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Experimental Study of the Effect of Hydraulic Parameters on Debris Flow Control in Inclined Slit Trapezoidal Check Dams

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ABSTRACT

Check dams are one of the structures used to control debris flows. In this study, in order to evaluate the effect of hydraulic parameters on debris sediment trapping rate by the slit trapezoidal check dams with different angles, and to develop an empirical relation for determination of trapping coefficient of the dam reservoirs, three physical models of the check dams were used. The tests were performed on a shapeable flume with 15, 20 and 25 ° slopes, under 20, 25 and 30 liters per minute flow rates, 60, 75 and 90 degrees of check dam angles to the horizontal and for a sediment aggregate with a non-uniform gradation. By determination of the effective dimensionless parameters, the effect of these parameters on debris sediment trapping rate was evaluated by plotting diagrams. The analysis of experiments showed that, the trapping rate of the check dam increased by decreasing the channel slope, increasing the check dam spillway height and decreasing the check dam angle. Different relations were evaluated using linear and non-linear multivariate correlation analyses of dimensionless parameters, and a multivariate relation for determination of the sediment trapping coefficient was proposed.

Keywords

Slit check dam, debris flow, sediment trapping, dimensional analysis

Introduction

Debris flows are mixtures of water and high concentrations of sediment. Such flows are formed when water and debris and also a river with an appropriate slope exist. Rivers with slopes steeper than 10 degrees are typically prone to this type of flow [1]. Due to high concentration, such flows have a high destructive energy. Debris flow control to manage flood induced damages, as well as conserve water and soil sources is of utmost importance. On the other hand, the lack of sediment debris control will cause further deposition of such sediments in rivers and dam reservoirs that will reduce the useful life of dams. Using check dams upstream of the rivers is one of the effective methods in controlling debris flows. These small dams are constructed across a stream in order to reduce the flow velocity, increase water quality, control and trap sediments [2]. Check dams are classified

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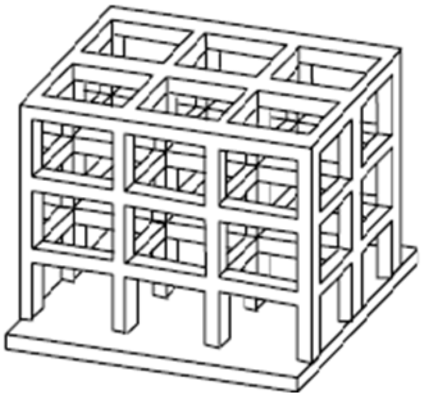
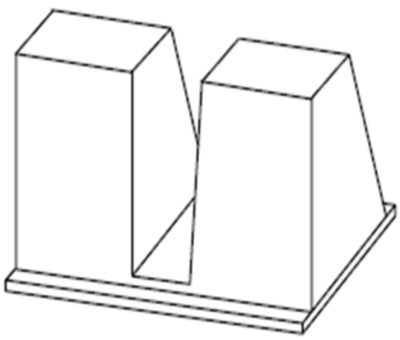
into open-type and closed-type check dams. Grid type check Dams and Slit check dams are of open-type check dams. The use of open-type check dams has been increased in recent years due to higher efficiency and useful life. Closed-type check dams have been widely used in Taiwan, Japan and Europe to encounter the effects of debris flows. However, due to limited capacity and low permeability, the reservoir of these dams are filled at low flow discharges and in the incidence of debris flows cannot control debris sediments efficiently. To overcome this shortcoming, open-type check dams have been developed in countries such as Austria, Japan and Taiwan [3] [4] [5] [6].

Figure 1 shows two open-type check dams.



Grid type check Dam



Slit Check Dam

Figure 1. Two examples of open-type check dams

In this study, the effecting parameters on trapping rate of inclined slit trapezoidal check dams were experimentally investigated and a proper relation to predict the trapping coefficient of these dams was presented.

Numerous researches have been performed by various researchers on check dams. Ashida and Takahashi (1986) performed studies in order to develop a proper empirical relation for determination of the slot width of the grid type crack dams to yield an effective trapping of the debris flows and concluded that the proper slot width is 1.5 to 2 times the largest sediment diameter [7]. Mizuyama et al. (1995) concluded that the efficiency of check dams in trapping the sediments, in addition to check dam opening width to the maximum sediment diameter ratio is also dependent upon the sediment concentration and debris flow velocity [8] .Pang Lin (2000) performed researches to present a design method for the slit check dams and proposed a relation for estimation of the sediment storage rate in check dam reservoir.

This method is formed based on three main parameters including dimensionless sediment output rate, sediment concentration and sediment storage rate [9]. Xiang Xu et al. (2002) performed a field study on one of the sub-catchments of the Yellow River of China and, concluded that construction of check dams in some parts of the ditches can reduce up to 70 percent of the catchment output sediment rate [10]. Catella (2005) performed researches on a number of closed-type check dams constructed in series in one of Italy's provinces and concluded that due to filling of the dam reservoir before occurrence of debris flows, they do not deserve the required efficiency and hence, open type check dams should be applied for this purpose [11].

Hassanli et al. (2009) performed studies on the effect of the porous check dams location on the trapping of fine sediment particles [12]. In this study, 5 rivers in DoroudZan catchment in southern Iran were case studied and samples of trapped sediment in the check dams and undisturbed soil adjacent to the channel were collected. Experimental analysis showed that undisturbed samples adjacent to the channel were of finer particles compared to the trapped sediment particles and check dams that are located more downstream of the river more efficiently trap the sediments. Shresta et al. (2009) numerically simulated the sedimentation and erosion upstream of check dams during debris flows and experimentally validated the results [13].Simulations and experiments were performed on closed-type and Grid type check dams and results indicated that the in the sediment trapping capacity of Grid type check dams was more than closed-type check dams. Abedini et al. (2012) performed studies to evaluate the effect of check dams located upstream of a river in Malaysia on sediment trapping and concluded that in studied area, the trapping rate significantly increased from the first check dam to the last one [14]. It was also observed that the studied check dams have proper efficiency in trapping the sediments, especially coarse grained sediments. Ghaffari et al. (1392) performed studies on the effect of hydraulic parameters on the sediment trapping rate and concluded that by increasing flow discharge and the slope of the flume, sediment trapping rate of Gabion Slit check dams is decreased [15].

Materials and Methods

Physical Model Characteristics

The physical model is composed of several parts Elevated flume, pump, flow meter, Sediment Reservoir, Tail Basket, check dam and manually controlled crane as described below:

Elevated Flume

Experimental flume with a length of 1.83 m, width of 0.15 m and height of 0.3 m was made of a 6 mm thick plexiglass. Its slope was variable and had a maximum slope of 25 degrees. A schematic view of the flume is presented in Figure 2.

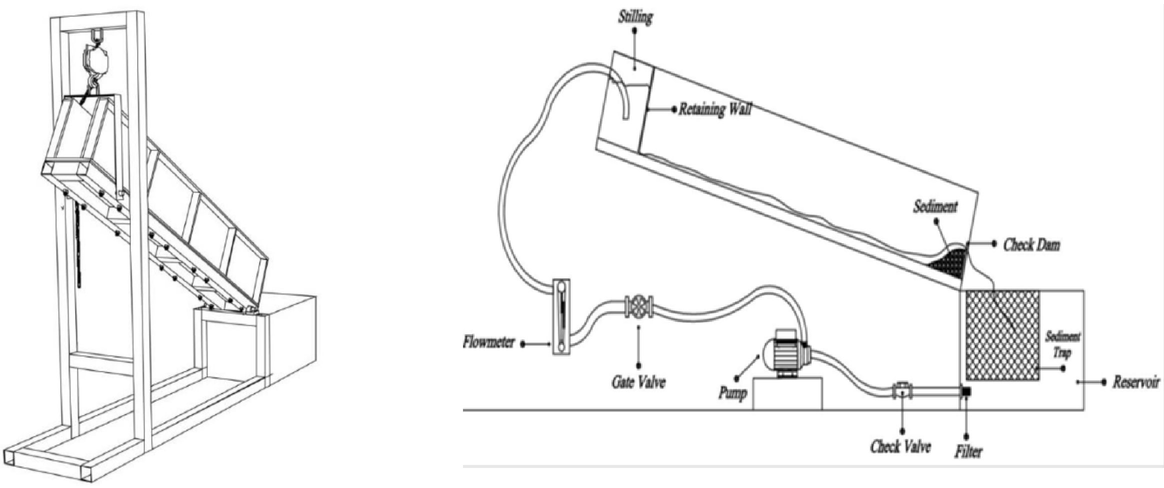
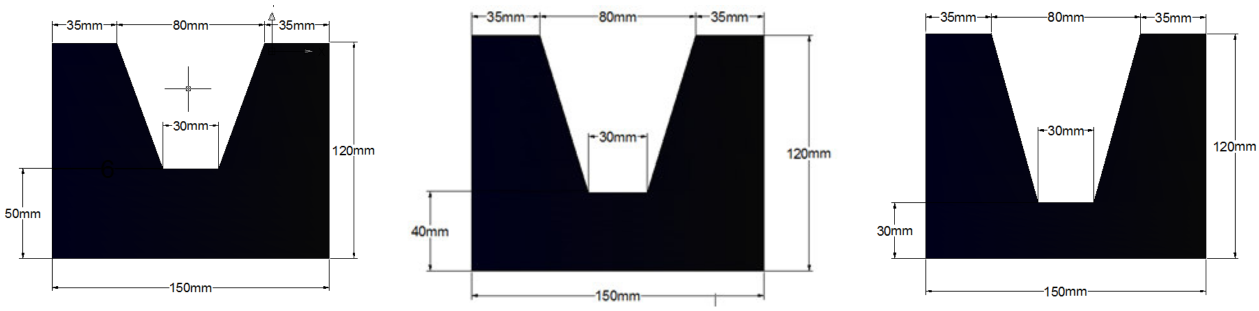


Figure 2. Structure of the built flume

Check Dam

Three Gabion trapezoidal Slit check dam models with a height of 12 cm, length of 15 cm, with slot openings of 7,8 and 9 cm at the downstream end of the flume were tested under different establishment angles (φ) to the horizon. Characteristics of the models are shown in Figures 3 and 4.



Model 3 ***Model 2*** ***Model 1***

Figure 3. Check dam models used in the experiments

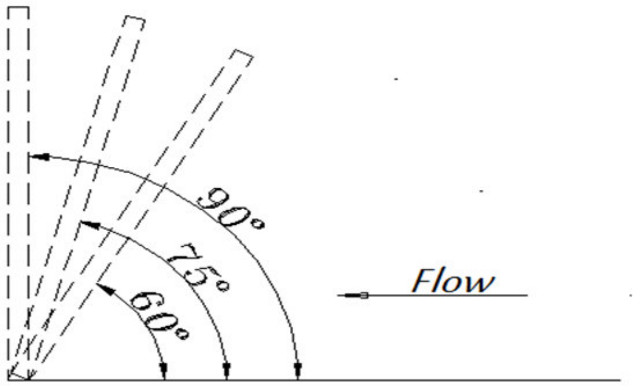


Figure 4. Establishment angles of the check dams in the experiments

Pump

A centrifugal pump with a power to create a maximum flow discharge of 40 liters per minute was used for the experiments.

Flowmeter

A flowmeter was used in the flow path to adjust input flow discharge from the pump. The flowmeter could measure flow discharges up to 35 liters per minute and its measurement error was measured about 5%.

Bed Materials

Silica sand with a specific gravity of 2.6 grams per cubic centimeter was used as bed sediment material. Grading curve of the used sediments in the experiments is shown in Figure 5.

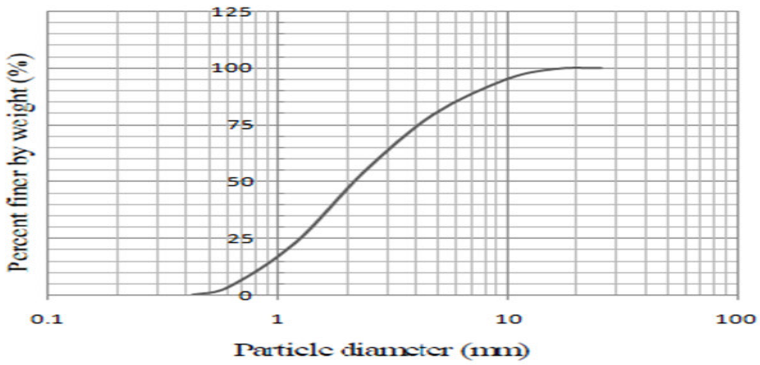


Figure 5. Grading curve of the bed sediments

Experimental procedure

To perform the tests, first the slope of the flume was adjusted by the hand crane to the desired slope. Three slopes of 15, 20 and 25 degrees were used in the experiments to simulate the flow in the river. Then, the flow discharge was adjusted using the flowmeter. In this study, three discharges of 20, 25 and 30 liters per minute were used. Sediments with the desired gradation were placed in an interval equivalent to 28 percent of the flume total length and at a distance of 60 cm from the end of the flume. Sediments in this range had an approximate dry weight and thickness of 8 kg and 7 cm, respectively. To prevent the movement of sediments under the flume slope, two partitions were placed at the beginning and end parts of the desired interval before starting the tests. At the end of the flume, check dams with establishment angles of 60, 75 and 90 degrees were placed. The water flow was regulated by a valve. Time recording was started using a timer and after passing through a flow quieter located upstream of the flume, water was flown. Before reaching the flow to the sediments, two partitions were removed and after being saturated, sediments flow and transferred to the downstream of the channel and check dam. Testing time was 20 minutes.

Then, trapped sediments behind the check dam were heated for 24 hours at 110 ° C and then, the weight of the dried sediments was carefully measured. By dividing dry weight of the trapped sediments by the weight of the total dry sediments, sediment trapping coefficient was obtained. The procedures were repeated for all the models, selected slopes and discharges and establishment angles of the check dams.

To obtain the trapping coefficient, Equation (1) was used:

$$TE = \frac{W_a}{W} \qquad (١)$$

Where W_a is the weight of the dried sediments trapped in the dam reservoir and W is the weight of the total sediments used.

Physical and hydraulic characteristics of the built flume along with the experimental conditions are listed in Table 1.

Table 1.
Physical and hydraulic characteristics of the experimental flume

characteristics	description
Flume dimensions	30*15*183 cm
Flow quieter length	35 cm from flume input – using porous quieter material
discharge	0 to 35 lit/min
slope	0 to 25 degrees
Check dam establishment angles	60, 75 and 90 degrees
Tested slopes	15, 20 and 25 degrees
Tested discharges	20, 25 and 30 lit/min
Sediment weight	8 kg
Equilibrium time	20 min
Number of tests	81

Dimensional Analysis

Factors affecting the check dam trapping coefficient are as follows:

$$TE = f(\rho, \rho_s, \sigma, b, B, Q, S, g, y, h, H, Ss, V_{sa}, V_m, \phi) \qquad (2)$$

Where T_e is the sediment trapping coefficient behind the dam, is water density, is sediment density, is standard deviation of the tested sediments, b is the slot width of the check dam, B is channel width, Q is flow discharge, S is flume slope, y is flow depth, g is the acceleration of gravity, h is the height of check dam slot, H is total check dam height, Ø is establishment angle of the check dam to the horizon, V_{sa} is sedimentation volume behind the dam, V_m is maximum capacity of the check dam reservoir, obtained from empirical Equation (3) [9] and S_s is slot angle of the check dam. (3)

Based on Buckingham dimensional analysis it is obtained.

Table 2.

Effective dimensionless variables on sediment trapping

$\pi_4 = \boldsymbol{S}$	$\pi_3 = \frac{V_{sa}}{V_m}$
$\pi_2 = \frac{\boldsymbol{H}}{\boldsymbol{h}}$	$\pi_4 = \boldsymbol{Fr_d}$

Where V_{sa}/V_m is relative magnitude of the debris flow and F_{rd} is densimetric Froude number that is obtained using Equation (4).

$$\mathbf{Fr_d} = \frac{\mathbf{Q}}{\mathrm{B.y.}\sqrt{\mathbf{gD_{50}}\times(\mathbf{G_s}-\mathbf{1})}} \quad (4)$$

Finally, the trapping coefficient based on dimensionless relations is as follows.

$$\mathrm{Te}= f\left(S,\frac{H}{h},\frac{V_{sa}}{V_m},Fr_d,\emptyset\right) \quad (5)$$

Results and Discussion

Qualitative analysis

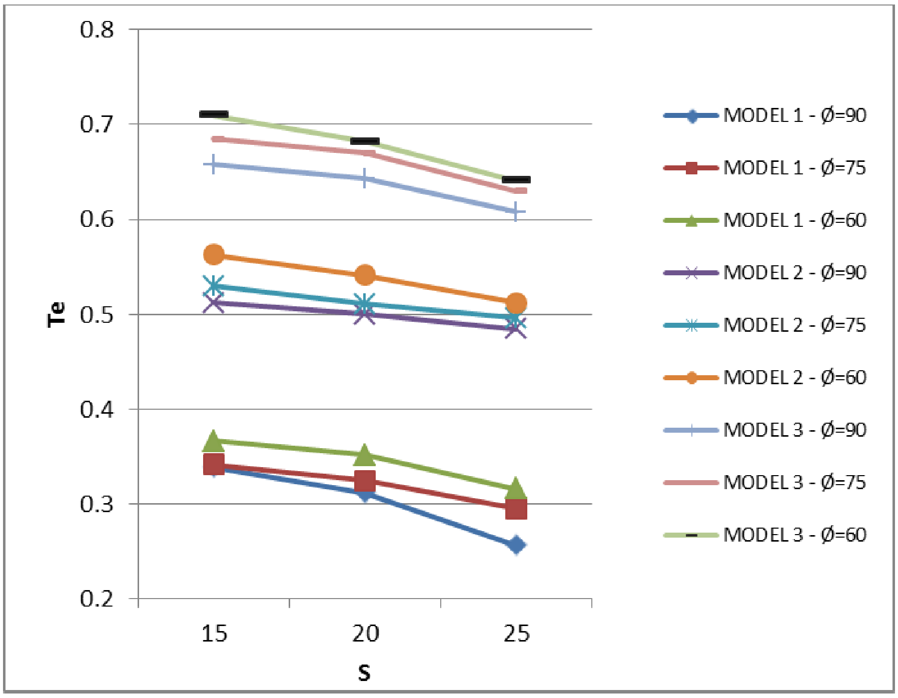
To better understand the effective parameters on sediment trapping, these parameters should be evaluated. Therefore, changes in trapping coefficient by changes in slope under a constant flow discharge were evaluated for three proposed check dams with different establishment angles and plotted in graphs that will be analyzed as follows.

Comparison of the sediment trapping coefficient behind check dams under 20 lit/min flow discharge

Table 3.

Sediment trapping coefficient for different models and establishment angles of the check dams in tested slopes

	MODEL1 Ø=90	MODEL3Ø =90	MODEL1Ø =75	MODEL2Ø =75	MODEL3Ø =75	MODEL1Ø =60	MODEL2Ø =60	MODEL3Ø =60
S=15	0.339	0.658	0.342	0.53	0.685	0.367	0.563	0.71
S=20	0.312	0.643	0.325	0.511	0.67	0.352	0.541	0.682
S=25	0.257	0.608	0.295	0.496	0.63	0.316	0.512	0.641



Graph 1. Comparison of the trapping coefficients (T_e) of the check dams for different establishment angles (Ø) and slopes for 20 lit/min flow discharge

According to the results obtained using graph 1 for 20 lit/min flow discharge, sediment trapping coefficient is decreased by increasing check dam establishment angle for the three different models, i.e. a decrease in the check dam establishment angle will increase the sediment trapping coefficient. Although the increasing rate of the sediment trapping coefficient is low for decreasing the establishment angle of the check dams. A reason for this increase can be attributed to the creation of vortex flow behind the check dam with angles less than 90 degrees so that the kinetic energy of the flow is decreased and hence, lower amount of sediments is passed from the check dam and the trapping coefficient is increased.

It can also be observed that type 3 check dam has the highest trapping coefficient and type 1 check dam has the lowest efficiency in sediment trapping. The reason is attributed to the height of the type 3 check dam spillway being higher than two other models. According to the above graph it is observed that by increasing the channel slope, the sediment trapping coefficient of the check dams is decreased and by increasing the channel slope, the decreasing rate is accelerated.

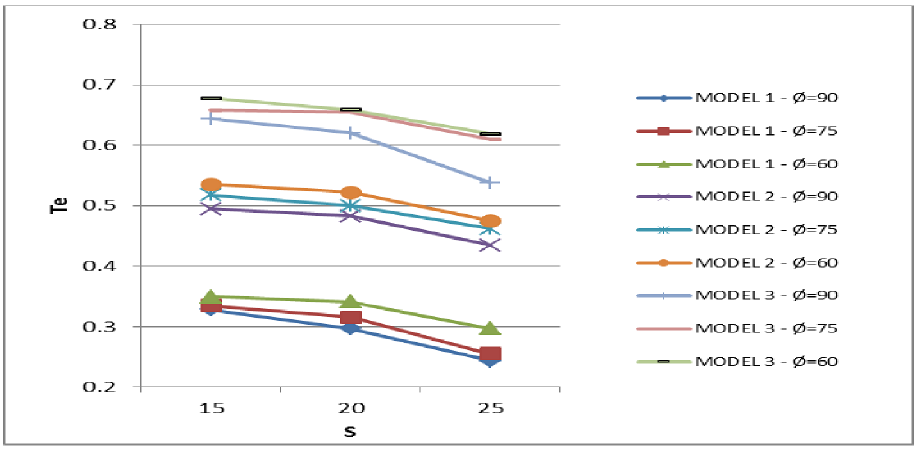
The highest sediment trapping coefficient of 0.71 occurs for type 3 model with 60 degrees angle to the horizon and channel slope of 15 degrees which is in fact the highest trapping coefficient in all the experiments. Also, the lowest sediment trapping coefficient of 0.257 occurs for type 1 model with 90 degrees angle to the horizon and channel slope of 25 degrees.

Comparison of the sediment trapping coefficient behind check dams under 25 lit/min flow discharge

Table 4.

Sediment trapping coefficient for different models and establishment angles of the check dams in tested slopes

	MODEL1 Ø=90	MODEL 2Ø=90	MODEL3 Ø=90	MODEL1 Ø=75	MODEL2 Ø=75	MODEL3 Ø=75	MODEL1 Ø=60	MODEL 2Ø=60	MODEL3 Ø=60
S=15	0.328	0.495	0.644	0.335	0.518	0.658	0.35	0.535	0.678
S=20	0.297	0.483	0.62	0.316	0.5	0.655	0.341	0.522	0.659
S=25	0.244	0.435	0.538	0.255	0.522	0.61	0.297	0.475	0.619



Graph 1. Comparison of the trapping coefficients (T_e) of the check dams for different establishment angles (Ø) and slopes for 25 lit/min flow discharge

According to the results obtained using graph 2 for 25 lit/min flow discharge, sediment trapping coefficient is decreased by increasing check dam establishment angle for the three different models, i.e. a decrease in the check dam establishment angle will increase the sediment trapping coefficient. Although the increasing rate of the sediment trapping coefficient is low for decreasing the establishment angle of the check dams. A reason for this increase can be attributed to the creation of vortex flow behind the check dam with angles less than 90 degrees so that the kinetic energy of the flow is decreased and hence, lower amount of sediments is passed from the check dam and the trapping coefficient is increased.

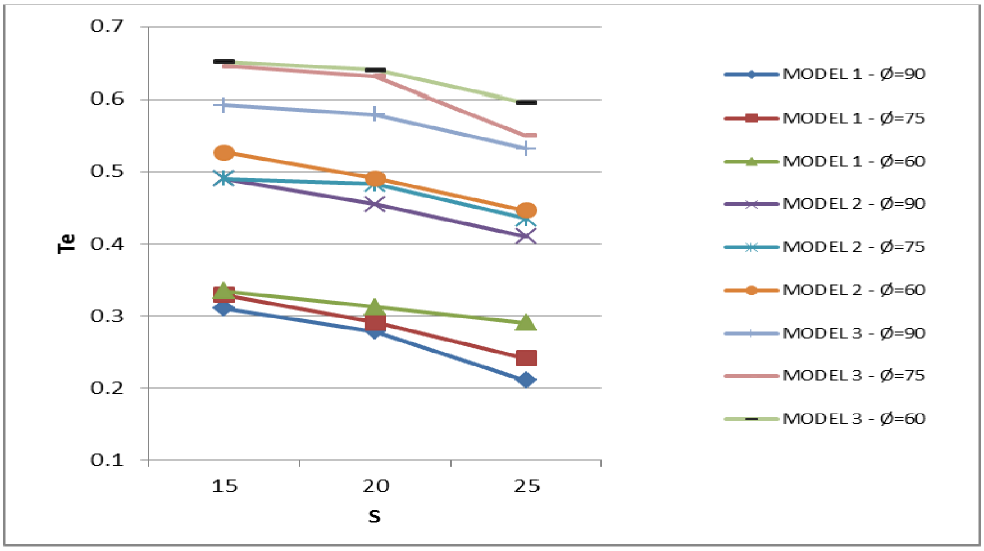
By increasing the channel slope, the sediment trapping coefficient of the check dams is decreased and by increasing the channel slope, the decreasing rate is accelerated. The highest sediment trapping coefficient of 0.678 occurs for type 3 model with 60 degrees angle to the horizon and channel slope of 15 degrees. Also, the lowest sediment trapping coefficient of 0.244 occurs for type 1 model with 90 degrees angle to the horizon and channel slope of 25 degrees.

Comparison of the sediment trapping coefficient behind check dams under 30 lit/min flow discharge

Table 5.

Sediment trapping coefficient for different models and establishment angles of the check dams in tested slopes

	MODEL1 Ø=90	MODEL2 Ø=90	MODEL3 Ø=90	MODEL1 Ø=75	MODEL2 Ø=75	MODEL3 Ø=75	MODEL1 Ø=60	MODEL 2Ø=60	MODEL3 Ø=60
S=15	0.31	0.49	0.592	0.329	0.49	0.645	0.334	0.527	0.651
S=20	0.278	0.455	0.579	0.291	0.483	0.631	0.312	0.491	0.64
S=25	0.21	0.41	0.532	0.241	0.435	0.55	0.29	0.446	0.595



Graph 3. Comparison of the trapping coefficients (Te) of the check dams for different establishment angles (Ø) and slopes for 30 lit/min flow discharge

According to the results obtained using graph 3 for 30 lit/min flow discharge, sediment trapping coefficient is decreased by increasing check dam establishment angle for the three different models, i.e. a decrease in the check dam establishment angle will increase the sediment trapping coefficient. A reason for this increase can be attributed to the creation of vortex flow behind the check dam with angles less than 90 degrees so that the kinetic energy of the flow is decreased and hence, lower amount of sediments is passed from the check dam and the trapping coefficient is increased.

The highest sediment trapping coefficient of 0.651 occurs for type 3 model with 60 degrees angle to the horizon and channel slope of 15 degrees. Also, the lowest sediment trapping coefficient of 0.21 occurs for type 1 model with 90 degrees angle to the horizon and channel slope of 25 degrees which is in fact the lowest trapping coefficient in all the experiments.

Statistical Analysis

According to the dimensionless parameters obtained from the dimensional analysis, the dimensionless parameter of trapping coefficient is expressed as a function of other dimensionless parameters. The shape of the function has been determined using linear and exponential multivariate correlation so that the trapping coefficient and other parameters has been considered as dependent and independent variables, respectively. So, the correlation rate of independent parameters to the dependent ones should be evaluated. Then, using linear and non-linear multivariate regressions a relation should be presented to verify the accuracy of the experiments. Coefficients and exponents of this relation have been determined using the correlation. The general form of the evaluated linear and nonlinear relations are as follows:

$$Te = a + b\left(\frac{H}{h}\right) + c(S) + d\left(\frac{Vsa}{Vm}\right) + e(Ss) + f(Frd) + g(\emptyset) \quad (6)$$

$$Te = a\left(\frac{H}{h}\right)^{b} + (S)^{c} + \left(\frac{Vsa}{Vm}\right)^{d} + (Ss)^{e} + (Frd)^{f} + (\emptyset)^{g} \quad (7)$$

To obtain the coefficients, the output coefficient table by SPSS software has been 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 and 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. Tables 5 and 6 show statistical documents of the effective output data and coefficients obtained by using SPSS software in multivariate linear modeling.

Table 5.
Summary of the statistical documents of the output data in multivariate linear modeling

Correlation coefficient	Determination coefficient	estimated error	Maximum residuals	Minimum residuals	Significance level of the model	Durbin Watson coefficient
۰.۹۹۱	۰.۹۸۲	۰.۰۱۹۵	۰.۰۵۰۶	۰.۰۴۹۷	۰.۰۰۰	**1.69**

Table 6.
Coefficients obtained for the linear multivariate equation

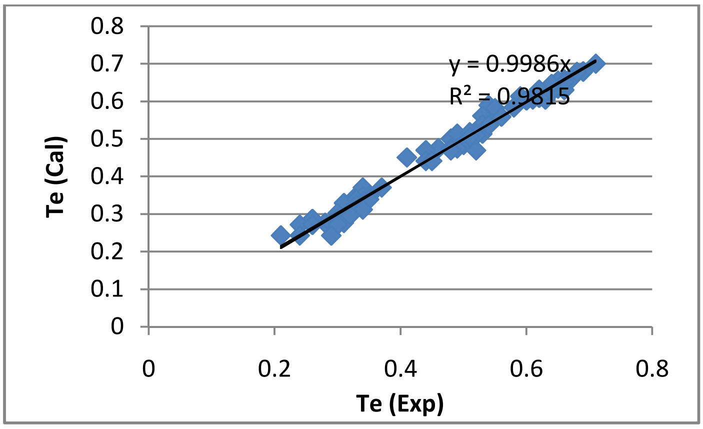
Model significance level	Coefficients of the dimensionless parameters						Y intercept	Effectiveness coefficient of the dimensionless parameters						Number of independent variables
	g	f	e	d	c	b	a	Ø	F_{rd}	Ss	$\frac{V_{sa}}{V_m}$	S	$\frac{H}{h}$	
0.000	-0.001	-0.075	-0.728	0.072	-0.002	-0.715	4.159	-0.122	-0.211	-1.719	0.06	-0.052	-0.783	6

As can be inferred from the tables, the determination coefficient for linear multivariate model is equal to 0.982. Determination coefficient shows a percentage of the dependent variable changes estimated by the model. This parameter ranges between zero and one, and the closer this value would be to one, the more appropriate the estimated model would be. The obtained error using the table is equal to 1.95 percent and the maximum and minimum residuals are equal to 0.0506 and 0.0497, respectively all indicating the accuracy of the estimated relation. Maximum and minimum differences indicate the maximum and minimum differences between observed and calculated values (values obtained using the extracted model). It is obvious that the lower values are indicative of a more reliable estimated model. Effectiveness coefficients of each independent variable show that S_s, $\frac{H}{h}$, F_{rd} , $Ø$,$\frac{V_{sa}}{V_m}$ and Shave the greatest effect on Sediment trapping coefficient (T_e), respectively.

According to the coefficients of the dimensionless parameters, the linear relation is proposed as follows:

$$T \tag{8}$$

In Graph 4, compliance between the linear multivariate correlation equation and experimental results are evaluated.



Graph 4. Compliance of the linear multivariate correlation equation and experimental results

Data distribution in this figure show a good correlation between the two variables. Also, R^2 coefficient is equal to 0.981, which is an indicative of the accuracy of the fit.

To obtain non-linear multivariate relation, the logarithmic function model was used. Tables 6 and 7 show statistical documentation of effective output data and the equation coefficients obtained by using SPSS Software in the non-linear multivariate modeling.

Table 7.
Summary of the statistical documents of the output data in non-linear multivariable modeling

Model	Independent variables	Correlation coefficient	Determinatio ncoefficient	estimated error	Maximum residuals	Minimum residuals	Significanc e level of the model	Durbin Watson coefficient
	6	0.974	0.97	0.032	0.11	0.096	0.000	1.84

Table 8.
Coefficients obtained for non-linear multivariate equation

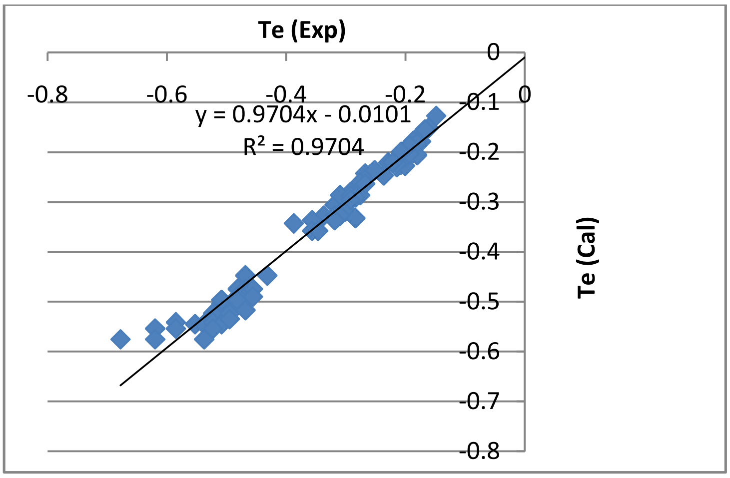
Model significance level	Coefficients of the dimensionless parameters						Y intercept	Effectiveness coefficient of the dimensionless parameters						Number of independent variables
	g	f	e	d	c	b	a	ϕ	F_{rd}	Ss	$\frac{V_{sa}}{V_m}$	S	$\frac{H}{h}$	
۰.۰۰۰	-۰.۳۴۶	-۰.۳۶۸	-	-۰.۰۷۴	۰.۰۱۷	۲.۷۵۴	-۰.۱۱	-۰.۱۸۱	-۰.۲۱۴	-	-۰.۰۵۴	۰.۰۱۱	۰.۷۷۲	۶

As can be inferred from the above tables, the determination coefficient of the linear multivariate modeling is equal to 0.95 which is far less than in the linear multivariate model. The obtained percentage of error, according to the above table was equal to 3.2 and the maximum and minimum residuals were equal to 0.096 and 0.11, respectively. It can be observed that the estimated error is higher than in the linear model. Effectiveness coefficients of each independent variable show that $\frac{H}{h}$, Fr_d , $\emptyset$, $\frac{V_{sa}}{V_m}$ and S have the greatest effect on sediment trapping coefficient, T_e, respectively.

Considering the dimensionless coefficients, the following linear relation was proposed:

$$\mathrm{Te} = \frac{0.776\left(\frac{\mathrm{H}}{\mathrm{h}}\right)^{2.754} \mathrm{S}^{0.017}}{\left(\frac{\mathrm{Vsa}}{\mathrm{Vm}}\right)^{0.074} \mathrm{Frd}^{0.368} \emptyset^{0.346}} \qquad (9)$$

In Graph 6, compliance between the linear multivariate correlation equation and experimental results are evaluated.



Graph 6. Compliance between the non-linear multivariate correlation and experimental results

By comparison of the two linear and non-linear correlations of the sediment trapping coefficient behind the check dam, as shown in Table 9, linear correlation was selected as the best relation.

Table 9.

Comparison of the linear and non-linear models proposed for calculation of the sediment trapping coefficient

Statistical model	Error (%)	Maximum residuals	Minimum residuals	Determination coefficient
linear	1.95	0.05	0.0497	0.982
Non-linear	3.2	0.11	0.096	0.97

Summary and Conclusions

In this study, based on results of 81 experiments performed on the slope-adjusted flume to evaluate the trapping coefficient of Inclined Slit Trapezoidal check dams, the linear and non-linear correlations were investigated and a proper relation for determination of the sediment trapping coefficient based ondimensionless parameters was proposed and the following results were obtained:

- By increasing the slope of the check dam, trapping of the check dam reservoir was decreased.
- By increasing the flow discharge, trapping of the check dam was reduced.
- Trapping coefficient of Model 3, 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.
- Linear multivariate relation with an error of 1.95% and a determination coefficient of 0.982 was selected as the best relation to predict the sediment trapping coefficient.

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