam, sedimentation and accumulation are present, because of reduced water velocity, meanwhile downstream the erosion process is intensified. One of visible erosion effect could be local scour hole nearby the foundations of the structure. Available methods to predict scouring are still very inaccurate because of velocity diversification and turbulences in water stream. In the case of the civil engineering, the modelling of the local scouring is one of the most important issues, due to its effect on the bed shape nearby bridges, piers or bank revetments, what is especially important in the case of flooding but also a durability of hydraulic infrastructure itself (Graf, 1998; Gaudio & Marion, 2003; Ettema, Kirkil & Muste, 2006; Kozioł, Urbański, Kiczko, Krukowski & Siwicki, 2016).

Numerous approaches to the sediment transport studies have been developed. All practical transport models are based on empirical formulas and are pointing at inseparable connection between water flow and sediment transport capacity, like for instance: Ackers–White, Engelund–Hansen, Laursen, Meyer--Peter–Müller, Toffaletti, Yang and Wilcock–Crowe. Available formulas are usually not general and can be applied for specified input ranges. In practical application, sediment transport is assessed using numerical models. One of the most widely used one is HEC-RAS, which utilizes the state-of-the-art description of sediment transport. HEC-RAS computations give more or less satisfactory results in various conditions, however the simulation results are affected often by significant uncertainty, as mathematical description is far from being general (Mutlu Sumer, 2007; Brunner, 2016).

The principal difficulties in solving a problem concerning bedload movement are inadequate knowledge

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of the natural processes and the unavoidable lack of similarity in model experiments. Sediment transport equations were formulated for specific set of geometric and hydraulic properties, though because of multiplicity of river or flume cases, to begin with various geometry of the bed, particle dimensions, water flow movement conditions or sediment load input, there is a need for further analysis of formulas for different flow conditions and sediment properties. Still, there is a lack of studies that validates complex modelling frameworks of the river transport, what indicates a need of extensive studies on their accuracy.

The shape and dimensions of the scour hole depend on many factors, though the biggest impact have: water flow, hydraulic conditions in the area of outflow and the nature of dissipated soil (Błażejewski, 1989; Breusers & Raudkivi, 1991; Graf, 1998). Increased diversification of water velocity and the presence of turbulences downstream the structure leads to lifting the sediment transport capability. Local scouring phenomenon is, therefore, the result of eroding forces of the water in the outflow area – soil particles are easily torn off from the bed because of increased flow velocity, then absorbed by the stream and transported down the river. The motion of sediment grains starts after exceeding the critical shear stress, and is followed by gradual scour until its shape stabilize. Then, the local scour obtains its maximum depth (z_{max}) with established water depth in control profiles, i.e.: H_1, H_2, H_3 (Fig. 1).

The transport model provided with HEC-RAS was used before to describe dynamics of riverbed shape changes both in laboratory and field conditions, comparing it (Haschenburger & Curran, 2012; Wicher-Dysarz & Dysarz, 2015; Berghout & Meddi; 2016) or not (Qasim, 2013; Szałkiewicz, Dysarz & Wicher-Dysarz, 2015), with the real bed shape. Others used their own database to verify formulas and calculate their own parameters (Wong & Parker, 2006). There are a few studies where models such as HEC-RAS was used for flume data. One of such approach is presented by Talreja, Yadav and Waikhom (2013), who demonstrated that the best verification results could be obtained using formulas specifically dedicated for recognised model properties, taking into consideration functions input ranges.

Therefore, the aim of the present study is to analyse the performance of the HEC-RAS transport module in predicting scouring for the laboratory data, obtained in experiments with a hydraulic flume. The study also addresses the problem of an identification of transport formulas parameters, which appears to be crucial in improving the model explanation of the process. Observed scouring was modelled using HEC-RAS transport model. The experimental part of the research was elaborated in a laboratory flume with a sandy section with mass median diameter $d_{50} = 0.91$ mm. There was no sediment feeding system adopted, what indicates local scour formation in clear-water conditions. The conditions for the transport of sediment in the experiment can be compared to situation where the continuity of the transport is interrupted in lowland alluvial river with the subcritical flow, e.g. below a transverse threshold or a weir with no opening for debris transportation downstream.
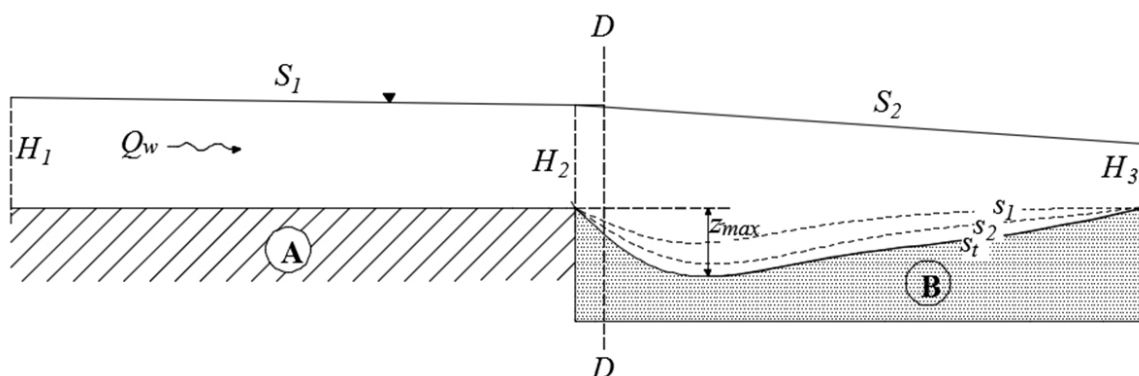
Fig. 1. Scheme of local scour: A – solid bottom; B – sandy bed; D–D – computational cross-section, H_1, H_2, H_3 – water depth; Q_w – water flow discharge; S_1, S_2 – energy grade line slope; z_{max} – maximal depth of local scour; s_1, s_2, s_t – shapes of bed while duration of experiment in time

Identification of formulas parameters, described widely in chapter "Identification of the transport functions parameters" has been done in three ways: (1) by using default values of parameters; (2) by using empirical equations to calculate parameters values; (3) by optimizing the parameter values in a respect of fit measures. As the optimization technique a Monte Carlo sampling was used, which despite its simplicity, appeared to be successful in minimization problem involving up to three parameters. Monte Carlo sampling is widely used in uncertainty analyses for sediment transport formulas (Shamsudin, Dan'azumi & Rahman, 2011), for inundation mapping (Huang & Qin, 2014) or in flood risk management (Dunn, Baker & Fleming, 2016).

MATERIAL AND METHODS

The HEC-RAS computations provide an extension of previously published results in Kiraga and Popek articles (Kiraga & Popek, 2016a, b). Laboratory flume geometry, granulometry and hydrodynamic properties were introduced into HEC-RAS model within a range of 21 sections with about 10 cm distance between them. Computations were performed for the averaged values of n coefficient in range 0.018–0.020 $m^{-1/3} \cdot s^{-1}$.

Laboratory research

The laboratory experiment included 13 tests, performed in Hydraulic Laboratory at Warsaw University of Life Sciences – SGGW. The laboratory flume had two bed sections: solid and sandy. The bottom material is coarse sand, uniform and well sorted. The second one consisted of sand with a median grain diameter $d_{50} = 0.91$ mm and $d_{90} = 0.99$ mm (Fig. 2). Each of 13 experimental series total time (t_t) was long enough to obtain a stable scour shape, i.e. 8 h. Laboratory conditions in this study may be compared to a case when the transport continuity is disrupted by the accumulation of the bedload material in a retention reservoir located in the upstream.

The laboratory flume of rectangular cross-section was 8.18-meter long, 0.6-meter high and 0.58-meter wide. The bottom structure was as follows: about 4-meter long solid bottom transformed into 2.18-meter long sandy bottom in the intake part. A pin water gauge was used in order to measure the water surface elevation, regulated with a gate. Water surface level was measured using a moving pin gauge, placed on the trolley pushed on guides along the flume. The washed-out material was collected in a collection chamber. The level of the bottom within the washout bed was measured with a moving disc probe in presumed cross-sections (Fig. 3). The flow rate was examined with the use of electromagnetic flow meter with the accuracy of 0.0001 m^3. The specific density of sand (ρ_s) in the washout bed was 2,610 kg·m^{-3}.

Various combination of steady water flow discharge (Q_w) and water depth (H) in each experimental series was assumed. Flow was subcritical with Froude number $Fr < 1$ (in a range of 0.25–0.70) and no hydrau-
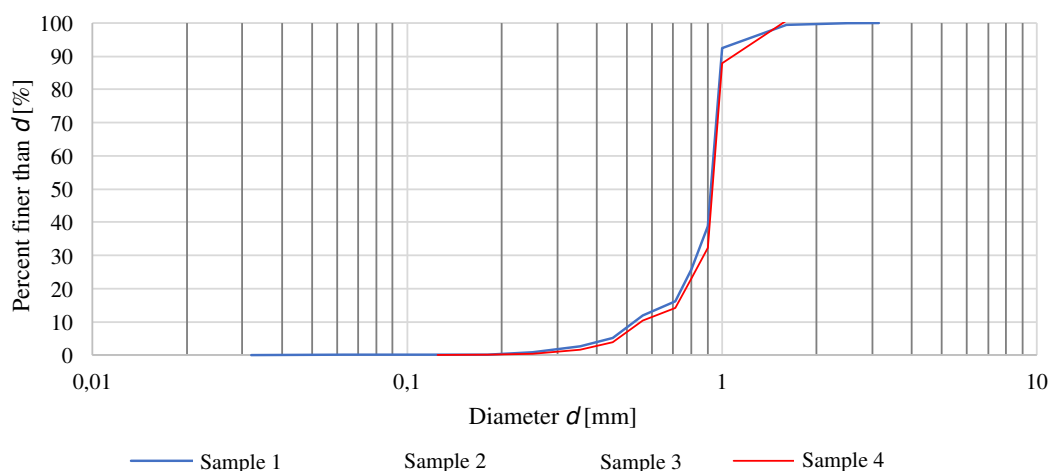
Fig. 2. Sieve curve of the examined soil
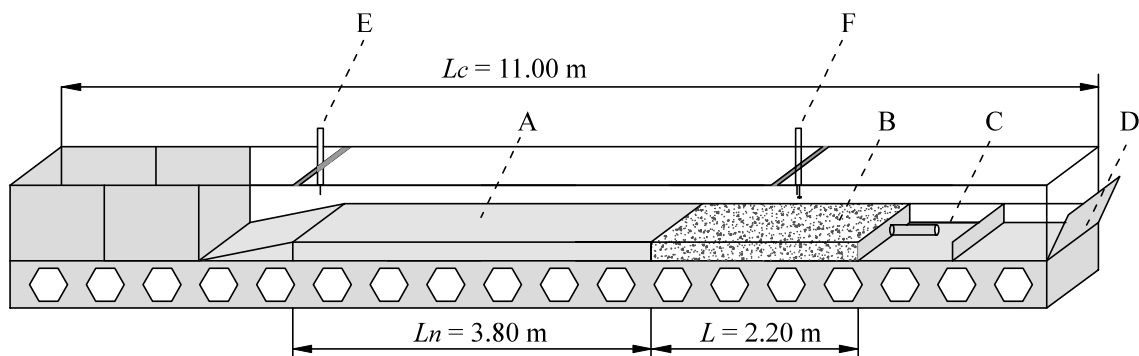
Fig. 3. Flume development schematics: A – solid bottom; B – alluvial bed; C – collection chamber; D – regulatory gate; E – pin gauge; F – moving pin gauge equipped with disc probe; L – the length of the sandy bed below the structure; L_c – total length of the flume; L_n – the length of the solid bottom upstream of the structure

lic jump was observed. With a time step of 0.5–1.0 h the level of water surface and the bed shape in chosen cross-sections were measured. When stable bed shape was achieved, the flume was drained. Volume of sand captured in the collection chamber was measured, providing information on the total volume of scour.

Sedimentation model

Further part of analysis consisted on the HEC-RAS software simulations, commonly used to mapping environmental processes, such as river bed and valley morphology shaping. Starting from the version 4.0 HEC-RAS includes a one-dimensional sediment transport model. The sediment transport module is based on the Exner sediment continuity equation, which is solved over control volumes formed between channel cross-sections. For each grain class a transport capacity is computed using one of eight transport functions (Ackers–White, Laursen, Meter-Peter–Müller, Yang, Toffaletti, Wilcock–Crowe and Wong–Parker). The calculated transport capacity is compared to the sediment mass entering to the control volume. Depending on the difference between the capacity and supply erosion or deposition is considered (Brunner, 2016; Sharma, Herrera-Granados & Kumar, 2019).

On the basis of the sediment continuity equation, channel geometry (cross-sections) is updated in each time step. In the present study, the quasi-unsteady model was used, which states hydrodynamics simplification, representing a continuous hydrograph with a series of discrete steady flow profiles. The division

pertains also to sediment mass – the whole sediment mass is performed as a sedigraph by attributing sediment loads to discrete hydrograph flows with the assumption that flow and load are related (Gibson, Pak & Fleming, 2010).

Typically, sediment transport functions predict rates of sediment transport from a given set of steady--state hydraulic parameters and sediment properties.

Identification of the transport functions parameters

The model's ability to reproduce observations was analysed for three sets of parameters. Results were evaluated on the basis of the calculated and measured volumes of scour, using statistics such as relative error, coefficient of correlation, a mean squared error and its root. In the first approach, calculations were performed using default parameters of transport functions, later using empirical formulas for parameters values and at the end, on the basis of the optimization, using the Monte Carlo sampling technique. Having in mind hydraulic conditions and flume geometry properties four transport functions were chosen: Ackers–White, Laursen (Copeland), Meyer-Peter–Müller and the modified version of Meyer-Peter–Müller, differing from the original version by values of function parameters of Wong–Parker.

Chosen formulas are widely used for sediment load calculations, verified on the grounds of laboratory research, including bed forms, such as ripples or dunes, working with sandy and gravel soils.

In HEC-RAS framework, parameters of transport formulas can be adjusted to improve the agreement between the model and observations. It can be done using empirical formulas (Table 1) to calculate parameter values. The sediment transport functions are the results of theoretical and empirical science, therefore the default formulas coefficients represent the central tendencies of the considered data. Commonly they will not likely reflect the transport of a specific site precisely, even if an appropriate transport function is selected. It is given the opportunity to calibrate the formulas by "exposing" some of them (Brunner, 2016).

In the final approach, parameter values were optimized on the basis of the Monte Carlo sampling,

Table 1. The chosen sediment transport function dimensionless data summary table

The predictor	Parameters of function
Ackers and White, 1973 (Brunner, 2016)	
Total load $$X = \dfrac{G_{gr}\, s\, d_{50}}{H\left(\dfrac{u_*}{v}\right)^{n_e}}$$ $$G_{gr} = C\left(\dfrac{F_{gr}}{A} - 1\right)^{m}$$	$C = \log C = -3.36 + 2.79 \log D_{gr} - 0.98(\log D_{gr})^2 \quad$ if $D_{gr} \leq 60$ $\qquad\qquad\qquad 0.025 \qquad\qquad\qquad\qquad$ otherwise $$D_{gr} = D_{50} = d_{50}\left[\dfrac{(s-1)g}{v^2}\right]^{1/3}$$ $A = \begin{cases} 0.14 + \dfrac{0.23}{\sqrt{D_{gr}}} & \text{if } D_{gr} \leq 60 \\ 0.17 & \text{otherwise} \end{cases}$
Laursen, 1958 (Brunner, 2016)	
Total load $$\tau_c = 0.432\,Re^{-2} + 0.04(1 - 3.32\,Re_*^{-1})$$	$$C_m = \alpha \gamma_w \left(\dfrac{d_{50}}{H}\right)^{P}\left(\dfrac{\tau_b}{\tau_c} - 1\right) f\left(\dfrac{u_*}{\omega}\right)$$ $$Re_* = \dfrac{d_{50}\,u_*}{v}$$
Meyer-Peter and Müller, 1948; Wong and Parker, 2006 (Brunner, 2016)	
Einstein number $$q_b^{\,*} = B(\tau^* - \tau_c)^e$$	$B = \begin{cases} 5.5 + 2.5\ln Re_s & \text{if } Re_s \leq 5 \\ 0.297918 + 24.8666 \log Re_s - 22.9885(\log Re_s)^2 + \dots \\ \dots + 8.5199(\log Re_s)^3 - 1.10752(\log Re_s)^4 \\ 8.5 \quad \text{otherwise} \end{cases} \quad \text{if } 5 \leq Re_s \leq 5$ $$Re_s = \dfrac{u_*\, d_{90}}{v}$$

G_{gr} – sediment transport parameter; s – specific gravity of sediments; $u_* = \sqrt{\dfrac{\tau_b}{\rho_w}}$ – shear velocity; v – average channel velocity; n_e – transition exponent; F_{gr} – expression of sediment mobilization; A – threshold condition, i.e. the value of F_{gr} at initial motion; C, m – sediment transport function coefficients; D_{gr} – grain parameter; C_m – sediment discharge concentration in weight/volume; a – Laursen function parameter; γ_w – unit weight of water; P – Laursen function exponent (power); τ_b – critical bed shear stress (Shields number); $f\left(\dfrac{u_*}{\omega}\right)$ – the function of the ratio of shear velocity to fall velocity (Laursen, 1958), τ^* – dimensionless shear stress, V – average water velocity, γ_s – unit weight of particles, τ_0 – bed shear stress, B – Schlichting coefficient (Schlichting, 1968; Brunner, 2016), Re_s – shear Reynolds number, H – water depth; S – energy gradient.

which can be used as a global optimization algorithm (Niederreiter, 1992). It was chosen, because of its simplicity and lack of restrictions concerning monotonicity of the optimized function. HEC-RAS model is a closed-source software and its variables can be obtained indirectly through an application interface (Brunner, 2016). Resulting output values are rounded up to several decimal places, what makes use of any gradient based, local optimization algorithm difficult, as it would require additional constrains on a minimal optimization step for each transport function. The Monte Carlo technique was applied for each transport function as follows: (1) for each parameter by trials and errors acceptable variability ranges were established; (2) within given ranges of parameters an ensemble of random parameter values was generated; (3) HEC-RAS computations were performed for each element in the parameter ensemble; (4) For each output set fit measures were calculated.

RESULTS

The framework of HEC-RAS allows to describe the flow resistance in the model using the Manning formula. The selection of Manning coefficients for sand bed (n_s) and glass panels (n_g) were performed in respect of the measured water surface level in the downstream cross-section. Values of coefficients were chosen within their physical ranges for given surface types, minimizing the difference between the computed and measured water level. Computations were performed for the averaged values of n coefficient in range 0.018–0.020 $m^{-1/3} \cdot s^{-1}$. The computation domain was discretized with 21 cross-sections with about 0.10 m spacing starting from the beginning of sandy bed.

The summary table of decisions, parameter values and input data, demanded in HEC-RAS framework, are gathered in Table 2.

Because HEC-RAS computations reflect only one--dimensional shape of the bed changes, the longitudinal scour profile was analysed (Fig. 4 a, b). It could be observed that both scour area and medium scour depth could be easily compared. The model output included bed elevations, reflecting the scour shape in time that could be transform into an area A_{HEC} below the initial sand surface elevation (in initial time $t_0 = 0$). Side-view area A_{HEC} multiplied by channel's width $W = 0.58$ m gives a volume V_{HEC} [m^3] of the scour in each simulation, that could be compared with a value V_{LAB}, obtained directly during the laboratory measurement for each experimental variant.

The main parameters of the laboratory experiment, such as water discharge (Q_w) and water depth (H) in control profile, are reported in Table 3. Laboratory

Table 2. The summary table of assumptions, parameter values and input data

Category	Decisions, parameter values and input data
Flow	− steady flow, for simulations quasi-unsteady flow assumption − downstream boundary condition: known water surface level
Bed sediment	− grain size distribution: invariable for each cross-section − specific density of solid particles: $s = 2.65$ − $d_{50} = 0.91$ mm, $d_{84} = 0.94$ mm, $d_{90} = 0.98$ mm
Sediment transport	− upstream boundary condition: sediment load series equal 0 − sediment transport functions used: Ackers–White, Laursen, Meyer-Peter–Müller − fall velocity: Van Rijn
Sediment sorting	Exner 5
Hydraulic conditions and flume geometry properties	− overall particle diameter: $d = 0.03$–2.50 mm − average channel flow velocity: $V = 0.34$–0.61 $m \cdot s^{-1}$ − water depth: $H = 0.10$–0.20 m − channel width: $W = 0.58$ m − hydraulic radius: $R = 0.78$–0.98 m
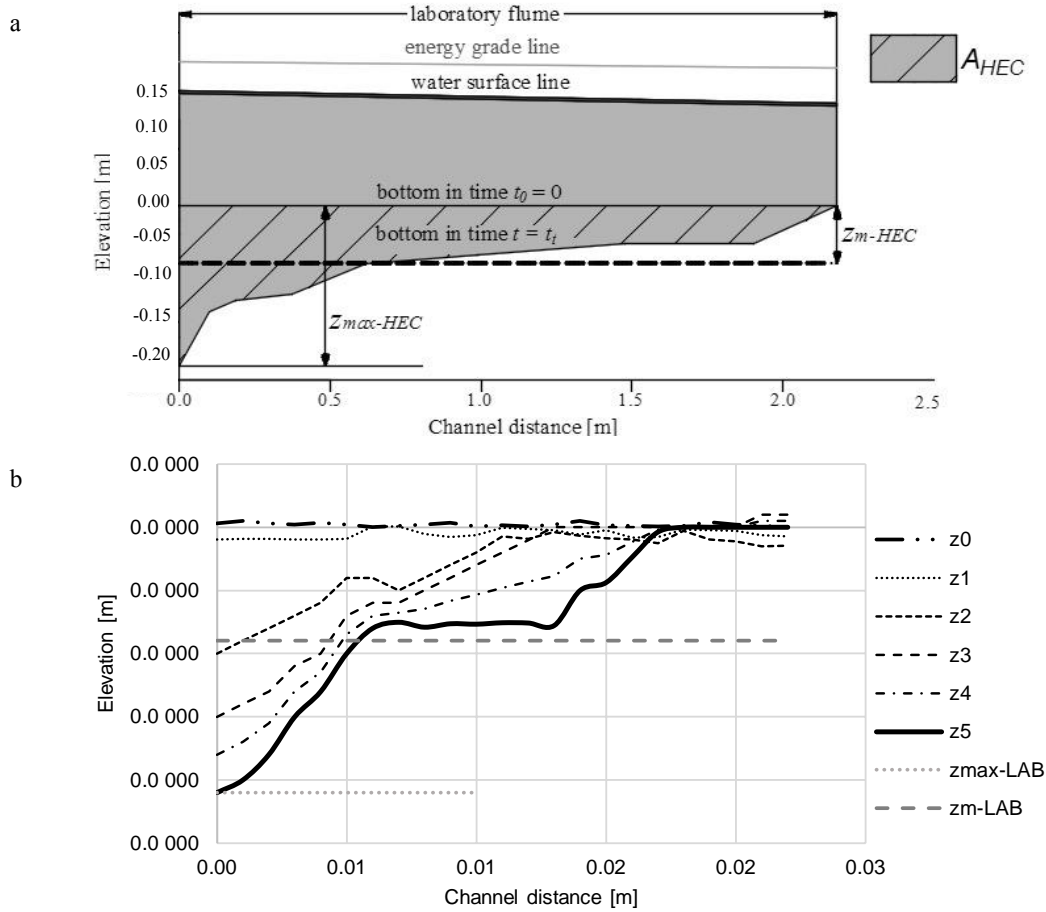
Fig. 4. Water and bed elevations at final time step of HEC-RAS simulations (a): $z_{m\text{-HEC}}$ – medium scour depth, $z_{\max\text{-HEC}}$ – maximum scour depth. The side view of local scour evolution during laboratory experiment (b): z_0 – initial shape of bottom, z_1–z_4 – medium bottom line in subsequent time steps, z_5 – final scour shape in clear-water equilibrium conditions, $z_{m\text{-LAB}}$ – real medium scour depth, $z_{\max\text{-LAB}}$ – real maximum scour depth

Table 3. Measurement results summary table

No of run	Q_w [m³·s⁻¹]	H [m]	t_t [h]	V_{LAB} [m³]	T [°C]	S_0	$z_{m\text{-LAB}}$ [cm]
1	0.020	0.10	7.25	0.002	16.8	0.0005	0.16
2	0.025	0.10	10.50	0.018	16.5	0.0008	1.50
3	0.025	0.12	6.50	0.002	16.1	0.0004	0.16
4	0.030	0.10	5.00	0.037	16.5	0.0013	2.93
5	0.030	0.15	6.00	0.002	16.7	0.0004	0.16
6	0.035	0.12	8.50	0.047	16.3	0.0011	3.72
7	0.035	0.15	7.50	0.004	15.9	0.0005	0.32
8	0.040	0.10	9.25	0.097	16.0	0.0012	7.83
9	0.040	0.12	10.50	0.055	17.2	0.0010	4.43
10	0.040	0.15	8.00	0.019	17.0	0.0008	1.50
11	0.040	0.20	6.00	0.002	16.8	0.0002	0.16
12	0.043	0.12	8.50	0.068	16.6	0.0013	5.38
13	0.045	0.15	8.50	0.045	16.0	0.0008	3.56

Q_w – water flow discharge; H – water depth; t_t – total time of experiment; V_{LAB} – total scour volume; T – medium water temperature; S_0 – dimensionless energy grade line slope over erodible bottom; $z_{\max\text{-LAB}}$ – maximum scour depth.

experiments time and HEC-RAS simulations duration was the same and equal to total time (t_t). After the flume was drained, the volume of sand captured in the collection chamber V_{LAB} was measured, providing information on the total volume of scour, which was transformed into scour area. Besides the final bed shape (characterised by medium scour depth $z_{m\text{-LAB}}$) and initial water surface elevation, allowing energy grade slope line appointment (S_0), also medium temperature (T) was measured.

Empirical equations used to calculate values of transport function parameters are based on hydraulic properties of the flume (Table 1). To determine critical bed shear stress, it was necessary to assign mean shear stress for the bottom part of flume (τ_b), which is calculated as the product of density of water (ρ_w), the gravity acceleration (g), hydraulic radius of the bottom part (R_b), and initial hydraulic gradient (S_0) ($\tau_b = \rho_w \cdot g \cdot R_b \cdot S_0$). To determine the R_b value Einstein division of velocity field was used (Indlekofer, 1981; for further description see Kiraga & Popek,

2016a). Calculated functions parameters, Froude numbers and values characterising hydraulic and granulometry properties (D_{gr}, R_b, τ_b, u_*, Re_*, τ_c, Re_s) are given in Table 4.

The sample size for parameter identification using Monte Carlo method was in the ranges of 1789–2449 (Table 5). Parameters were sampled using a uniform pseudo-random number generator in bands obtained by trials and errors. For the Ackers––White equation A, C and m coefficients values were sampled, for Laursen – critical bed shear stress, so-called Shields number (τ_c), coefficient a and power (P). In Meyer-Peter–Müller–Wong–Parker formula parameters are represented by critical shear stress (τ_c), Schlichting coefficient (B) and exponential parameter (e).

Table 6 discloses result of the identification with statistical characteristics assigned: relative error (δ), coefficient of correlation (r), a mean squared error (MSE) and its root ($RMSE$). Both scour volumes and medium scour depth were compared.

Table 4. Calculated parameters summary table

No of run	Fr	D_{gr}	A	C	m	R_b [m]	τ_b [Pa]	u_* [m·s⁻¹]	Re_*	τ_c	Re_s	B
1	0.35	21.61	0.19	0.041	1.99	0.0923	0.45	0.021	17.8	0.034	18.4	9.3
2	0.44	21.50	0.19	0.041	1.99	0.0923	0.72	0.027	22.4	0.035	23.1	9.2
3	0.33	21.37	0.19	0.041	1.99	0.1088	0.43	0.021	17.0	0.034	17.6	9.3
4	0.52	21.50	0.19	0.041	1.99	0.0923	1.18	0.034	28.5	0.036	29.5	9.0
5	0.28	21.57	0.19	0.041	1.99	0.1325	0.52	0.023	19.1	0.034	19.7	9.3
6	0.46	21.44	0.19	0.041	1.99	0.1088	1.17	0.034	28.4	0.036	29.3	9.0
7	0.33	21.31	0.19	0.041	1.99	0.1325	0.65	0.025	20.9	0.035	21.6	9.2
8	0.70	21.34	0.19	0.041	1.99	0.0923	1.09	0.033	27.1	0.036	28.0	9.0
9	0.53	21.74	0.19	0.041	1.99	0.1088	1.07	0.033	27.6	0.036	28.5	9.0
10	0.38	21.68	0.19	0.041	1.99	0.1325	1.04	0.032	27.1	0.036	28.0	9.0
11	0.25	21.61	0.19	0.041	1.99	0.1692	0.33	0.018	15.3	0.033	15.8	9.4
12	0.57	21.54	0.19	0.041	1.99	0.1088	1.39	0.037	31.1	0.036	32.1	8.9
13	0.43	21.34	0.19	0.041	1.99	0.1325	1.04	0.032	26.5	0.036	27.4	9.0
Medium value			0.19	0.041	1.99	×	×	×	×	0.035	×	9.1

Fr – dimensionless Froude number, D_{gr} – dimensionless grain parameter, A – dimensionless threshold condition, C – dimensionless sediment transport function coefficient, m – dimensionless sediment transport function exponent, R_b – hydraulic radius of the bottom part, τ_b – bed shear stress, u_* – shear velocity, Re_* – dimensionless local Reynolds number, τ_c – dimensionless critical bed shear stress, Re_s – dimensionless shear Reynolds number, B – dimensionless Schlichting coefficient.

Table 5. Sediment transport formulas parameters' combination ranges summary table

| Formula | No of simulation[a] | Parameters | | | No of Monte Carlo sampling combinations |
		A	*C*	*m*	
Ackers–White	0	0.19	0.025	1.78	–
	1	0.19	0.041	1.99	–
	2	*const.* = 0.19	0.020–0.060	1.5–2.5	1 798
	×	τ_c	*a*	*P*	×
Laursen	0	0.039	0.01	1.17	–
	1	0.035	0.01	1.17	–
	2	*const.* = 0.035	0.001–0.01	1.00–2.00	2 498
	×	τ_c	*B*	*e*	×
Meyer-Peter–Müller	0	0.047	8.00	1.50	–
	1	0.035	9.1	1.50	–
	2	*const.* = 0.035	8.04	1.74	2 498
	×	τ_c	*B*	*e*	×
Wong–Parker	0	0.0495	3.97	1.50	–
	2	*const.* = 0.035	3.86	1.60	1 998

[a] 0 – number of simulation using default parameters of transport function; 1 – calculated parameter values using empirical equations; 2 – the value range of parameters during of Monte Carlo sampling.

Table 6. Sediment transport functions' parameters identification summary table

| Formula | No of simulation[a] | Parameters | | | Scour volume (*V*) analysis | | | | Scour medium depth (z_m) analysis | | | |
		A	*C*	*m*	*r*	*MSE*	*RMSE*	*δ* [%]	*r*	*MSE*	*RMSE*	*δ* [%]
Acker–White	0	0.19	0.025	1.78	0.96	0.0003	0.017	184	0.91	0.0002	0.014	153
	1	0.19	0.041	1.99	0.89	0.0011	0.033	199	0.89	0.0002	0.014	167
	2	0.19	0.044	2.17	0.86	0.0011	0.033	175	0.86	0.0002	0.014	146
	×	τ_c	*a*	*P*								
Laursen	0	0.039	0.01	1.17	–0.12	0.0630	0.251	3 445	–0.11	0.0132	0.113	2 744
	1	0.035	0.01	1.17	–0.08	0.0643	0.254	2 947	–0.08	0.0133	0.115	2 441
	2	0.035	0.001	1.67	0.96	0.0005	0.022	299	0.96	0.0001	0.010	244
	×	τ_c	*B*	*e*								
Meyer-Peter–Müller	0	0.047	8.00	1.50	0.98	0.0001	0.010	52	0.98	0.0000	0.005	51
	1	0.035	9.1	1.50	0.94	0.0016	0.013	200	0.94	0.0003	0.017	168
	2	0.035	8.04	1.74	0.96	0.0003	0.016	43	0.96	0.0001	0.007	42
	×	τ_c	*B*	*e*								
Wong–Parker	0	0.0495	3.97	1.50	0.97	0.0004	0.020	66	0.97	0.0001	0.010	58
	2	0.035	3.86	1.60	0.96	0.0003	0.018	47	0.96	0.0001	0.008	43

[a] 0 – number of simulation using default parameters of transport function; 1 – simulation results using calculated parameter values; 2 – the group of parameters that gives the best fit in the scope of Monte Carlo sampling.

DISCUSSION

Rich database reports that in many cases the greater was the scour volume, the lower was the value of relative error (example shown in Fig. 5). The best statistics were delineated for volumes bigger than 0.019 m^3. For example, in case of original Meyer-Peter–Müller equation, rejecting mentioned range reduces relative error from 52 to 9%. In the case of lower volumes, quantitative error of expected and received from simulation volumes is small, however percentage error is significant.

Inversed phenomenon is reported in Talreja et al. research (2013). Paper presented that the higher capacity of sediment transport is analysed, the bigger is difference between calculation and actual capacity. Talreja et al. (2013) presented the verification of sediment transport formulas using HEC-RAS framework for a set of laboratory conditions, including 0.2-meter wide and 30-meter long flume with movable sand bed of mass median diameter d_{50} = 0.32 mm. Verification dealt with Ackers–White, Engelund–Hansen, Laursen, Yang, Toffaletti and Meyer-Peter–Müller sediment transport equations, whereas only Laursen (Copeland) were compatible with the morphological characteristics of studied flume.

Research reported that the best results were obtained for formulas, acknowledged as a proper for this laboratory case, basing on function's input ranges. The best explanation of the data was provided using Engelund–Hansen formula, with a mean normalized error of 11.23% and for Laursen with 11.29%. For extant ones, the error was higher, up to 90%.

Present research gave bigger inequalities between actual and computed values of scour hole values, and the mean relative error reached even up to more than 3,400%. Comparing Talreja et al. (2013) and presented in this paper model properties it must be distinctly emphasized that sediment transport capacity calculations in case without local scouring phenomenon is less complicated than with it. The variability of roughness coefficients in the flume length induces hydrodynamic conditions changes, such as mean water velocity, the velocity distribution and stream turbulences occurrence. These variabilities lead to intensifying the water potential to sediment movement induction. The increment of kinetic energy of the flowing water imparts an erosive ability of the stream. Turbulence intensity increases even twice in the scour hole and it becomes the main reason of further sediment movement and hole evolution, however its direct impact on local scouring process is not eventually recognized.

CONCLUSIONS

The verification of sediment transport formulas, implemented into HEC-RAS framework, was performed. It was chosen Ackers–White, Laursen, Meyer-Peter–Müller and Wong–Parker formula on the grounds of their input ranges. The verification was divided into
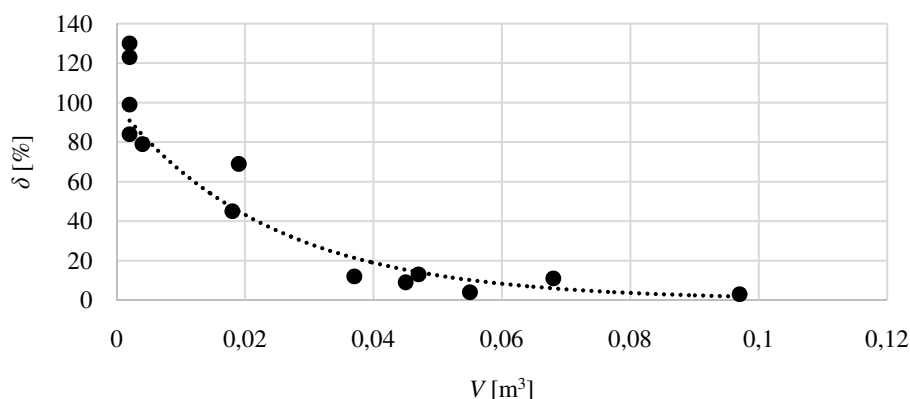
Fig. 5. The relation between relative error (δ) and the scour volume (V) in the case of Meyer-Peter–Müller formula simulation

three parts. Functions are provided with default parameter values, established by their authors for a specific set of geometric and hydraulic properties (first part), however it is possible to adjust their values to improve the agreement between the model and observations. In the second part, there were empirical equations used to calculate the parameters. The third part contains Monte Carlo sampling technique in the scope of choosing the parameters set, that lead to the best model fit. The subject of comparison was local scour volume and medium local scour depth. Scour hole was formed in the 8.18-meter long laboratory flume with partially sandy bed, preceded by solid bottom, as a result of energy gradient increment due to bed roughness variability.

The main statistic parameter that was the basis for choosing the best agreement between actual and calculated was medium relative error and the comparison was complemented with correlation coefficient, mean squared error and its root. First part of analysis identified Meyer–Peter Müller formula as the best description of laboratory conditions. The second part of identification pointed at Ackers–White formula and Meyer-Peter–Müller with parameters calculated using empirical formulas, with a mean relative error ranging to 199 and 200%, however rejecting the minor scour volumes diminish the error four times in those cases. Despite of high complexity of the process, that present paper deals with, and high errors between actual and calculated scour hole volumes, it was possible to optimize the sediment transport equations parameters in the aim to obtain better data fit. Monte Carlo sampling technique allowed to diminish relative error in any case of verified formula – in presumed groups of parameters, within their physically reasonable ranges, it could be possible to find the better data fit than in case of result of functions with default parameters simulation. To sum up, taking into consideration the main statistic parameter, such as mean relative error for each examined forms of functions, it was claimed that Meyer-Peter–Müller formula describes the most properly laboratory experiment, with parameters, found during Monte Carlo sampling.

The best match between formula and data within the whole experimental series group was obtained with the Meyer-Peter–Müller formula described by parameters, discovered on a way of the Monte Carlo

simulation (error was equal to 43%). Also small error (52%) was obtained in the case of Meyer-Peter––Müller formula in its original form. It could be also highlighted that Wong–Parker formula in its default form gives very satisfactory results in analysed dataset and the relative error was 66% that could be diminished to 47% by Monte Carlo sampling application. The worst results were obtained in the case of Laursen formula (up to 3,445% in its default form, diminished using Monte Carlo sampling to 299%). Therefore it could be stated that Monte Carlo procedure leads to obtain better match of dataset and the formula. Moreover extended studies have to be recommended before generalizing obtained results.

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MODELOWANIE LOKALNYCH ROZMYĆ NA PODSTAWIE BADAŃ LABORATORYJNYCH

STRESZCZENIE

W artykule przedstawiono weryfikację formuł służących do szacowania transportu rumowiska wleczonego, zaimplementowanych w programie HEC-RAS na podstawie badań laboratoryjnych. Zweryfikowano wyniki obliczeń z wykorzystaniem funkcji Ackersa–White'a, Laursena i Meyera-Petera–Müllera. Analiza składa się z trzech części. W pierwszej części wykorzystano funkcje z ich domyślnymi wartościami parametrów, ustalonymi przez ich autorów dla określonego zestawu właściwości geometrycznych i hydraulicznych. Następnie parametry funkcji obliczono za pomocą równań empirycznych i wprowadzono do programu. Trzecia część zakładała wykorzystanie techniki próbkowania Monte Carlo w celu doboru zestawu parametrów, które prowadzą do najlepszego dopasowania modelu. Przedmiotami porównania były objętość i średnia głębokość lokalnego rozmycia. Badania prowadzono na modelu laboratoryjnym z częściowo piaszczystym dnem, poprzedzonym dnem stałym, gdzie rozmycie powstawało w wyniku zróżnicowania gradientu energetycznego wynikającego ze zmienności chropowatości podłoża.

Słowa kluczowe: transport sedymentacyjny, HEC-RAS, erozja, wzory empiryczne, modelowanie hydrologiczne, próbkowanie Monte Carlo