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Recalling Meyer-Peter and Müller Approach for Assessment of Bed-Load Sediment Transport

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Abstract

In this paper is discussed sediment transport as a mechanical process that characterises a natural stream or channel flow regime. The objective of experimental work presented in this paper is to recall and to give another prospect of well-known Meyer-Peter and Müller approach for estimation of Shield's number (θ_c, θ) in laboratory conditions, and calibration of dimensionless MPM number (A). For this purpose two different experiments are conducted, during the first experiment water amount flushed on the flume and bed slope was changed simultaneously until equilibrium state is achieved, meanwhile is estimated the critical Shield's number (θ_c). While, during the second experiment, water amount was kept constant, only bed slope of flume was continuously tilted, meanwhile sediment, discharge and Shield's number (θ) was determined for given hydraulic conditions. In addition calibration of dimensionless MPM number (A) was performed, where several iteration were considered until for $(A = 3.42)$, sediment discharge measured become almost equal with sediment discharge computed by using MPM formula. After these experiments, is concluded that MPM formula can be used also for other certain initial condition and similar procedure may be adopted to calibrate the dimensionless MPM number (A) .

Keywords: *MPM Formula, Shield's Number, Sediment Transport, Sediment Motion, Hydraulic Regime,*

1 Introduction

Sediment transport is a mechanical process associated with the movement of a particular mass of particles along the torrents, streams, and rivers bed, or along the swash zone of shoreline by changing the continuous morphology of their flow path. Sediments are fragmented materials formed as results of the different physical-chemical process. Sediment transport process in torrential rivers begins with massive size sediments represented by rocks, while at the downstream part; the main part of rocks is fragmented up to tiny particles, [5]. Therefore, sediment transport is divided into three categories: regular bed load, suspended load (clay) and saltation (Figure 1). Bed load transport is an essential physical process in open channels; construction and maintenance of channels are linked directly with the hydraulic regime and rate of sediment transport, [6], [12]. The interaction between river bed and sediment transport have been given significant attention since sediments transport is also associated with erosion process that has a high indication of landscape evolution, [9], [26]. However, except sediments obtained because of erosion process of lands, rill erosion is another process that has a significant contribution on entire types of sediment transport, [22]. During floods large volume of water occupies the whole area around the river bed by forming a floodplain, within the water volume significant amount of sediment is deposited as well, [1], [3], and [14].

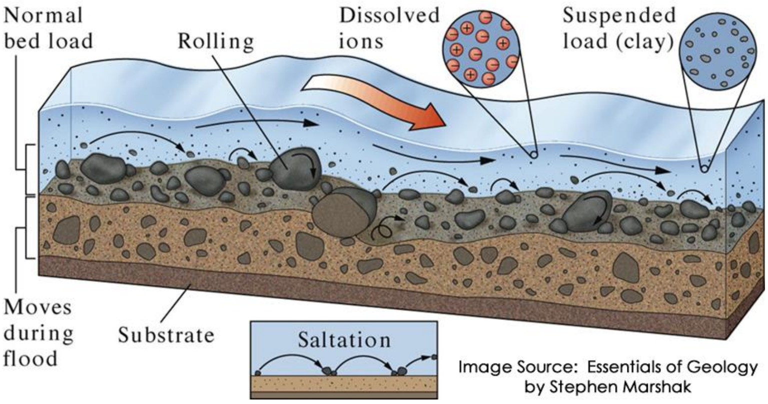

Figure 1. Categories of sediment transport, from rolling to dissolved ions, after [5]

Assessment of the hydraulic regime for sediment motion and transport rate as well is the crucial task in hydraulic, [4], [7], [2]. The river morphology change concerning time, these changes depends on not only on local environmental and geological conditions but also from the regime of sediment transport along the riverbed. Typical bedload particles usually skip, roll slightly, and hope along the bottom of the riverbed. Whereas, the suspended load is represented by particles that are supported by the turbulence regime which spend few moments in contact with the riverbed, [17]. While saltation process is described by particles that are removed from riverbed but that still move over the bed surface. The frequency of efficient discharge of the sediments in the river depends on upon to the magnitude of hydraulic forces acting on river channel or forces inducing motion of bedload transport, [8], [19].

Since climatic, geological, and environmental conditions are primary factors influencing a rate of sediment transport, efficient discharge of sediments vary from one river to another, [15], and [16]. Bed load transport mostly occurs during flood events, [18] where coarse particles are rolling down along the riverbed. Bed load transports, especially in mountain region are presenting a grave risk by eroded rocks with large dimensions. However, this type of bed load sediments with large size being reduced at the downstream part regarding dimensions, the potential risk is reduced as well.

In all kind of sediment transport, the threshold of sediment motion presented regarding either critical discharge or critical shear stress is a crucial parameter for estimating and predicting sediment transport rate, [23], [10], [12]. To obtain accurate results and to make the right prediction, is crucial to know the regime of the river and physic-mechanical parameters of sediments; in this way, we can adjust the current methods and formulas. Many researchers nowadays are focusing on developing more accurate models (e.g., BASEGRAIN, CCHE2D, HSCTM2D and TELEMAC 2D), to obtain precise information about sediment transport and in particular, to estimate more accurately gravel transport in a natural stream, [20], [25]. There are many empirical methods and formulas proposed by different research, but Meyer-Peter and Müller's approach remains the most used in numerical models and field investigation as well, [24]. The purpose of this paper is to estimate the Shield number (θ) under different hydraulic condition, for given flume parameters, and calibration of the dimensionless number MPM number (A) as well. Especially in modified rivers, flow regime is significantly altered that´s why is crucial to understand the implications imposed in the riverbed as result of water depth variability. These implications can be adequately explained through relation between flow regime and physical parameters like: Shield number (θ), parameter that is discussed hereafter in this manuscript.

2 Materials and Methods

Most of the rivers are characterised by the wide range of the grain size, in this condition's hard to conduct numerical or physical modelling, [13]. However, in our case, the experimental process is carried out in a flume with specific dimension shown (Figure 2, Table 1).

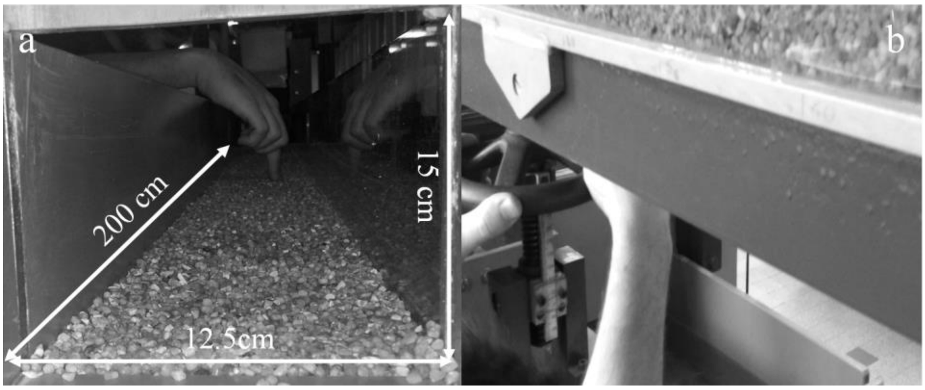

Figure 2. Flume used to conduct the experiments: a) flume cross-section and b) flume slope adjuster

Computation of Shield number (θ, θ_c) is done in two ways by performing two different experiments. Detailed information about the physic mechanical parameters of particles and other components used during the experimental work are presented below, (Table 1). In both experimental works, is used the same grain size in order to investigate how the MPM number (A) effect the Shield number and other parameters as well. Specifically during, the first experiment is computed the (θ_c), which is the threshold value of the Shields number.

Table 1. Physical and mechanical parameter of grains, water amounts, and flume dimensions

Width of channel $b\ (m)$	**Length of channel** $L\ (m)$	**Depth of channel** $h\ (m)$	**Particles' diameter** $d_m\ (mm)$	**Particles' density** $\rho_s\ (^{kg}/_{m^3})$	**Water density** $\rho\ (^{kg}/_{m^3})$	**Gravity** $g\ (^{m}/_{s^2})$
0.125	2	0.15	3.5	2700	1000	9.81

2.1 First Experiment

During the first experiment, a particular water discharge is released continuously while tilting the channel bed slope (i.e., increasing the slope, four replicates were conducted in range of slope between 0.98-2.18 %), while is noticed that the sediment particles start moving uniformly along the flume bed until reaching equilibrium (Figure. 3). At this stage is recorded the slope and water depths as well for different intervals channel length respectively 0.3 and 1.20 m.

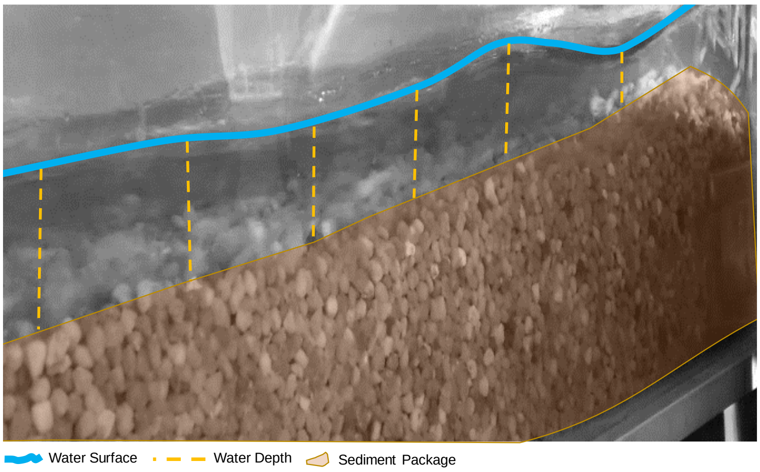

Figure 3. Uniform transport of the particles along the flume bed during the first experiment

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The same procedure is repeated by increasing channel slope (Figure 2b); waiting until sediment discharge reaches equilibrium (i.e., until uniform sediment discharge occurred along the flume), while the corresponding water depths are measured. Gradually it is noticed that sediment discharge is increasing while increasing the channel slope due to the friction force induced between the fluid with the flume bed and the vertical walls as well. This friction force also depends on the particles size that could vary from one channel type to another, [21]. Moreover, the friction force exerted on the fluid is directly proportional to the energy grade line, which depends on the slope. Thus, according to the equation (1), it is deduced that the resisting force (F) is counter-balanced by the component of the fluid weight parallel to the bed.

$$F = \rho.g(h.b.l).i \qquad (Pa) \qquad (1)$$

Where: F is the resisting force, (kg/m^3) is the water density, (m^2/s) is the gravity acceleration, $h\ (m)$ is the water depth, $b\ (m)$ is channel width, $l\ (m)$ is the channel length, and $i\ (\%)$ is the flume bed slope. In our case, is neglect the friction force exerted by the vertical wall, therefore the stress that is induced by the bed it also represents the stress exerted by the fluid on the bed sediments, equation (2).

$$\tau = \rho.g.h.i \qquad (Pa) \qquad (2)$$

The resistance force corresponding to the particle ability, to withstand the dragging effect is proportional to its apparent weight, where $(\rho s - \rho)$ is the particle apparent density depending on its type, so resistance force can be expressed as shown in equation (3).

$$F' = K.(\rho_{s-}\rho).g.d_m^3 \qquad (Pa) \qquad (3)$$

Where: (F) is the resisting force, (θ_c) dimensionless critical Shields number, (K) dimensionless coefficient denoting the grains shape, $\rho_s\ (kg/m^3)$ is the sediment particles' density, and $d_m(mm)$ is the mean particles diameter. Thus, the shear stress required to put the sediment particles into motion will be characterised by the equation (4, 5), [27] by neglecting the weight component parallel to the bed.

$$\tau_c = 29.\sqrt{(\rho_S - \rho).g}.d_m/M \qquad (Pa) \qquad (4)$$

$$\theta_c = \tau_c / \Delta\rho g d_m \qquad (5)$$

Where: (τ_c) is the critical shear stress for incipient motion.

2.2 Second Experiment

The second experiment has been conducted to determine the sediment discharge (g_v) and the Shields number (θ) for different hydraulic conditions (i.e., imposed by variable hydraulic depth along the flume); in this experiment are conducted six replicate, (θ) is computed by using equation (6).

$$\theta = (h.i)/(\rho_s - \rho).(\frac{d}{\rho}) \qquad (6)$$

The various sets of $(g_v - \theta)$ that were obtained, are used to determine the general correlation between these two values as it is described by MPM formula, equation (7).

$$g_v = A.\sqrt{g.\left(\frac{\rho_s - \rho}{\rho}\right).d_m^3}.(\theta - \theta_c)^{\frac{3}{2}} \qquad (m3/s)/m \qquad (7)$$

It is evident that since all other values are already known, finding the correlation between (g_v) and (θ) actually means the determination of the value of (A)**.** The channel slope has been fixed to the maximum value (i.e. 0.1%). The sediment inflow to the channel has been set to a certain rate and the appropriate time was provided for the system to reach equilibrium state (Figure 4).

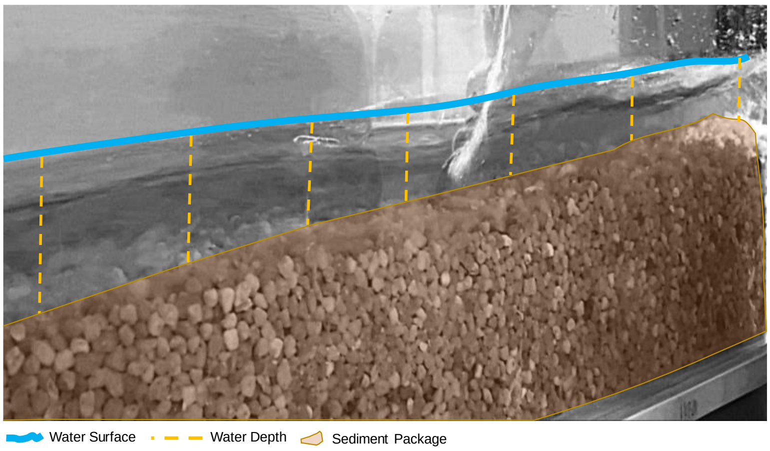

Figure 4. Intensive transport of sediments until the equilibrium is reached

Flow conditions need some time to adjust to the new sediment inflow motion. According to the sediment inflow rate, the channel bed is aligned almost uniformly, by either depositing or eroding sediment, and a new flume bed slope will uniformly form the channel. When equilibrium is finally reached, a smooth channel bed slope is formed, and the sediment outflow discharge is stabilised. Then, measurement takes place for one minute; during that time the sediment inflow and outflow are measured. Incoming sediment is determined by the gauge of the silo’s outlet and out coming, sediment is collected in a sieve, and the weight is measured (Figure 5).

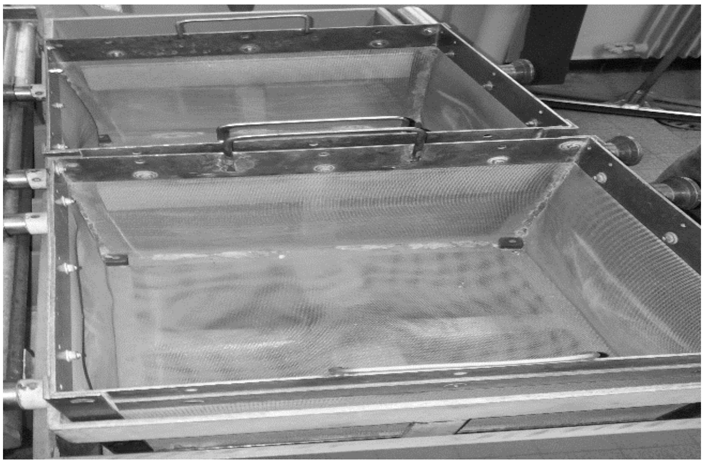

Figure 5. Sieve for capturing the sediment discharge

Additional measurements comprise sediment depth and water depth measurements. These measurements are conducted to determine the channel bed slope (i.e., the total slope is equal to the initial present value of the canal $(i = 0.1\%)$ and the one determined by the sediment depth measuring), and the water depth along the channel. For enhanced accuracy, measurements are made in three points (for $x = 0.1, 1\ and\ 1.9m$). The process described above was repeated four times and during four different sets of measurements were obtained the different values of sediments discharge.

3 Results and Discussion

3.1 First Experiment

As mentioned above, to compute various hydraulic parameters for certain hydraulic condition; two separate experiments are conducted in a laboratory flume. Specifically, during the first test is calculated critical Shields number(θ_c), while $(\Delta\theta/\theta)$ is computed by following equation (8):

$$\Delta\theta/\theta = \left(\frac{H}{\rho * h} + \frac{i}{s}\right) \tag{8}$$

Where:$H = 0.15m$, is the initial water depths in the flume, S is the slope of the entire flume, the rest of the parameters are explained above $\Delta\theta$ is computed by equation: $\Delta\theta = (\theta_c * (\frac{\Delta\theta}{\theta}))$, summary of results achieved during the first experiment are presented below (Table 2).

Table 2. Summary of results achieved during the first experiment regarding the computation of $(\boldsymbol{\theta_c})$ and other parameters

		Discharge	**Flume Slope**	**Shields Number**	**Precision**	
	Water Depth (h) **(m)**	Q(m^3/s)	S **(%)**	(θ_c)	$(\Delta\theta/\theta)$	$(\Delta\theta)$
	0,036	0,00253	1,29	0,078	0,11	0,008
	0,027	0,002	1,58	0,072	0,10	0,007
	0,021	0,0015	2,18	0,075	0,09	0,007
	0,042	0,003	0,98	0,069	0,13	0,009
Mean	**0,031**	**0,002**	**1,508**	**0,074**	**0,107**	**0,008**

During the experimental process, flow discharge (Q) released and flume bed slope are changed simultaneously. Prior releasing the certain water amount on the flume, there is placed a certain amount of the solid particles (sediments) with respective physic-mechanical characteristic as shown in (Table 1). It is noticed that at the initial phase where flow discharge flushed is about $(Q = 0.00253 \text{ m3}/s)$ and flume bed slope is $(i = 1.29\ \%)$ highest value of critical Shields number is achieved (i.e. $\theta_c = 0.078$). After the initial phase of the experimental process, flow discharge flushed on the flume and bed slope continually are changed but critical Shields number is characterised by decreasing trend, the minimum value achieved is about $(\theta_c = 0.069)$. As shown in (Figure 6) the flow discharge flushed on the flume is lower while bed slope at an initial phase is higher than last one, critical Shields number at last phase is lower than at initial phase. This phenomenon happens due to the lack of water content surrounding (i.e., sediments has been in dry condition before flushed by certain flow discharge in the flume) the particles at the initial phase and higher flow discharge during the last phase of the experimental process; also reduction of flume slope impose significant impact on Shields number.

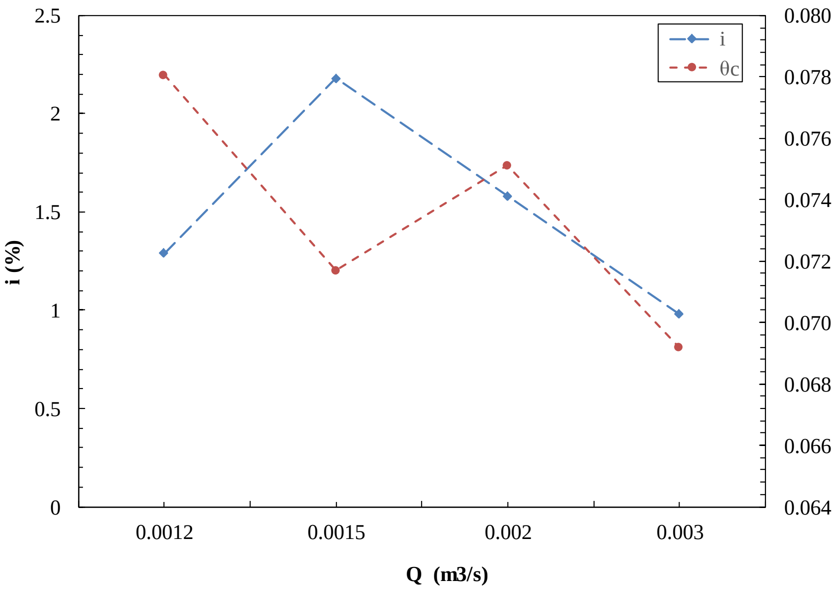

Figure 6. Variation of critical Shields number $(\boldsymbol{\theta_c})$ for certain bed slope of flume and flow discharge

3.2 Second Experiment

While during the second experimental work, as mentioned above, is determined the sediment discharge (g_v) and the Shields number (θ) for certain hydraulic conditions. Compare with the first experiment, where both flow discharge flushed on the flume and bed slope of flume are changed simultaneously, afterwards critical Shields number (θ_c) is determined, during the second experiment flow, discharge remain constant while bed slope of flume is changed continuously. More specifically second experiment is conducted by performing several tests for different MPM number (A). The mean values for sediment discharge (g_v), the Shields number (θ) and different other hydraulic parameters as well are presented below on (Table 3).

Table 3. Summary of mean values concerning to the sediment discharge ($\boldsymbol{g_v}$), Shields number ($\boldsymbol{\theta}$) and other hydraulic parameters for initial and last conditions

A	**Nr. Tests**	**Total Depth** h (cm)	**Sediment Depth** $h_s\ (m)$	**Water Depth** h_w (cm)	**Total Slope** $i\ (\%)$	**Sieve empty** (gr)	**Sieve full** (gr)	**Weight of sediments** (gr)	**Sediments discharge measurement** $(l/s)/_m$	**Shields Number** (θ)	**Precision** $(\Delta\theta/\theta)$	$(\Delta\theta)$	**Sediments Discharge Computed** (g_v) $(l/s)/_m$
8	First Iteration	10.1	0.078	2.3	3.9	3820	4920	1100	0.0543	0.14857143	0.0698	0.0104	0.139
	Second Iteration	9.2	0.070	2.2	5.2	3820	6340	2520	0.1244	0.18935574	0.0654	0.0124	0.267
	Third Iteration	9.5	0.073	2.2	5.4	3820	6510	2690	0.1328	0.19815126	0.0643	0.0127	0.298
	Fourth Iteration	9.7	0.075	2.2	6	3820	7010	3190	0.1575	0.22184874	0.0621	0.0138	0.386
3.42	First Iteration	10.1	0.078	2.3	3.9	3820	4920	1100	0.0543	0.14857142	0.0698	0.0104	0.059
	Second Iteration	9.2	0.070	2.2	5.2	3820	6340	2520	0.1244	0.18935574	0.0654	0.0124	0.114
	Third Test	9.5	0.073	2.2	5.4	3820	6510	2690	0.1328	0.19815126	0.0643	0.0127	0.127
	Fourth Iteration	9.7	0.075	2.2	6	3820	7010	3190	0.1575	0.22184873	0.0621	0.0138	0.165

Shields number(θ), is an important parameter that induce movement of sediments along the flume bed or riverbed in natural conditions, [11]. It is noticed that during the second experiment, with reduction of the dimensionless number, (A) for certain highest value of (θ) computed sediment discharge by MPM formula is decreasing, (Figure 7). However, for lowest value of dimensionless number $A = 3.42$ considered in our case, hydraulic conditions, and physic-mechanical characteristic of sediments; the equilibrium between computed and measured sediment discharge is reached.

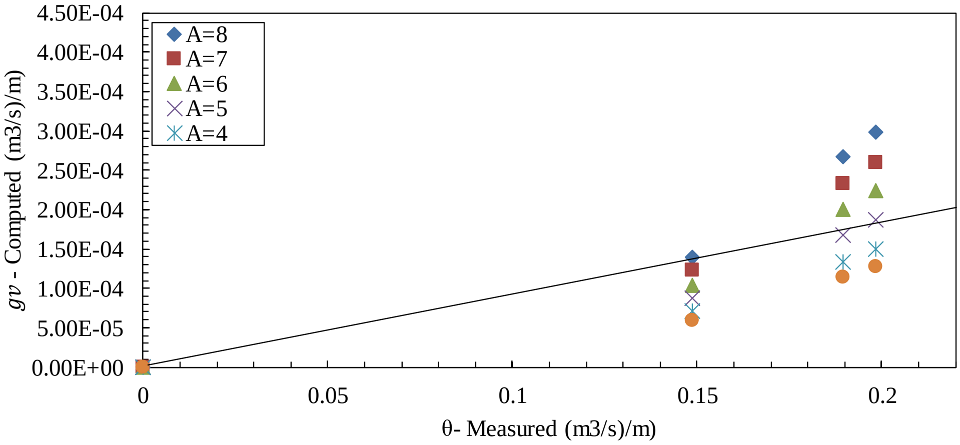

Figure 7. Relation between ($\boldsymbol{\theta}$) measured and ($\boldsymbol{g_v}$) computed sediment discharge for different values of dimensionless numb ($\boldsymbol{A}$)

During the second experiment, since only bed slope is changed while water amount flushed on the flume is constant, it is noticed that following hydraulic parameter: total depth (h), sediment depth (h_s) and water depth (h_{sw}) changes very slightly. While a slight changes is observed on Shields number and sediment discharge computed with MPM formula. During this experiment, except determination of the sediment discharge (g_v) and the Shields number(θ), in addition since several measurement is conducted, dimensionless number (A) is calibrated as well. This process is done by using MPM formula until equal value of measured sediment discharge with computed sediment discharge is reached; this equilibrium is reached for $A = 3.42$, (Figure 8).

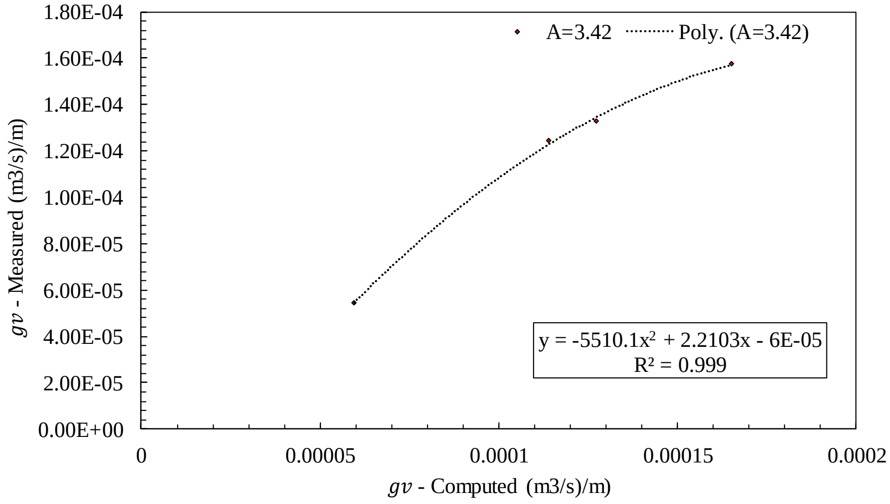

Figure 8. Relation between measured and computed sediment discharge for $\boldsymbol{A = 3.42}$

Although between calculated and measured sediment discharge is noticed a good correlation, still there are slight differences. So this differences error, (ε) between computed and measured sediment discharge is estimated as following equation (9):

$$\varepsilon = \frac{g_{vco}-g_{vme}}{g_{vme}} \qquad (9)$$

Where: $g_{vco}\left(\frac{\frac{m^3}{s}}{m}\right)$ computed sediment discharge and $g_{vme}\left(\frac{\frac{m^3}{s}}{m}\right)$ measured sediment discharge. The estimation of error (ε) is done respectively for each iteration performed regarding to the dimensionless numbers (A) considered during this experiment, (Table 4).

Table 4. Estimation of error $(\boldsymbol{\varepsilon})$ regarding different dimensionless numbers $(\boldsymbol{A})$

Iteration	**Dimensionless Numbers** (A)					
	$(A = 8)$	$(A = 7)$	$(A = 6)$	$(A = 5)$	$(A = 4)$	$(A = 3.428)$
	ε					
First Iteration	0.609539106	0.553759	0.4793855	0.3752626	0.2190782	0.0866412
Second Iteration	0.533452999	0.4668034	0.3779373	0.2535248	0.066906	-0.091338
Third Iteration	0.553753173	0.4900036	0.4050042	0.2860051	0.1075063	-0.043852
Fourth Iteration	0.592407908	0.5341805	0.4565439	0.3478527	0.1848158	0.0465682

As shown in the (Table 4) MPM number $(A = 3.42)$ reveals the lowest error. Lower error stands for more accurate results related to estimated and observed sediment discharge.

4 Conclusions

In this study, two experimental work was conducted. The first experimental work scope was to compute the critical Shields number(θ_c) for different hydraulic condition and slope. During this experiment Shields number(θ_c) in generally tend to decrease; this is due to slope reduction for each replicate. Whereas during the second experiment, discharge (g_v) and the Shields number (θ) were computed for constant hydraulic condition and with a slope that was continually tilted. The dimensionless MPM number (A) was calibrated during the second experiment. The equilibrium between computed and observed sediment discharge was achieved for MPM number $(A = 3.42)$. So, from what we have introduced above, it is observed that the particles motion depend mainly on the differences between the driving and resisting stresses. The stress (τ_c) depends mainly on particles characteristics, such as volumetric mass (ρ_s) and particle size (d_m). Whereas for (τ), it is principally related to the water depth as well as the slope; which brings us to the following conclusion related to Shields coefficient(θ). The Shields (θ) value that is obtained could be compared to a critical value (θ_c) that lies in the range of $(\theta_c = 0.06)$ for turbulent flow and $(\theta_c = 0.047)$ according to the Meyer-Peter Muller MPM formula that is mainly described for granular soils. In addition, the motion will be induced and sediment discharge will take, place if and only if the value of $(\theta > \theta_c)$, otherwise the particles will remain at rest and no sediment transport will occur. After those experiments, we can say that MPM formula can be also adopted for different condition while the calibration of the dimensionless MPM number (A) can be conducted by following the same methodology as presented in this manuscript.

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