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Empirical Relation for Prediction of Sediment-Trapping Coefficient in the Experimental Flume of the Stepped Slit Check Dams

Mohammad Reza Pirestani[1], Arash Razmkhah[2*], Amir Hosein Behroozi Fard[3]

1.Assistant Professor Department of Civil Engineering Islamic Azad University South Tehran Branch, Iran

2.Assistant Professor Department of Civil Engineering Islamic Azad University South Tehran Branch, Iran

3.Msc Hydraulic Structures of Civil Engineering Islamic Azad University South Tehran Branch, Iran

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ABSTRACT

Eroded sediments from catchment areas transport by streams and deposit in downstream less steep areas. Despite reducing the useful life of various hydraulic structures including reservoir dams, flood walls, and bridges, this phenomenon changes the main river hydraulic conditions and increases the flood prone farms in the riverbank area. Check dams are among the structures that can prevent form such phenomenon. In addition to the technical performance, hydraulic structures including dams can provide beautiful view in the areas that have the potential to attract tourists. Stepped Slit Check Dams are combination of stepped and slit check dams. The present study investigated the effects of slope, discharge, gradation type, and check dam geometry on the sediment-trapping coefficient of the dam. Finally, a relation for prediction of the sediment-trapping coefficient in the reservoir of Stepped Slit check dams was presented.

Keywords

Sediment, performance, stepped check dam, trapping

1. Introduction

Sedimentation and erosion have been among the problems that numerous catchment areas in Iran and other parts of the world face (Ahmadi, 1374). Development of human societies and unconscious interference into nature has changed the natural process of erosion to a destructive one so that the intensity and size of the damage is increasing day by day. Heavy sediment production in catchment areas will induce problems such as filling the large and small dam reservoirs, filling the khanat furnaces with sediments, mud clogging in channels and rivers, destruction of agricultural lands and orchards due to sediment accumulation during floods (Nakhjavani, 1371). Sediments from the erosion of the catchment areas transport by streams and deposit in downstream less steep areas. Despite reducing the useful life of various hydraulic structures including reservoir dams, and bridges, this phenomenon changes the main river hydraulic conditions and increases the flood prone farms in the riverbank areas. Riverbank areas have been always under particular attention by the human being, due to specific characteristicsin terms of agriculture and settlement, and therefore floods will cause huge damages to communities living in these areas. Therefore, special measures should be taken to prevent

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*Corresponding author email: A_Razmkhah@azad.ac.ir

such problems, among which is the construction of Slit check dams or check dams (Kelarastaghi et al., 1389). Slit check dams are small dams constructed in streams or ditches to decrease control flow velocity (Gray, 1982), control trapping of the sediments, decrease peak flood discharge (Moore, 1996), increase water quality (Heede and Mufich, 1973), channel infiltration capacity and vegetation (Bombino et al., 2008) and concentration time and lagtime of the catchment (Najafi Nejad, 1381) and finally will modify the longitudinal and transverse profilesof the stream. According to the researches, these dams have a simple structure and in most cases are cost-effective (Esmaili Namghi et al., 1386). According to Hudson (1976), the main purpose of the construction of such dams is to trap sediments and decrease flow velocity. Stepped check dams, Slit check dams, and Gabion check dams are among such dams that have been tested and have been sometimes implemented in nature. Obviously, performing studies and evaluations about the efficiency and performance of the considered dam in comparison with other constructed dams before design, implementation, and paying costs is necessary. A common method to evaluate the performance of a check dam is modeling in hydraulic laboratory and performing experiments considering different conditions of hydraulic parameters the results of which will clarify the advantages and disadvantages of such dam construction in nature. Today, many researches and laboratory studies in hydraulics deal with this issue (Bani Habib and Nazariye, 1390).

2. Materials and Methods

2.1. Flume

This paper is part of the results of an experimental project entitled "Modeling and Evaluation of Sediment Trapping in Stepped Slit check dams". In order to evaluate the dependency between the parameters in obtained relations, several experiments were conducted in which parameters such as bed slope, discharge, gradation type and check dam structure were evaluated using an elevated flume. Experimental flume specifications are listed in Table 1. The flume channel was made of plexiglass and was equipped with a flow meter, pump, sediment reservoir,tail basket and a 1-ton hand crane to set the elevation in desired angles. The main dimensions of the flume are width and length, respectively. Minimum length of the flume can be considered almost 12 times the flume width (Shafai-Bajestan, 1390, S. B. M and K. G., 2011). The present study aimed to identify and select important parameters affecting sediment-trapping rate of check dams, present experimental relations, variation process analysis and presentation (Takahashi et al., 2002).

Table1. Physical and hydraulic characteristics of the used flume in experiments

Geometric parameters	***descriptions***
Length	183 cm
Width	15cm
Depth	30cm
elevation	40 cm bed height from ground level, and 190 cm maximum flume height
Reservoir characteristics	36*40*70cm
Bed changes	43 cm from the starting point of the flume to the output channel
Length of the flow quieter	35 cm from the flume inlet-using porous material quieter
Hydraulic parameters	
discharge	0 to 35 liters per minute
slope	0 to 25 degrees
Equipment	
pump	40 m head, Maximum discharge of 40 lit/min, PM-45Model
flowmeter	Rotary Meter with5% error
crane	Manual crane of 1 ton capacity
Sediment tail	Stainless steel screen with mesh diameter of 0.3 mm
reservoir	Made of compressed plastic

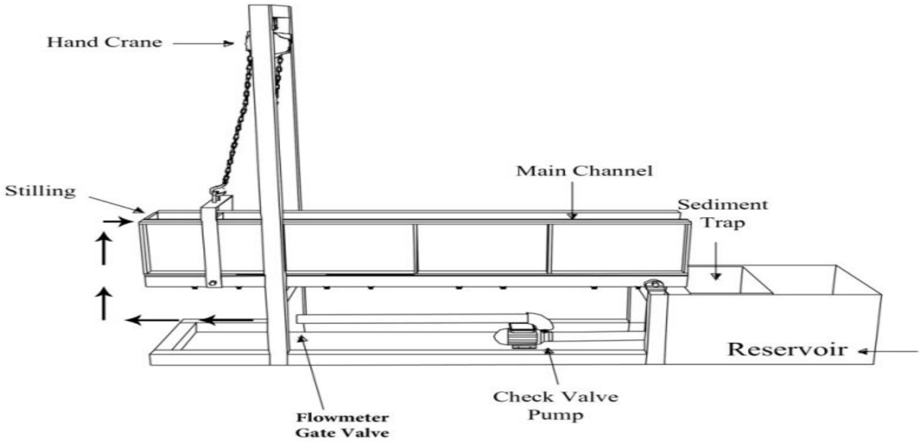

Fig. 1: Schematic view of the flume structure

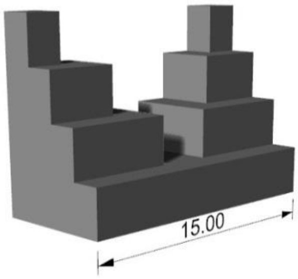	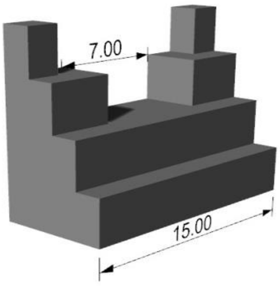	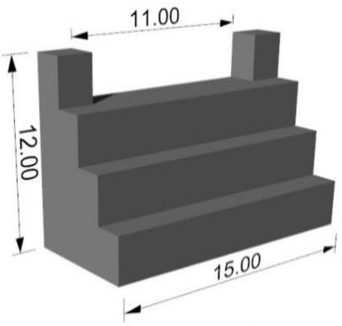
Check dam A	Check dam B	Check dam C

Fig. 2. Front view of the check dams

Fig. 3. Side and front views of the check dam and experimental flume

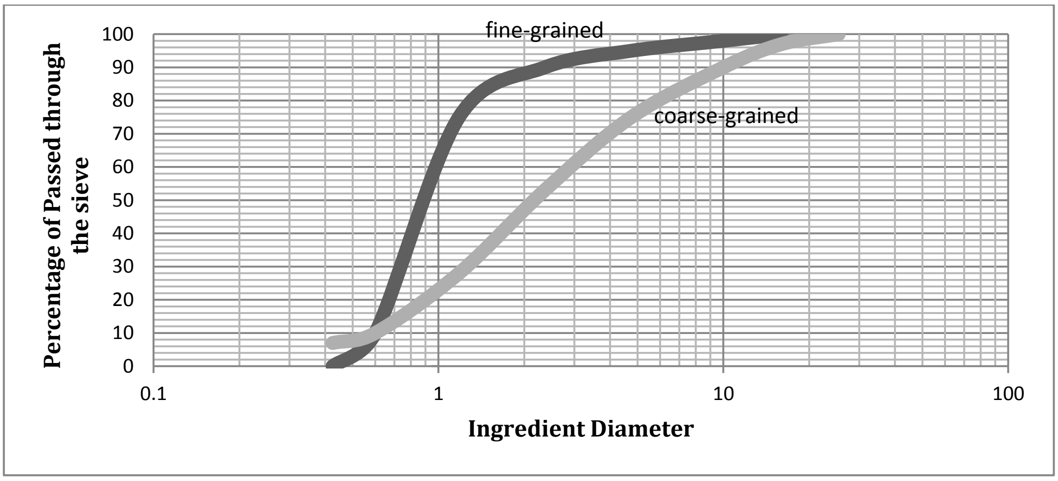

Fig. 4. Gradation curve

2.2. Check dams

The following figures show the constructed check dams. These check dams only differ in terms of width of smallest middle slit of check dam (b) and the height from the flume bed up to the first slit (h). The existing dams in nature were scaled down and models were made from waterproof wood and installed in flumes for performing experiments.

Used sediments with the above-mentioned specifications in both fine-grained and coarse-grained models had a total weight of 8Kg during the experiment.

2.3. Bed material

Silica with specific gravity of 2.60 g/cm^3 was used as bed sediments. Sediments remained on each sieve size were read and recorded separately and the following gradation curve was obtained.
Therefore, for geometric standard deviation of particles (σ) it was obtained:

$$\sigma = \sqrt{\frac{d_{84}}{d_{16}}} \Rightarrow \sigma\sqrt{\frac{6.8}{0.76}} = 2.99 \qquad (1)$$

$$\sigma_b = \sqrt{\frac{d_{84}}{d_{16}}} \Rightarrow \sigma_b = \sqrt{\frac{1.6}{0.64}} = 1.58 \qquad (2)$$

Sediments were scaled relative to natural riverbed materials specially mountain river sand verified by comparing to the average bed particle diameter of other similar experiments.

2.4. Dimensional analysis

Dimensional analysis calculated using π Buckingham method and the most important relations are listed in Table 2. After performing some algebraic operations, the parameters converted to other dimensionless relations, which occasionally used in the analysis.

Table 2. Dimensional analysis using π Buckingham method

$\pi_1 = \frac{b}{h}$	$\pi_2 = \frac{y}{h}$	$\pi_3 = \frac{B}{h}$	$\pi_4 = \frac{H}{h}$
$\pi_5 = S$	$\pi_6 = \sigma$	$\pi_7 = \frac{Vsa}{h^3}$	$\pi_8 = \frac{\mathrm{Vm}}{\mathrm{h}^3}$

Combination of some of the above-mentioned dimensionless relations resulted in Densimetric Froud Number:

$$Fr_{\mathrm{d}} = \frac{\mathrm{Q}}{\mathrm{B.y.}\sqrt{\mathrm{gD_{50}} \times (\mathrm{G_S} - 1)}}$$

Finally, Sediment-trapping coefficient obtained in terms of the dimensionless relations as a function of the following parameters:

$$Te=f\ (S,\frac{B}{b},\frac{H}{h},\frac{Vsa}{Vm},Fr_d,\sigma\ )$$

Dimensionless parameters were needed for plotting the diagrams and study the changes and the calculations were performed in this step.

3. Results and Discussion

In this paper, results of the sediment-trapping coefficient of three different check dams were compared using two gradations and various discharges. The important parameters are summarized in the following table:

Table 3. The effective parameters used in the experiments

	Q(lpm)	S(deg)	H(cm)	h(cm)	B(cm)	h(cm)
Check dam A	30	15,20,25	12	3	15	3
Check dam B	30	15,20,25	12	6	15	7
Check dam C	30	15,20,25	12	9	15	11

Vsa/Vm parameter used in the results analysis and regression, where V_{sa} is the total volume of sediment used in the experiment, and V_m is the maximum volume of the sediments that can be stored in the dam reservoir (Lien, 2003). This parameter calculated for the rectangular channels using the following equation (soil conversation handbook, 1995):

$$V_m=\frac{1}{2}\frac{BH^2}{Io-I_d} \tag{3}$$

where H is height of the dam side walls; B is channel width; I_o is the initial channel bed slope; I_d is the channel bed slope after sedimentation that is about 2/3 times the I_o.

Sediment-trapping changes for 20, 25 and 30-degree slopes were then plotted for two gradation types (*G1*: coarse-grained/ *G2*: fine-grained), which will be explained here after. It is worth noting that in the diagrams below, the purpose of *Te** is sediment passed of the control dam and *Te* is the number of trapping in upstream of the control dam. In other words: Te = 1-Te*

Table 4. Comparison of sediment-trapping ratios of check dams versus slope angles for 20 lit/min discharge and two gradation types

Te* / S.Sigma	Check dam A - G1	Check dam A - G2	Check dam B - G1	Check dam B - G2	Check dam C - G1	Check dam C - G2
15	0.264	0.344	0.223	0.289	0.05	0.088
20	0.308	0.428	0.279	0.363	0.053	0.104
25	0.414	0.538	0.323	0.438	0.126	0.155

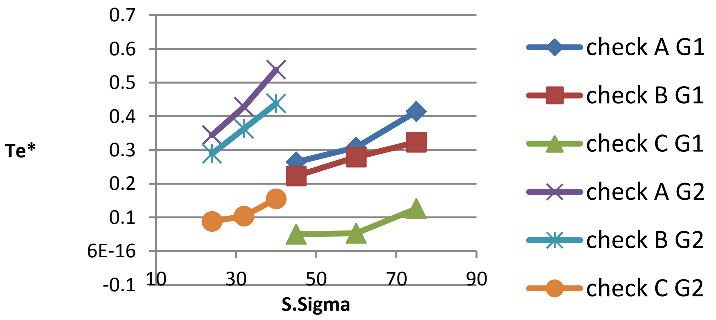

Fig. 5. Sediment changes for 20 lit/min discharge

As can be seen in the above figure, fine-grained sediments were trapped more than coarse-grained ones, i.e. higher amounts of sediments are passed from the check dam in the case of coarse-grained sediments. In the case of coarse-grained sediments, significant sediment-trapping improvement is obvious in the graph. It is evident that by increasing the slope, sediment-trapping coefficient of the dam is increased, but the important point is the significant improvement in the sediment-trapping coefficient of check dam C in comparison to A and B check dams in both fine-grained and coarse-grained cases.

In Fig. 6, it can be seen in the case of coarse-grained sediments that the ascending trend of the graph is almost the same as the previous graph (for 20 lit/min discharge) with the exception that sediment-trapping coefficient of the check dam increased about 10 percent for the investigated slopes which seems natural (by increasing the slope, more sediments pass the check dam). In the case of fine-grained sediments, a similar trend observed. Again, fine-grained sediments were trapped more than coarse-grained ones. Sediment-trapping coefficient of the check dam in case of 25 lit/min was higher than 20 lit/min case.

Table 5. Sediment-trapping coefficient versus slope of check dams for 25 lit/min discharge for two gradation types

Te* S.Sigma	Check dam A - G1	Check dam A - G2	Check dam B - G1	Check dam B - G2	Check dam C - G1	Check dam C - G2
15	0.288	0.519	0.223	0.309	0.063	0.113
20	0.353	0.603	0.279	0.435	0.083	0.19
25	0.464	0.663	0.323	0.533	0.175	0.363

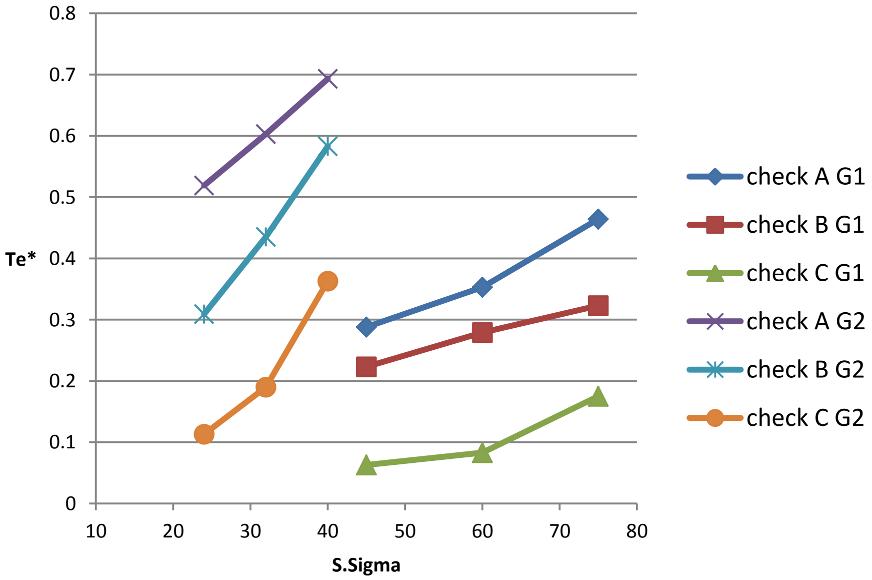

Fig. 6. Sediment changes in the case of 25 lit/min discharge

Table 6. Sediment-trapping coefficient versus slope of check dams for 30 lit/min discharge for two gradation types

Te* / S.Sigma	Check dam A - G1	Check dam A - G2	Check dam B - G1	Check dam B - G2	Check dam C - G1	Check dam C - G2
15	0.396	0.625	0.371	0.483	0.081	0.13
20	0.5	0.738	0.401	0.538	0.1	0.281
25	0.862	0.9	0.536	0.696	0.238	0.463

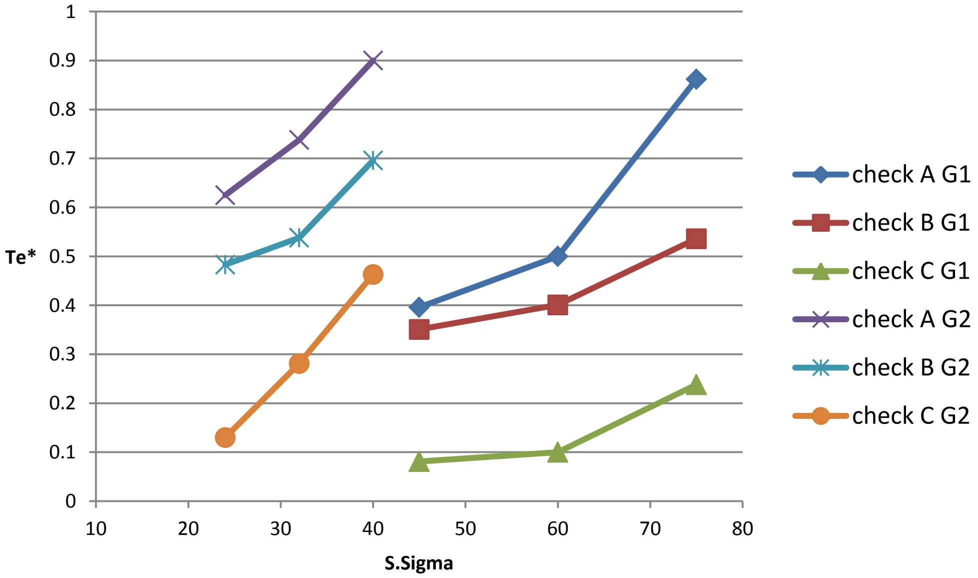

Fig. 7. Sediment changes in the case of 25 lit/min discharge

Figure 7 shows the most critical sediment-trapping case for both fine-grained and coarse-grained sediments, where in 30 lit/min discharge in case of coarse-grained sediments, maximum sediment-trapping coefficient was evident for all tested slopes. In case of 25-degree slope, sediment-trapping coefficient of the check dam A was near the maximum experimental value of 0.9. In similar previous figures, this value with a significant reduction was about 0.4 to 0.5. This was the case for C and B check dams in similar conditions. Almost similar graphs to the previous cases were resulted for fine-grained sediments in case of 30 lit/min discharge. Maximum sediment-trapping coefficient occurred in the case of fine-grained sediments with 30 lit/min discharge, where all the three tested slopes showed maximum measured values.

In summary, it can be stated that higher trapping rate of fine-grained sediments is due to smaller diameters of these particles and more coarse-grained sediments pass all three check dam models under similar conditions. Check dam model A, due to its geometric shape, passes higher amounts of sediments, and B and C check dam models were rated, respectively. Check dam C, due to almost a closed space prevents the passage of large amount of sediments, and can be classified as closed-type check dams. Therefore, after obtaining the experimental results, three check dam models can be placed in the following order in terms of sediment-trapping rate:

Check dam C> Check dam B> Check dam A

4. Statistical Analysis

As it was observed, sediment-trapping coefficient was expressed as a function of dimensionless parameters obtained from the dimensional analysis. The shape of the function has been determined using linear and exponential multivariate correlations so that the trapping coefficient and other parameters have been considered as dependent and independent variables, respectively. Therefore, the correlation rate of the independent parameters to the dependent ones should be evaluated. Then, using linear and non-linear multivariate regressions, a relation was presented to verify the accuracy of the experiments. Coefficients and exponent of this relation were determined using the obtained correlation. The general form ofthe evaluated linear and non-linear relations are as follows:

$$T_e = a + bS + c\left(\frac{H}{h}\right) + d\left(\frac{V_{sa}}{V_m}\right) + e(F_{rd}) + f\left(\frac{B}{b}\right) + g(\sigma) \qquad (4)$$

$$T_e = a\, S^b\, (\frac{H}{h})^c\, (\frac{V_{sa}}{V_m})^d\, (F_{rd})^e (\frac{B}{b})^f (\sigma)^g) \qquad (5)$$

To obtain the coefficients, the output coefficient table of SPSS software was used. Regression analysis is a widely used technique in scientific studies and makes it possible to predict changes in the dependent variable using the independent variables and determine the contribution of each independent variable in explaining the dependent variable. The goal of regression is to use the regression equation, a random sample and some statistical methods to predict the dependent variable by knowing the values and characteristics of the independent variables. To this end, by substituting the independent variables in the regression equation, the dependent variable will be predicted.

One of the most notable points in the analysis after regression is to determine the effectiveness of each parameter that has been focused in all engineering, computing and statistics sciences. Therefore, effectiveness values of each independent variable for both linear and non-linear models have been presented in the following table and figure.

Table 7. Effectiveness coefficients of computational parameters

	B/b	H/h	sigma	Frd	S
Linear model	6.3E-20	3E-21	2.1E-14	1.3E-16	4.4E-17
Nonlinear model	2.8E-36	2E-37	4.7E-12	1.8E-18	3.7E-22

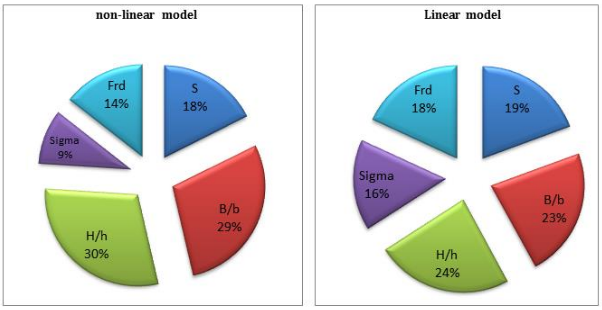

Fig. 8. Effectiveness coefficients of independent variables for linear and non-linear models

As can be seen from Fig. 8, in both linear and non-linear models, the highest effectiveness coefficients observed for width ratio, height ratio and the slope of the flume, respectively. This was more evident in nonlinear model, so a lower error was expected in the non-linear model.

Other statistical documents of the effective output data and equation coefficients obtained by using Excel software in linear and non-linear multivariate modeling have been presented in the following table.

However, by comparing the coefficients of the two linear and non-linear correlations of the sediment trapping behind the Sit check dam, non-linear correlation selected as the best relation.

The correlation between the measured and calculated sediment trapping values in the non-linear model can be observed in the diagram below. As it is evident, the points are located around the fitted line indicating a good correlation.

Table 8. Statistical documents of the output data in modeling

model	Independent variables	Correlation coefficient	Determination coefficient	Estimated error	Maximum residuals	Minimum residuals	Significance level
linear	$S,\frac{H}{h},\frac{B}{b},F_{rd},\frac{V_{sa}}{V_m},\sigma$	0.943	0.901	0.063271	0.5002	0.00544	0.00
Non-linear	$S,\frac{H}{h},\frac{B}{b},F_{rd},\frac{V_{sa}}{V_m},\sigma$	0.971	0.944	0.061742	0.8125	0.00883	0.00

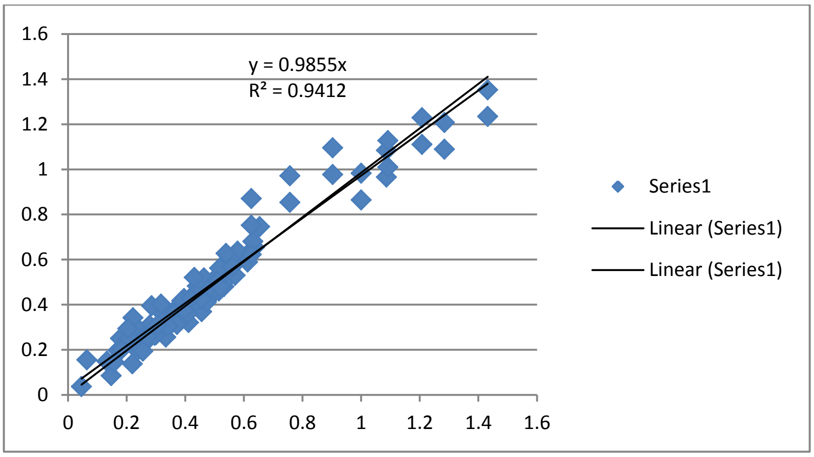

Fig. 9. Compliance between the non-linear multivariate correlation and experimental results

As mentioned, the fitted line to the data was very close to the bisector line. Therefore, coefficients of two linear and non-linear equations were presented using Table 9 and the above mentioned equations and then, the non-linear correlation was selected as the best relation.

$$T_e = -1.305 + 0.018\,S + 1.967\left(\frac{H}{h}\right) - 2.2\,\left(\frac{V_{sa}}{V_m}\right) + 4.092(F_{rd}) - 1.336\left(\frac{B}{b}\right) - 0.082\sigma$$

$$T_e = \frac{(S)^{1.16}(\frac{H}{h})^{33.53}(F_{rd})^{1.28}}{1.691\ (\frac{V_{sa}}{V_m})^{7.44}(\sigma)^{0.48}(\frac{B}{b})^{27.09}} \qquad (6)$$

5. Summary and conclusions

In this study, based on results of 100 experiments performed on the elevated flume to evaluate the sediment-trapping coefficient of Stepped Slit check dam reservoir, the linear and non-linear correlations were investigated and a proper relation for determination of the sediment-trapping coefficient based on dimensionless parameters was proposed. The following results obtained:

By increasing the slope of the flume, higher amount of sediments pass the check dam.

By increasing the discharge, sediment-trapping rate of the Stepped Slit check dam decreased and the amount of passed sediments increased.

Trapping coefficient of the proposed C Model, in which the slot opening height was more than the other two models, was higher and hence, had a better performance in controlling debris flows. Sediment-trapping efficiency of the check dams can be listed in the following order:

Check dam C > Check dam B > Check dam A.

Dimensionless parameters of $\frac{B}{b}$, $\frac{H}{h}$, F_{rd} and $\frac{V_{sa}}{V_m}$ had the greatest effects on the Sediment-trapping coefficient (T_e), respectively.

Non-linear multivariate relation with the lower error rate selected as the best relation for prediction of the sediment-trapping rate.

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