A Laboratory Study Attempt of Flow and Energy Dissipation in Stepped Spillways

Thulfikar Razzak Abdul-Mehdi
Lecturer Ph.D
College of Engineering - University of AL-Qadisiyah
Thulfikar.AbdulMehdi@qu.edu

Haider Ali Al- Mussawy
Lecturer Ph.D
College of Engineering -Al-Mustansiriyah University
E-mail:h_a_m_s76@yahoo.com

Abdul- Sahib Taufeeq Al-Madhhachi
Lecturer Ph.D
College of Engineering -Al-Mustansiriyah University
E-mail:abdu@okstate.edu

ABSTRACT

A new laboratory study conducted on stepped spillways in order to investigate their efficiency of dissipating flow energy. All previous study on stepped spillway indicated that the flow energy dissipation decreased as increasing in discharge. Increasing in the step numbers and the spillway slope led to energy dissipation decrease. In this study, an experimental attempt to increase energy dissipation at variable discharges was performed on stepped spillway and that leads to decreasing the cost of initiating the stilling basin or may be ignoring it. Five spillways were constructed from concrete and tested to investigate and compare among them. Three were roughed by gravel with different size for each one, one of them was stepped without any addition, and the last one was stepped with cavitation. The height of stepped spillways was 18 cm with unique numbers of steps ($n = 3$), and unique downstream slope of stepped face ($\theta = 30^0$) were utilized. The percentage of relative energy dissipation (R.E.D) was increased using rough surface with coarse gravel. When the size of gravel increased, the R.E.D was increased and when using the ratio between heights of gravel to steps of 0.5, the R.E.D was increased to about triple compared with traditional spillways. The R.E.D was decreased when the cavitation on the stepped surface was utilized compared to the stepped spillway without any addition for large discharges and that was inverse for small discharges. Comparing to steps without any addition, the rouged steps with the larger size of gravel maximized the energy dissipation for both small and large discharges. The relative energy dissipation was 26.73 % compared with traditional spillway and 16.73 % compared with stepped spillway without any addition, since the stepped spillways more effective than traditional spillways by 10 %. In general, the R.E.D was decreased when increasing the discharge.

Key words: Flow energy dissipation, stepped spillways, flow types, gravel roughed surface, cavitation.

محاولة دراسة مختبرية للجريان و الطاقة المتشتتة في المطافح المدرجة

ذو الفقار رزاق عبدالمهدي
مدرس دكتور
كلية الهندسة-جامعة القادسية

حيدر علي مهدي الموسوي
مدرس دكتور
كلية الهندسة - الجامعة المستنصرية

عبدالصاحب توفيق عبدالصاحب المذحجي
مدرس دكتور
كلية الهندسة-الجامعة المستنصرية

الخلاصة

تم تقديم دراسة مختبرية جديدة على المطافح المدرجة لغرض التحري عن كفاءتها في تشتيت طاقة الجريان. ان كل الدراسات السابقة عن المطافح المدرجة بينت ان نسبة تشتت طاقة الجريان تقل عند زيادة التصاريف. وان زيادة عدد مدرجات المطفح وزاوية ميلانه يؤدي الى تقليل تشتيت الطاقة. في هذه الدراسة تم اجراء محاولة عملية لزيادة تشتيت الطاقة على المطافح المدرجة عند عدة التصاريف. وذلك لان زيادة تشتيت الطاقة عند تلك المطافح يؤدي الى تقليل او الاستغناء عن احواض تشتيت الطاقة وبالتالي التقليل من مخاطر القفزة الهيدروليكية. تم انشاء خمس نماذج خرسانية من المطافح المدرجة لغرض اجراء تلك الدراسة والمقارنة بينها. تم تخشين سطح ثلاث من تلك النماذج باستخدام حصى ذات اقطار مختلفة لكل واحد منها وواحد بدون أي إضافة والأخير تم تخشين سطحه باستخدام التجوفات. تم استخدام ارتفاع موحد قدره 18 سم وعدد مدرجات موحدة وهي 3. كذلك تم استخدام زاوية ميلان واحدة لجميع تلك النماذج وهي 30 درجة. تم زيادة تشتيت نسبة طاقة الجريان (R.E.D) باستخدام الحصى وكلما زاد قطر الحصى زاد تشتيت الطاقة وخصوصا عند معدل نسبة ارتفاع قطر تلك الحصى الى ارتفاع المدرجة وقيمته 0.5 وهذا أدى الى زيادة تشتيت طاقة الجريان الى تقريبا ثلاث اضعاف مقارنة بالمطافح التقليدية غير المدرجة. ان نسبة تشتيت الطاقة تقل عند استخدام التجوفات عند التصاريف العالية وتزداد عند التصاريف القليلة مقارنة بالمطافح المدرجة التي لا تحوي أي إضافة. اما فيما لو استخدم الحصى فان ذلك يؤدي الى زيادة تشتيت الطاقة عند التصاريف العالية والقليلة. ان الزيادة في نسبة تشتيت طاقة الجريان كانت 26.73% مقارنة بالمطافح التقليدية و16.73% مقارنة بالمطافح المدرجة التي لا تحوي أي إضافة. لان المطافح المدرجة التي لاتحوي أي إضافة تكون اكثر كفاءة في تشتيت طاقة الجريان بنسبة 10% مقارنة بالمطافح التقليدية غير المدرجة. وبصورة عامة فان نسبة تشتيت طاقة الجريان تقل بزيادة التصاريف.

الكلمات الرئيسية: تشتيت الطاقة ، المطافح المدرجة، انواع الجريان ،خشونة سطح الحصى ،تجويف.

1. INTRODUCTION

Usually the flood flow is released through the dam by spillway. A major part of the dams construction cost was due to design and contraction of spillways. A 20% and 80 % of total dam construction costs were for small and large dams, respectively **,Yousefian, 1996**. The design and construction of spillways are very complicated and usually faced with difficulties such as cavitation and high flow kinetic energy due to the high flow discharge over the spillways , **Novak et al., 1990**. It becomes usual to protect the spillway surface from cavitation erosion by introducing air next to the spillway surface using aeration devices located on the spillway bottom and sometimes on the sidewalls ,**Chanson, 1997**. Stepped spillways allow continuously dissipating a considerable amount of the flow kinetic energy. For instant, the downstream stilling basin of the residual energy was dissipated by hydraulic jump. This could be largely reduced in dimensions of spillway. In addition, the cavitation risk along the spillway decreases significantly due to smaller flow velocities and the large air entertainment rate ,**Rajarantnam, 1990**.

Al- Talib, 2007 found that stepped weirs were more efficient than flat sloped weirs and the maximum energy dissipation ratio in stepped weirs was approximately 10 % higher than in flat sloped weirs. **Chamani and Rajaratnam, 1999** showed that in a stepped spillway, jet flow occurred at relatively smaller discharges and skimming flow occurred at larger discharges. **Alghazali and Jasim, 2014** performed 12 stepped spillway models to investigate flow regime limits. They performed three downstream slope angles (25, 35, and 45^0), and four numbers of steps (5, 10, 15, and 20). **Alghazali and Jasim, 2014** tested five configurations of steps (conventional flat, pooled, porous end sills, pooled with gabions, and porous end sills with gabions). Their results showed that the end sills highly affect flow regime type for the lower limits of skimming flow. **Alghazali and Jasim, 2014** found that gabions reduced the effects of end sills on the lower limit of skimming flow regime to near the limit of flat steps. They suggested new empirical equations based on the experimental results.

Barani, et al., 2005 investigated the energy dissipation of the flow over stepped spillways of different step shapes; a physical wooden model has been built. Experiments have been carried out for different types of step shapes (plain steps, end sill steps with thickness of 1, 2, 3, and 4 cm and steps with bottom adverse slope of 15^o, 26^o, 36^o, and 45°). Overall, the hydraulic parameters of flow over the model were measured, and the energy dissipation of flow was calculated. The results showed that the energy dissipation of the flow over the end sill and inclined stepped spillways were more than the plain one. The energy dissipation was increased by increasing the thickness of end sill or the adverse slope size.

El-Jumaily and Al-Lami, 2009 studied the flow characteristics and energy dissipation over traditional and stepped spillway with semicircular crest. Their experimental results showed that when increasing the ratio between upstream water depth to the water depth at crest and Froude number at spillway toe led to increase energy dissipation on traditional and stepped spillway. **El-Jumaily and Al-Lami, 2009** suggested a design of Bastora stepped spillway as a prototype to build a physical wooden model with scale of 1:20 (length of model to length of prototype). Experiments have been carried out on the model with slope of upward inclined steps of 420, 280, 140 and 100. For every slope of the steps, experiments were conducted in three flow regimes, nappe, transition, and skimming. Results showed that the energy dissipation decreases with increasing the discharge, and the energy dissipation of flow on stepped spillways with upward inclined steps is more than on the horizontal stepped spillways, it increases with increasing the adverse slope of steps. **Chen, et al., 2002** examined the flow of the stepped spillway by applying the finite volume method and utilized the kinetic energy model for the determination of the flow turbulence. They found that the turbulence numerical simulation is an efficient and useful method for the complex stepped spillway overflow.

Recent studies (**Wuthrich and Chanson, 2015; Zhang and Chanson, 2016; Sabbagh-Yazdia and Misaghiana, 2016**) were investigated and performed gabion stepped spillway to study flow characteristics, interactions between free-surface, cavity, and seepage flows. No study till now investigated the influence of roughed steps spillway by gravel on energy dissipation. The aim of this study is to investigate the flow characteristics and the energy dissipation on roughed stepped spillway using different sizes of gravel and on cavitation stepped spillway.

2. GENERAL THEORETICAL IN STEPPED SPILLWAY

The following general relationships for the flow energy dissipation were applied at upstream and downstream of each stepped spillway (**Chen, et al., 2002**):

$$E_0 = y_0 + \frac{\alpha v_0^{\;2}}{2g} \tag{1}$$

$$E_1 = y_1 + \frac{\alpha v_1^{\;2}}{2g} \tag{2}$$

$$\frac{\Delta E}{E_0} = \frac{(E_0 - E_1)}{E_0} \tag{3}$$

where y_0 is depth of water at upstream, cm, y_1 is depth of water at toe of spillway, cm, v_0 is velocity at upstream, m/sec, v_1 is velocity at downstream at toe of spillway, m/sec, α is kinetic correction coefficient for turbulent flow and it is generally equal to 1.1 according to (**Chen, et al., 2002**), g is acceleration due to gravity, m/s^2, E_0 is upstream energy, m, E_1 is downstream energy, m, and $\frac{\Delta E}{E_0}$ is relative energy dissipation (R.E.D) between upstream and downstream of stepped and flat sloped spillway, %.

3. MATERIALS AND METHODS

3.1. Laboratory Flume and Stepped Spillway Models

The experimental work was performed using a flume at the hydraulic laboratory, college of Engineering, Al- Mustansiriyah University. The flume is a rectangular with a length of 5 m, width of 30 cm, and depth of 30 cm as shown in **Fig.1**. A sharp crested weir with a height of 2.5 cm was installed at the end of flume to obtain required flow condition. Discharges were measured by a calibrated flow meter installed at the channel outlet and the maximum discharge of the flume was 0.05m^3/sec. The upstream flow heads were initiated to measure at a location more than (9 y_c) upstream of the spillway model, where y_c is the depth of water over the spillway crest. Using an accurate point gauge reading to 0.1 mm, the water surface levels were measured at different locations. A large sump tank was constructed beside the flume and above the laboratory floor. Water was stored in this tank and pumped to the flume through a 10cm pipe. A manually operated valve, installed on the circulation system pipe, was utilized to control the flow discharge.

Chow, 1959 and **Henderson, 1966** presented the crest length and radius of curvature of upstream face as:

$$\frac{L_{crest}}{H_T - h_e} > 1.5 - 3 \tag{4}$$

$$R = 0.2(H_T - h_e) \tag{5}$$

where L_{crest} is the broad crested weir length, cm, H_T is upstream total head above the channel bed, cm, h_e is the weir height above the channel bed, cm, and R is the radius of curvature of upstream face.

In this study, the height of all models used was constant and equal to 60 % of the flume height (i.e. 18 cm). All spillways were installed at distance of 0.75 m from the flume entrance to eliminate turbulence flow. One angle ($\theta = 30^{o}$) of the spillway faces were used for each model. These angles are equal or greater than the critical value as defined by **Chanson, 1994** of $\theta = 27°$. The installation allows mainly observing the different flow regimes. The maximum upstream head above bed channel was 26 cm, and the height of spillways that was considered in this work was 18 cm. Therefore, the length of crest was about 15 cm from using equation 4 and the upstream edge radius of all spillways was 2 cm using equation 5 to prevent separation of stream flow from the crest. Five models were constructed from concrete and utilized in this study as shown in **Fig.2** and **Table 1**.

For each model ten runs were utilized to measure the following parameters: the discharge (Q), upstream flow depth (y_0), critical flow depth over spillway (y_c), and the downstream flow depth (y_1) for each run. Overall, 50 experiments were done, the hydraulic parameters of flow over the models were measured and the energy dissipation of flow were calculated.

3.2. Flow type limits

Normally, there are three types of flow in stepped spillway: nappe, transition, and skimming flows. The experimental results showed that the nappe flow was less than 8 m^3/h, while the skimming flow was larger than 24 m^3/h, **Table 2**. Both shape characteristic and the step surface quality were affecting the flow regime variation. **Fig.3** shows the three types of flow which was established in this study. From **Tables 1** and **2** the range of flow types for nappe flow was increasing when using rough surface with size (20-25) mm and cavitation at small discharges. Therefore, the efficiency of energy dissipation using these two cases was increased at small discharges.

3.3. The limits of transition flow

The limits of transition flow in this experimental application were observed. To govern these limits, the depth of water at spillway crest (y_c), and the spillway shape (which is the non-dimensional ratio, y_c / h, where h is the height of step) were considered in this study. **Table 3** represents the values of y_c / h for all models. **Table 4** indicated several authors who have taken this proposition into account in their researches. The maximum value of the ratio (y_1/y_c) which corresponds to the structures of this experiment is equal to 20.84. This value is remarkably less than the limit value of ($y_1/y_c < 35$) according to **Chafi, et al., 2010**.

4. RESULTS AND DESCUSSION

4.1. Energy dissipation analysis

The energy dissipation for the stepped spillway without any addition was analyzed according to experimental data. The relationship between discharge and relative energy dissipation (R.E.D) was shown in **Fig.4**. It could be observed that the R.E.D decreased when the discharge increased with a good fit of $R^2=0.97$ and inverse relation of ($R.E.D = 99.21e^{-0.03Q}$).

4.2. Roughed step with gravels

The main aim of this research was to increase the energy dissipation on stepped spillway with different roughed gravel sizes. Therefore, three cases were used which were the stepped roughed with gravel size (10-14) mm, roughed steps with size (14-20) mm, and roughed stepped with size (20-25) mm. In order to increase energy dissipation on stepped spillway, the steps of spillway was roughed with gravel size of (10 -14) mm having porosity of 41 % within the recommended range (38-41) % according to **Alghazali and Jasim, 2014**. **Figs. 5a** and **6a** showed the application of roughed steps and the relationship between discharges and relative energy dissipation with fit of goodness of $R^2=0.93$ and inverse relation of ($R.E.D = 105.80e^{-0.023Q}$), respectively.

The steps of spillway was also roughed with gravel size of (14 -20) mm having porosity of 40.5 % within the recommended range also in order to increase energy dissipation on stepped spillway. **Figs. 5b** and **6b** showed the application of roughed steps and the relationship between discharge and relative energy dissipation with fit of goodness of $R^2=0.95$ and inverse relation of ($R.E.D = 100.20e^{-0.017Q}$), respectively. The steps of spillway were roughed using gravel with size (20 -25) mm having porosity of 39.4 % within the recommended range. **Figs. 5c** and **6c** presented the application of roughed steps and the relationship between discharge and relative energy dissipation with fit of goodness of $R^2=0.97$ and inverse relation of ($R.E.D = 98.12e^{-0.015Q}$), respectively. In this study, the average ratio between gravel height and step height was 0.5.

4.3. Roughed steps with cavitation

As a novel of this study, the steps of spillway were caveated using cavitation holes to increase the energy dissipation on stepped spillway. The average ratio between volume of cavitation and volume of each step was 0.12. **Figs. 7** and **8** presented the application of cavitation on steps and the relationship between discharge and relative energy dissipation with a good fit of $R^2=0.88$ and inverse relation of ($R.E.D = 126.44e^{-0.041Q}$), respectively.

4.4. Results analysis

As expected, the relative energy dissipation (R.E.D) was decreased when the discharge increased for all cases utilized in this study. **Fig.9** shows that the roughed steps with gravel (20- 25) mm have the maximum relative energy dissipation (R.M.S.E = 16.73) compared to other cases. **Al-Talib, 2007** found that stepped weirs were more efficient than flat sloped weirs and the maximum energy dissipation ratio in stepped weirs was approximately 10 % higher than in flat sloped weirs due to roughed surface by stepped sloped in stepped spillway compared to flat one of flat sloped. Therefore, in this study the stepped spillways were more efficient by 26.73% than the flat sloped spillway of pervious researches. The results of this study lead to understand that when the size of gravel increased the relative energy dissipation was increased. The steps with cavitation have large efficiency of energy dissipation for small discharges but have the lowest efficiency for large discharges compared with all cases of steps including steps without any addition.

Mann-Whitney rank sum tests (**Mann and Whitney, 1947, Al-Madhhachi, et al., 2014**) were performed to determine statistical differences of relative energy dissipation (R.E.D) among all five models. The mean values, median values, standard deviation, standard error, and the difference between the 25th and 75th percentiles were informed for R.E.D of all five models as shown in **Table 5**. The results confirmed that the roughed steps with maximum gravel size of (20- 25) mm have the maximum relative energy dissipation compared to other models and there was significant statically differences among all models with P-value of less than 0.001 regarding to R.E.D values.

4. CONCLUSIONS

In this experimental study, an attempt to increase the relative energy dissipation over stepped spillway compared with flat sloped spillways using roughed steps with gravels have three different sizes and steps with cavitation. By a comparison with steps without any addition, the maximum energy dissipation occurred with larger gravel size for small and large discharges, and that led to increase relative energy dissipation by 26.73 % compared with flat sloped spillway and 16.73 % compared with stepped spillway without any addition. Using the ratio between heights of gravel to steps of 0.5, the R.E.D was increased to about triple compared with traditional spillways. On the other hand, the results showed that the cavitation has large energy dissipation for small discharges but have smaller energy dissipation for large discharges.

REFERENCES

- Alghazali, N.S., and Jasim S.M., 2014, *Experimental study on the limits of flow regimes for different configurations of stepped spillway*, Civil and Environment Research, Vol. 6 (6), pp (30-40).
- Al-Madhhachi, A.T., Fox G. A., Hanson G. J., Tyagi A. K., and Bulut R., 2014, *Detachment rate model for the erodibility of cohesive soils due to fluvial and seepage forces*, J. Hydraulic Eng., ASCE, Vol. 140 (5), 10.1061/(ASCE)HY.1943-7900.0000836, 04014010.

- Al-Talib, A. J., 2007, *Laboratory study of flow energy dissipation using stepped weirs*, MSc., Engineering College, Mosul University, Iraq.

- Barani, G.A., Rahnama M.B., and Sohrabipoor N., 2005, *Investigation of flow energy dissipation over different stepped spillways*, AM J APPL SCI, Vol. 2 (6), pp (1101-1105).

- Chafi, C., Hazzab A., and Seddini A., 2010, *Study of flow and energy dissipation in stepped spillway*, Jordan Journal of civil engineering, Vol. 4 (1), pp (1-11).

- Chamani M.R., and Rajaratnam N., 1999, *Characteristic of skimming flow over stepped spillways*, Hydraulic Eng., ASCE, Vol.125, pp (361-367).

- Chanson, H., 1997, *Air bubble entrainment in free surface turbulent shears flows*, Academic Press, London, UK.

- Chanson H., 1994, *Comparison of energy dissipation Nappe and skimming flow regime on stepped chutes*, Journal of hydraulic research I.A.H.R., Vol. 32 (2), pp (213-218).

- Chen Q., Dai G., and Liu H., 2002, *Volume of fluid model for turbulent numerical simulation of stepped spillway over flow*, Journal of Hydraulic Engineering, ASCE, Vol. 128 (7), pp (683-688).

- Chow, V. T., 1959, *Open-Channel Hydraulics*, McGraw- Hill Book Company.

- Degoutte, G., Peyras L., and Royet P., 1992, *Skimming flow in stepped spillways: Discussion*, Journal of Hydraulic Engineering, ASCE, Vol. 118 (1), pp (111-114).

- El-Jumaily K., and Al-Lami M.H., 2009, *Study of convenience of using stepped spillway in roller compacted dams (RCCD),* Eng. And Tech. Journal, Vol.27 (16), pp (415-426).

- Essery, I.S., and Horner M.W., 1978, *The hydraulic design of stepped spillways*, CIRIA report, 3rd edition, London, UK.

- Henderson, F.M, 1966, *Open channel flow*, MACMILAN PUBLISHING CO. IN., NewYork.

- Kells, J.A, 1995, *Comparison of energy dissipation between nappe and skimming flow regimes on stepped chutes*, Journal of hydraulic research, I.A.H.R., Vol. 33 (1), pp. (128-134).

- Mann, H. B., and Whitney D. R., 1947, *On a test of whether one of two random variables is stochastically larger than the other,* Annals of Mathematical Statistics, Vol.(18), pp. (50-60).

- Matos, G., and Quintela A., 1995, *Flow resistance and energy dissipation in skimming flow over stepped spillways,* Journal of hydraulic research, I.A.H.R., Vol. 33(1), pp (135-139).

- Novak, P., Maffat A.I., and Narayanan R., 1990, *Hydraulic structures*, The academic division of uniwin, Ltd.

- Rajaratnam, N., 1990, *Skimming flow in stepped spillways*, Journal of Hydraulic Engineering, ASCE, Vol. 16(4), pp. (587-591).
- Sabbagh-Yazdia, S., and Misaghiana M., 2016, *Effect of water infiltration through concrete block spillways on the slope stability of earth overflow dams*, European Journal of Environmental and Civil Engineering, DOI:10.1080/19648189.2016.1150898.
- Wuthrich, D., and Chanson H., 2015, *Aeration performances of a gabion stepped weir with and without capping*, Environmental Fluid Mechanics, Vol. 15(4), pp. (711-730).
- Yousefian, H., 1996, *Hydraulic design of Labyrinth spillways based on the physical model*, M.Sc. Thesis, Isfahan University of Technology, Iran.
- Zhang, G., and Chanson H., 2016, *Gabion Stepped Spillway: Interactions between Free-Surface, Cavity, and Seepage Flows*, J. Hydraul. Eng., ASCE, Vol. 142(5), 10.1061.

Table 1. Characteristics of the five step spillway models.

Step spillway cases	without addition	gravel (10-14) mm	gravel (14-20) mm	gravel (20-25) mm	cavitation
Model No.	1	2	3	4	5

Table 2. Flow type limits.

Step cases	Limit of flow
Stepped without addition	- Nappe ≤ 8.3 m3/h - transition (8.4 ≤ Q ≤ 18) m3/h - skimming (Q ≥ 18.1) m3/h
Roughed with gravel size (10-14) mm	- Nappe ≤ 8.2 m3/h - transition (8.3 ≤ Q ≤ 18) m3/h - skimming (Q ≥ 18.1) m3/h
Roughed with gravel size (14-20) mm	- Nappe ≤ 8.0 m3/h - transition (8.1 ≤ Q ≤ 18) m3/h - skimming (Q ≥ 18.1) m3/h

Roughed with gravel size (20-25) mm	- Nappe ≤ 10 m3/h - transition (10.1 ≤ Q ≤ 18) m3/h - skimming (Q ≥ 18.1) m3/h
Stepped with cavitation on surface	- Nappe ≤ 10 m3/h - transition (10.1 ≤ Q ≤ 18) m3/h - skimming (Q ≥ 18.1) m3/h

Table 3. Values of ratio (yc / h) in this study.

Step case	values of yc / h
Stepped without addition	0.5-0.73
Roughed with gravel size (10-14) mm	0.5-0.73
Roughed with gravel size (14-20) mm	0.5-0.71
Roughed with gravel size (20-25) mm	0.5- 0.69
Stepped with cavitation on surface	0.53-0.71

Table 4. Values of ratio (yc / h) as recommended in pervious researches.

Authors	Essery et.al. (1978)	Rajaratnam (1990)	Degoutte (1992)	Chanson (1994)	Kells (1995)	Matos et. al. (1995)	Chafi (2010)
yc / h	0.81	0.80	0.69	0.80	0.50	0.83	0.67

Table 5**.** Results from Mann-Whitney Rank Sum tests for differences among five models of R.E.D values. All tests were performed with n = 10.

Model type	Mean	Median	Standard Deviation	Standard Error	25% Percentiles	75% Percentiles	P-value
Without gravel	58.41	51.97	19.77	6.25	38.6	80.07	<0.001
Gravel (10-14) mm	67.38	69.34	18.05	5.71	49.04	85.48	<0.001
Gravel (14-20) mm	71.51	73.96	14.31	4.53	57.86	85.71	<0.001
Gravel (20-25) mm	73.18	75.07	12.78	4.04	60.05	85.89	<0.001
Cavitation	59.41	59.79	25.53	8.07	39.58	85.46	<0.001

Figure 1. Indoor flume with stepped spillway at Al- Mustansiriyah University Hydraulics Laboratory used for testing.

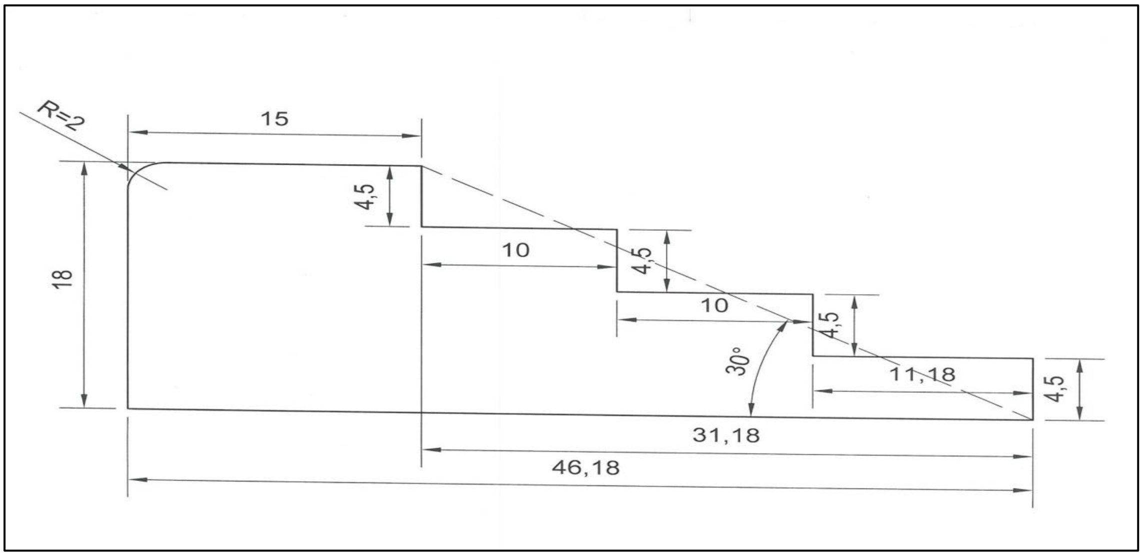

Figure 2. Dimension designs of five step spillway models.

a) Nappe flow

b) Transition flow

c) Skimming flow

Figure 3. Image of flow regimes: a) nappe flow, b) transition flow, and c) skimming flow.

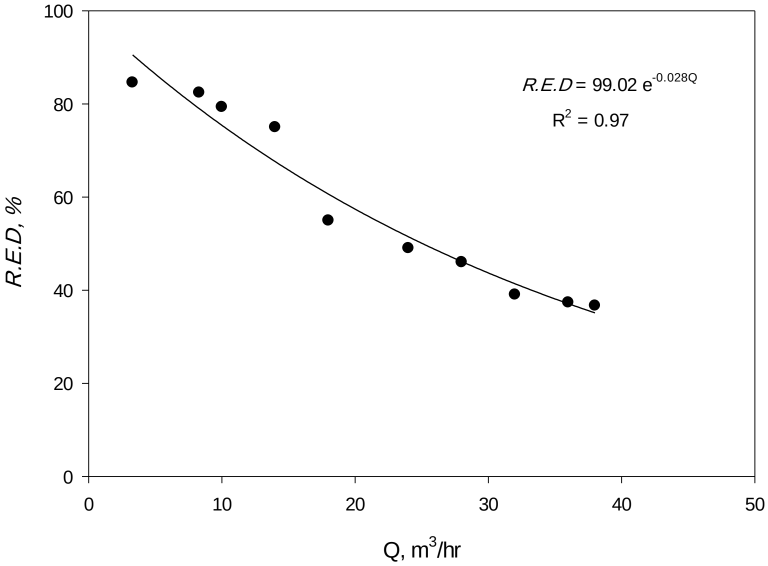

Figure 4. The R.E.D relationship of stepped spillway without addition.

a) Gravel size (10-14)mm b) Gravel size (14-20)mm

c) Gravel size (20-25)mm

Figure 5. Stepped spillway provided with different gravel sizes: a) (10-14) mm, b) (14 -20) mm, and c) (20-25) mm.

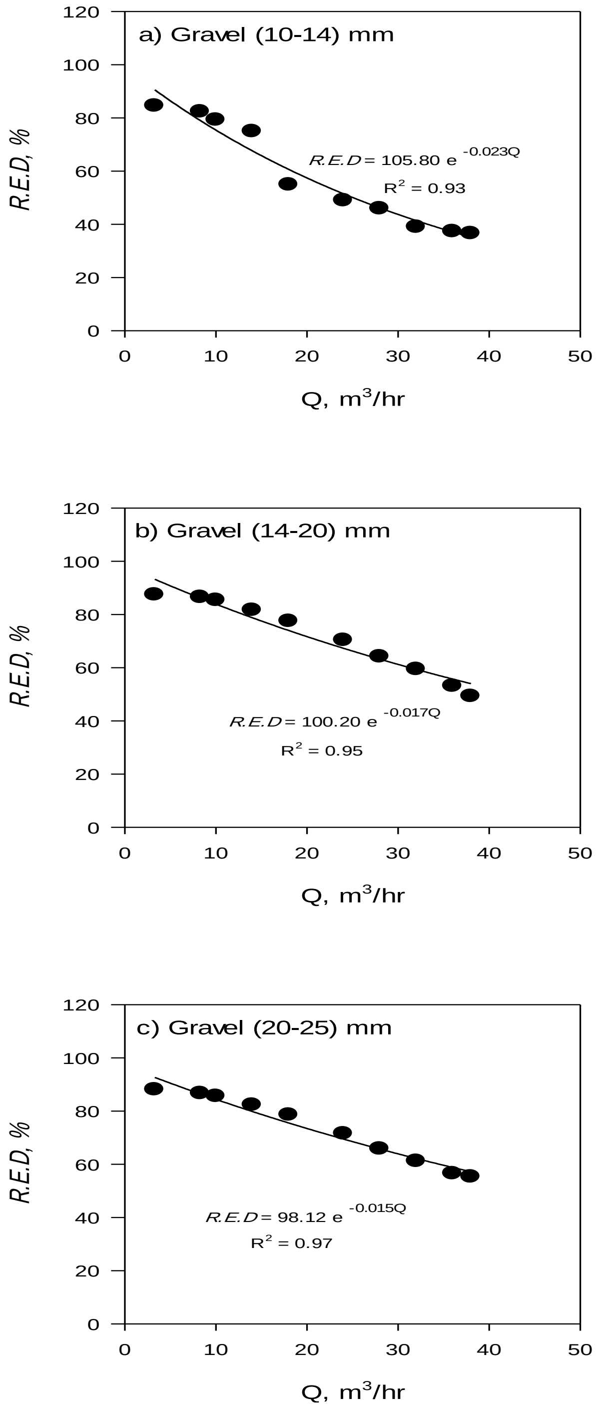

Figure 6. Relation between relative energy dissipation and discharges for Stepped spillway with different gravel sizes: a) (10-14) mm, b) (14 -20) mm, and c) (20-25) mm.

Figure 7. Stepped spillway provided with cavitation.

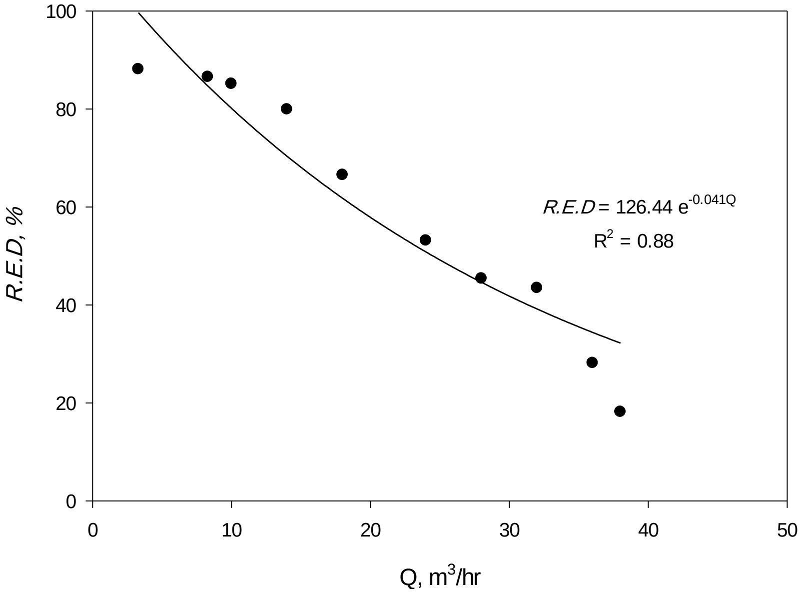

Figure 8. Relation between relative energy dissipation and discharges for stepped spillway with cavitation.

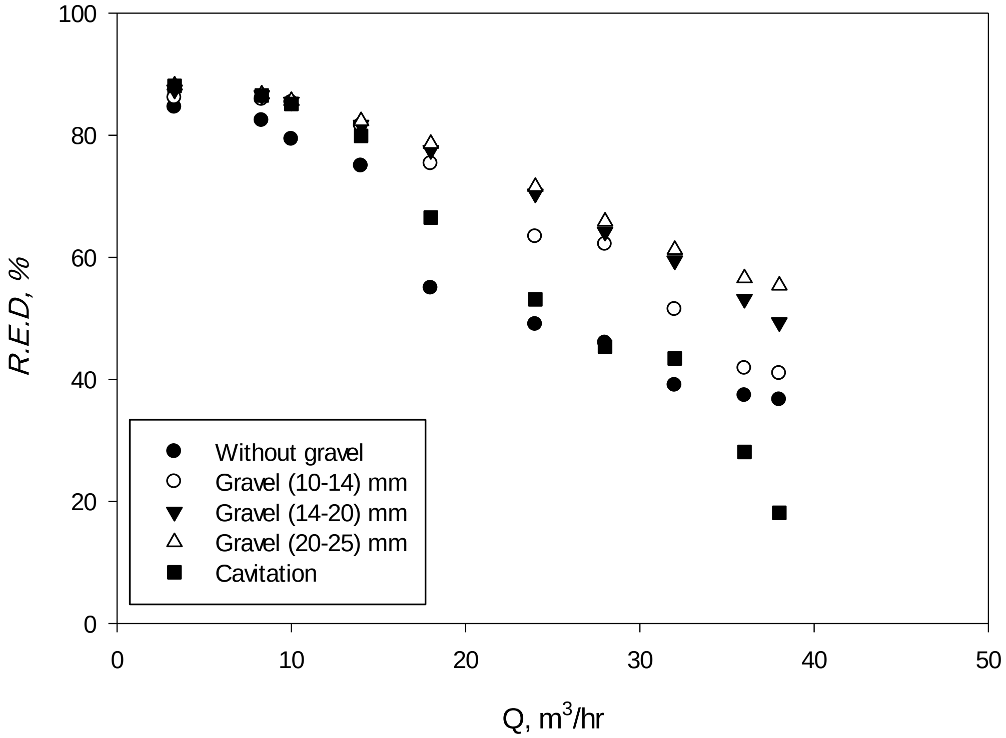

Figure 9. Relation between relative energy dissipation and discharges for five models.