ISSN: 1687-1006 p
ISSN: 2682-3640 e

The Egyptian International Journal of Engineering Sciences and Technology

https://eijest.journals.ekb.eg/

Vol. 45 (2024) 1–9

DOI: 10.21608/EIJEST.2023.169927.1187

+ Investigation of hydraulic characteristics down stream of Gabion dams

Amany A. Habib [a], Eman H. Elghandour [b*], Maha R. Fahmy [a] and Eslam Eltohamy [a]

[a] *Staff members, Water and Water Structure Engineering Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt, Zagazig 44519, Egypt*

[b] *Civil engineering, M.Sc. researcher, Zagazig 44519, Egypt*

ARTICLE INFO

Article history:

Received 20 October 2022
Received in revised form 01 April 2023
Accepted 25 May 2023
Available online 25 May 2023

Keywords:

Gabion spillway
Energy dissipation
scour

ABSTRACT

Gabions are water structures that consist of metal mesh boxes contain rocks. This makes gabions very economic and simple. Those structures are widely used in small head works to dissipate the potential energy, and decrease scour. This study aims to investigate the effect of particle grain size on the hydraulic performance and its impact on scour downstream gabion stepped spillway to provide the designers with a wide range of available diameters for use in construction. For this purpose, six experimental models of gabion stepped spillway were tested. The used stepped gabion spillway model has 5 steps with 20 cm height, the steps are 7cm horizontal and 4 cm vertical each. The gabions models of different single particles diameters (5mm, 10mm, 14mm, 20mm and 30mm) and solid spillway model were tested. Also six additional models of two mixtures have been tested, the first with particles diameter 10 mm and 30 mm, the other with diameter 5 mm and 20 mm, they have been mixed in three different volume ratios (1:1, 1:2, 1:3), the equivalent diameter was calculated for each mixture. The results indicated that the increase in relative diameter in single size and mixed models increases energy dissipation and decreases scour. The model with relative diameter 0.15 gave the best results. It causes reduction of Y_2/Y_{up}, D_s/Y_{up} by about 9.69%, and 40.19 % respectively and increase in $\Delta E/E_{up}$ by 11.7% compared to the solid gabion model. Finally, the results of this study may be recommended in the field of applications.

1. Introduction

Aggregate is considered one of the structural elements that are abundant in nature. The designers used it as a basic structural element in structures exposed to static or flowing water with suitable velocities. In the case of rushing water with high velocities, the use of aggregates is impossible because of their instability, which leads to the structural collapse.

Gabions flood plains are considered one of the most vulnerable Gabion facilities due to high water speeds. Gabion structure as shown in figure 1 is an example of field application. Located at Brisbane, Queensland, Australia which have been constructed since 2015.

* Corresponding author. Tel.: +201068946133, +201117489843
E-mail address: eman.elghandour35@gmail.com

Figure 1 gabion structure. Brisbane, Queensland, Australia.

Many researchers have tended to study this type of facility as soon as it spread due to its effectiveness in energy dissipation. **Shafai-Bajestan, et al. [1].** Investigated the mechanism of scour hole development. The results of this study reveals that the scour hole dimensions in simple stepped spillway is larger than the pooled stepped spillway. **Hunt & Kadavy [2].** Investigated physically the effect of steps height on energy dissipation. A two-dimensional model was constructed to evaluate the energy dissipation on a 4:1(H:V) slope spillway chute. It was found that the increasing of step height increases the energy losses at similar locations within the spillway chute. **Salmasi, et al. [3].** Studied the flow over and through the gabion stepped spillways to evaluate the energy dissipation and it was found that increasing slope led to less energy dissipation. **Vicari, et al. [4].** Studied the application of gabion structures as river control structures and it`s particularly on transversal gabion weirs and spillways in flood storage projects. Some applications of gabion structures in offline flood storage projects in france and Italy were showed in this study. **Elnikhely, E. A. [5].** Conducted experimental study to investigate the effect of using single curved vertical sill on the scour hole dimensions downstream of a spillway with different flow conditions. Results indicated that the suggested curved vertical sill gave from 20% to 43% reduction in maximum scour depth and from 45% to 66% reduction in scour length compared to the case of flat floor, also the best location of sill was found to be at the first one-third of the floor with relative diameter of 0.122 of spillway height. **Taebi, H., et al. [6].** Used hydraulic model of Namrood dam to check the stability of stone size to withstand scour resulted from basin turbulent outlet flow. Results confirmed considerable reduction of the stone size with increase in elevation of the river bed and tail water depth for same flow discharges, while stone size increased with increasing flow discharge and decreasing tail water depth. **Elnikhely, E. A. [7].** Investigated the effect of using cylinder blocks fixed on the back slope of the spillway on the scour hole dimensions downstream of spillway under different flow conditions. The case of staggered cylinder blocks over sloped spillway gives the smallest values of scour and deposition parameters. **Awad, A. S., et al. [8].** Studied experimentally the effect of the contracted stepped spillways on scour characteristics. The contraction ratio was about 60% from the channel width. By using a breaker with 10% perforated area, and the divergent angle about 10 degrees the maximum scour depth was minimized by about 65.38 %. **Aal et al. [9]** Studied the gabion and buttress gabion spillway and found that the using of large particles increase the energy dissipation and the coefficient of discharge. Also, as the number of buttress walls increases, the energy dissipation and the coefficient of discharge decrease. **Shariq et al. [10]** Studied experimentally the flow through gabion weir of various sizes and for varying boulder sizes and discharges. It was found that Ergun's equation predicts the hydraulic gradient more accurately than the other available equation. A qualitative performance of the present model indicates that it has the highest coefficient of correlation (R = 0.956) and the lowest MAPE (16.902), RMSE (0.002), AAD (15.52). Sensitivity analysis shows that the discharge through the gabion weir is more sensitive to the boulders diameter and upstream depth as compared to the downstream depth of the gabion weir. **Zuhaira et al. [11]** Numerically investigated the influence of the non-uniform geometry of gabion-stepped spillways (GSS) on the inception point. The software, NEWFLUME, was adopted to examine the flow over the GSS. The empirical equations developed in this investigation yielded better predictions of the inception point location compared to the existing equations. **Daneshfaraz et al. [12]** Investigated the behaviour of hydraulic parameters of solid and gabion inclined drops. A comparison between solid and gabion inclined drops showed that the relative energy loss and downstream relative depth increases by 82% and 50%, respectively. **Salmasi et al. [13]** Studied the discharge coefficients (C_d) for rectangular broad-crested gabion weirs. The broad-crested gabion weir was made of galvanized metal sheet with a thickness of 3 mm and the gabion weir was made of natural sand with four different particle diameters. The average size of the rocks was 3, 1.55, 1, and 0.5 cm; the tests were performed for different ranges of weir length (L), weir height (P), and discharge (Q). The results showed that the C_d of gabion weirs is 10.5% greater than that of similar solid weirs. In addition to this, the C_d for porous weirs in free flow conditions is 17.2% greater than that for submerged flow. For H=L > 0.45 (where H is the water depth over the weir crest and L is the weir length), the porous weir acts similar to the solid weir, and the effect of porosity (n) nearly vanishes. For a specified value of H=L, the ratio of submergence (Sr) for the solid weir is higher than that for porous weirs. Porous weirs with 50% porosity have lower values of Sr as compared to solid weirs and weirs with lower porosities, of 45%, 41%, and 30%. **Aamir et al. [14]** Experimentally studied the scour downstream of rough and smooth stiff aprons under the influence of wall jets. Maximum equilibrium scour depth initially decreases with increasing tail water level, but thereafter an increase is observed. Based on the conclusions of this study, it is recommended to use roughness over the surface of stiff apron to confine scour under-wall jets. **Nasralla[15]** Employed an experimental study to investigate the stepped spillway with the movable bed material. Different downstream divergent angle was studied to minimise the scour depth, the results showed that the relative scour depth was reduced by 23% for divergent angle is equal to 170°, buffer where tested and it decreased the relative scour depth up to 84%. This study was simulated by flow 3d program to analyse the scour hole formed using velocity vectors at the bed. The simulated results well agreed with the measured data.

From the previous survey the studies in the field of gabion and buttress gabion spillways are few, whether in energy dissipation or scour, so this study tends to focus on buttress gabion in the field of energy dissipation and scour.

2. material and method

The study depended on identifying the factors affecting the phenomenon and studying them using the dimensional analysis firstly, and then identifying the practical experiments required to obtain the necessary results for analyzing the variables obtained in dimensional analysis as shown in the following sections

2.1. Dimensional analysis

Dimensional analysis was used to correlate the different variables as shown in figure 2, affected on dissipated energy and scour downstream gabion dams. The dimensional analysis based on Buckingham theory was used to develop a functional relationship between the maximum depth of the scour hole and the other variables as indicated in Eq. 1 for single diameter and Eq. 2 for mixed diameters where Dequ was used instead of D. The maximum dimensions of the scour hole (Ds , Ls) downstream gabion dams can be defined as follows:

$$\frac{D_s}{Y_{up}}, \frac{L_s}{Y_{up}} = f(F_{up}, \frac{Y_2}{Y_{up}}, \frac{d_{50}}{Y_{up}}, \frac{\Delta E}{E_{up}}, \frac{D}{H_s}) \quad \text{Eq. (1)}$$

$$\frac{D_s}{Y_{up}}, \frac{L_s}{Y_{up}} = f(F_{up}, \frac{Y_2}{Y_{up}}, \frac{d_{50}}{Y_{up}}, \frac{\Delta E}{E_{up}}, \frac{D_{equ}}{H_s}) \quad \text{Eq. (2)}$$

Where, B is a width of the canal, D is the uniform particle diameter, D_{equ} is the equivalent particle diameter of the mix (the average of particle size diameters in each mix) , d_{50} is the Median Diameter of Sand sample of movable bed, D_s is maximum depth of the scour hole , g is gravitational acceleration , H_s is dam height , L_s is length of the scour hole , V is the water velocity , Y_1 is initial water depth , Y_2 is the sequent depth of hydraulic jump, Y_{up} is upstream water depth, ΔE is energy loss between upstream the dam and the end of jump and E_{up} is energy upstream the dam .

The effect of d_{50}/Y_{up} can be neglected because it is constant.

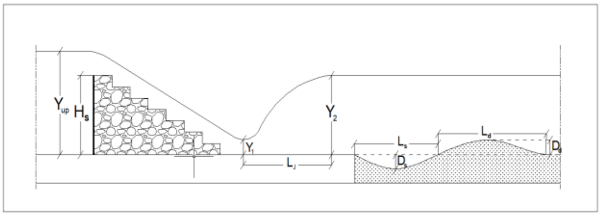

Figure 2 Definition sketch of experimental model elevation.

2.2. Experimental set up

Experimental work was carried out in the Hydraulic Engineering Laboratory of the Faculty of Engineering, Zagazig University, Egypt. The used flume is 29.8 cm width, 45.6 cm depth with an overall length of about 15.6 m. The tailgate at the end of the flume used to control the tail water depth. A pump used to circulate the water from the tank to the flume inlet. The water runs through the flume working section then returns back to the tank in a closed circle. A pre-calibrated orifice meter installed in the feeding pipe line used to measure the passing discharge.

The used stepped gabion spillway model was made from stainless steel covered with steel narrow mesh with 20 cm height and 5 steppes 7cm horizontal and 4 cm vertical each. The model has 5 steppes with 20 cm height. Figure 3 shows the used experimental model. Six gabion models are used to investigate the studding phenomena. Gabion models were filled with six different gravel particle size diameters (5mm, 10mm, 14mm, 20mm and 30mm) and solid model. Another six gabion models of two mixtures were tested, the first mixture consists of 10 mm and 30 mm particles diameter while the second mixture consists of 5 mm and 20 mm particles diameters. the two mixtures were mixed in different ratios (1:1), (1:2) and (1:3). as shown in table 1. The results indicated that when particle diameter increased the relative energy dissipation increased, the relative depth of jump and the maximum scour depth decreased. The research optimal design of particle size diameter was found to be 30 mm, that gave the optimum values of energy and scour parameters, led to reduction of Y2/Yup and Ds/Yup by about 9.69%, and 40.19 %, respectively and increase in ΔE/Eup by 11.7 % compared to the solid gabion spillway model. The model set on a solid base with length 40 cm followed by a sandy soil to simulate scour. The sand sample was tested using sieve analysis in the laboratories of faculty of engineering zagazig university to find the percentage of each particle size as shown in figure 4. The data analysis showed that the median particle diameter d_{10} = 0.2 mm, d_{50} = 0.5 mm and d_{90}= 1.1 mm. Discharges ranges from 9.5 to 22 lit/s and upstream Froude number ranged from 0.09 to 0.12. A diagram of the gabion spillway model is provided in figure 2 and figure 3.

About 84 runs were tested; with different flow rates for each model. After placing the desired gabion model, the required flow discharge was adjusted by the inflow valve and the tailgate to form the hydraulic jump just downstream the model. Flow characteristics were measured during each test (Q, Y_1, Y_2, L_s, D_s, D_d, L_d and Y_{up}) were measured.

Table 1 All Studied Mixtures.

Case A(1:1)		Case B(1:2)		Case C(1:3)		
50%	50%	33.3%	67.67%	25%	75%	
10mm	30mm	10mm	30mm	10mm	30mm	First group
D_{aqu}=(1*50+3*50)/100 D_{equ}=2 CM		D_{equ} = (1*33.3+3*67.67)/100 D_{equ}=2.36CM		D_{equ} = (1*25+3*75)/100 D_{equ}=2.5 CM		
Mix. no. 1		Mix. no. 2		Mix. no. 3		
5mm	20mm	5mm	20mm	5mm	20mm	Second group
D_{equ} = (0.5*50+2*50)/100 D_{equ} =1.25 CM		D_{equ} = (0.5*33.3+2*67.67)/100 D_{equ} =1.5 CM		D_{equ} = (0.5*25+2*75)/100 D_{equ} =1.75 CM		
Mix. no. 4		Mix. no. 5		Mix. no. 6		

(3.a) (3.b)

Figure 3 The experimental gabion stepped spillway model

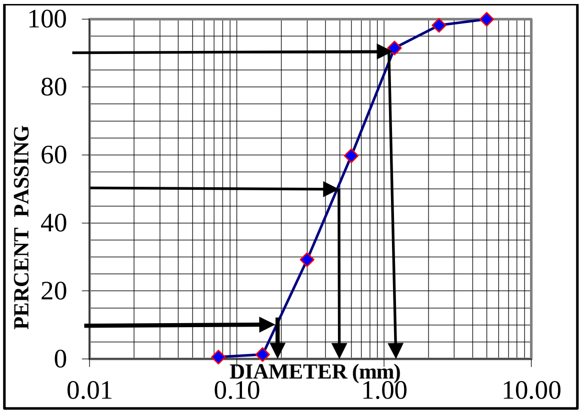

Figure 4 sieve analysis chart

3. Analysis and discussion

The different flow characteristics were analyzed as a function of the inflow Froude number such as the scour depth, energy loss and tail water depth to select the best dimension of grain size which gives the best scour and flow characteristics parameters.

Figure 5 shows the appositive relationship between the upstream Froude numbers (F_{up}) and the relative depth of the hydraulic jump (Y_2 / Y_{up}) for different relative particle sizes. The effect of increasing the upstream Froude number on the relative depth of the hydraulic jump can be vanished at higher Froude numbers, and the all relative depths close to each other regardless the value of Froude number. When the Froude number reaches to 0.12 all relative depth of jump approximately the same. More over at a constant upstream Froude number less than 0.12, the relative depth of the jump decreases with the increases of the relative particle sizes. This increasing has a linear decreasing relationship as shown in figure 6. The relative depth of the hydraulic jump (Y_2 / Y_{up}) reached its minimum values at particle size diameter=30 mm (D/H_s =0.15) with difference of 9.69% compared to the solid spillway case.

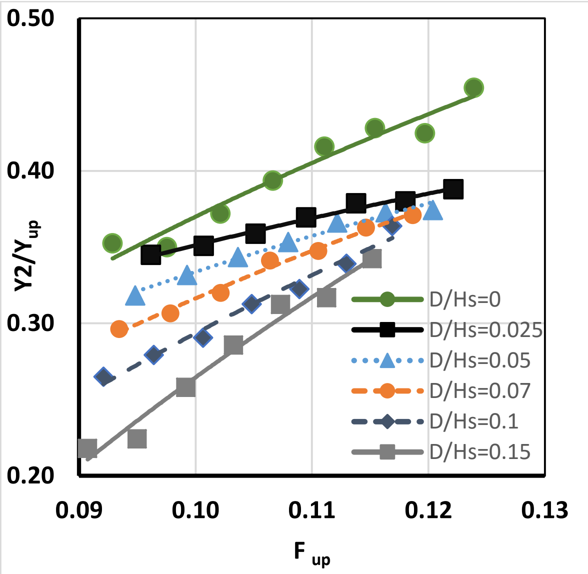

Figure 5 Relations between F_{up} and Y_2 / Y_{up} for different relative particle sizes.

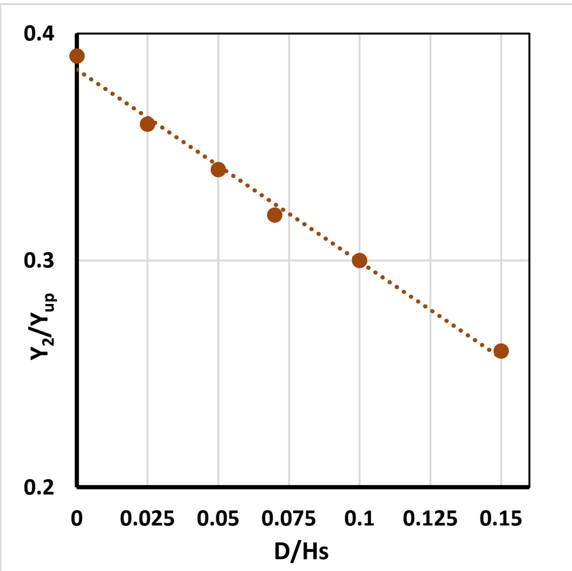

Figure 6 relationship between D/H_s and Y_2/Y_{up} at (F_{up}) = 0.1

It believes when mixing soil with different particle sizes the soil void ratio decreases, this decreasing retains a little amount of flow discharge passing through the soil. This decreasing depends on the equivalent soil particles diameter (D_{equ}). The mix with the same equivalent soil particles diameter has a very little negative effect on the hydraulic jump characteristics as shown in figure 7. For example at Froude number = 0.1 the mix of soil 1cm and 3cm with the same ratio 1:1 (D_{equ}=2 cm), the relative depth of jump in this case is more than the corresponding soil with uniform particles = 2cm by about 6.4 % .

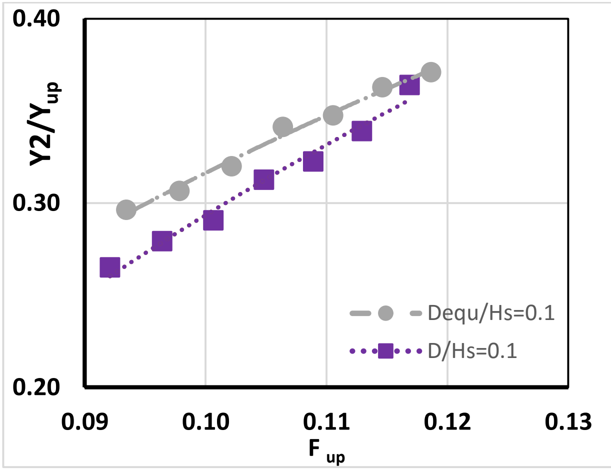

Figure 7 Relations between F_{up} and Y_2/Y_{up} for mix1 (D_{equ}/H_s = 0.1) and (D/H_s=0.1).

The behavior of the hydraulic jump due to the effect of soil mix with different particles diameters has the same trend of the uniform soil particles diameters as shown in figure 8 and figure 9. Again, at Froude number = 0.12 the relative depth of jump is approximately the same for different soil particles diameters.

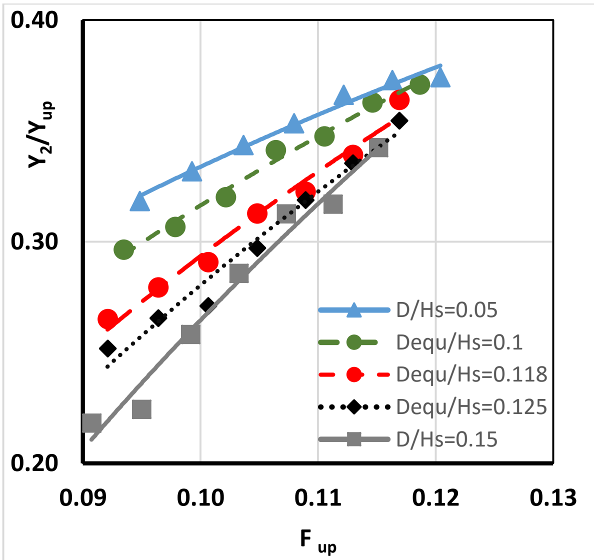

Figure 8 Relations between F_{up} and Y_2/Y_{up} for (D/H_s=0.05), (D/H_s=0.15) and their mixes (D_{equ}/H_s = 0.1, D_{equ}/H_s = 0.118, D_{equ}/H_s = 0.125).

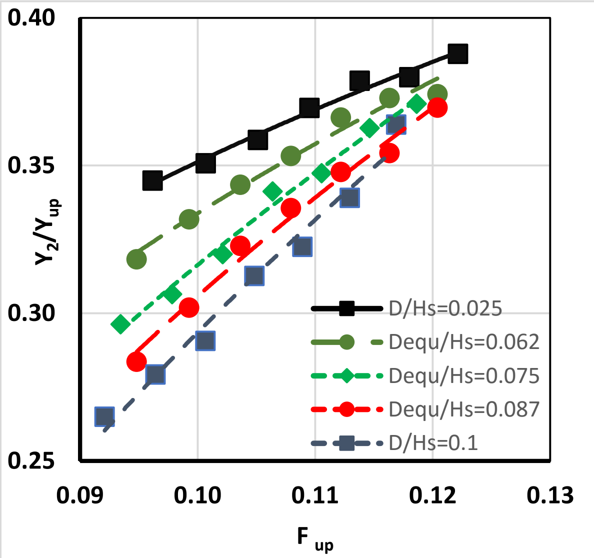

Figure 9 Relations between F_{up} and Y_2/Y_{up} for $(D/H_s=0.025)$, $(D/H_s=0.1)$ and their mixes (D_{equ}/H_s = 0.062, D_{equ}/H_s = 0.075, D_{equ}/H_s = 0.087).

Also Figure 10 shows the relationship between the upstream Froude numbers (F_{up}) and the relative energy loss $\Delta E/E_{up}$ for different relative particle sizes. The figure showed that the energy dissipation increases with the increase of the relative diameter of the particles (D/HS) at a specific Froude number, while for the same relative diameter the energy dissipation decreases with the increase of Froude numbers (F_{up}). It's meaning that there is an inverse relationship between scour and energy dissipation.

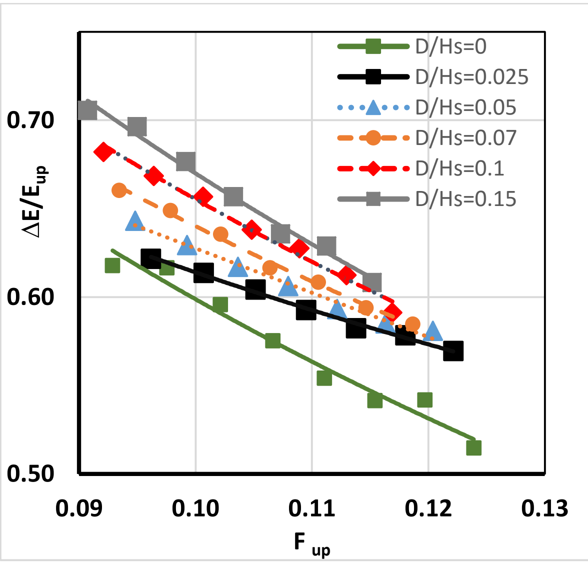

Figure 10 Relations between F_{up} and $\Delta E/E_{up}$ for different relative particle sizes.

The energy dissipation due to the presence of stepped spillway in water ways is a similar to other heading up structures. The energy dissipation in a prismatic channel is due to the transition in water depths between the two sides of the control volume. Beside the above mentioned reason, the kinetic energy through the control volume plays an important role in the total energy dissipation through it. The convert of kinetic energy to potential energy needs to a more depth of water. The kinetic energy over the spillway is very higher compared to the steady state condition at the end of the control volume. Some of flow discharge passes through the voids of the gabions stones, as the gabion stone size increases the void ratio also increases and hence the flow underneath the gabions soil increases. So the interaction of water streamlines through the gabion and above it at the toe of spillway leads to slow down the velocity at the end of water establishment. The amount of water passes through the gabion forms a breakers of water velocity, so amore energy dissipation is occurred. This explains the positive relationship between the gabion sizes and the energy dissipation as shown in figures 10, 11 and 12.

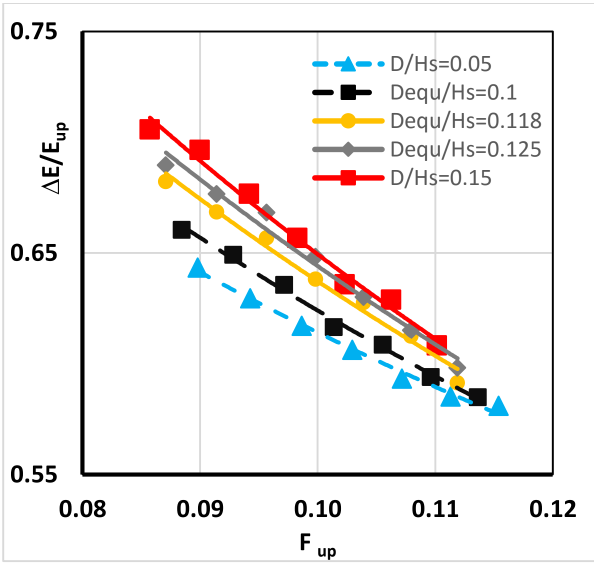

Figure 11 Relations between F_{up} and $\Delta E/E_{up}$ for relative particle sizes $(D/H_s=0.05)$, $(D/H_s=0.15)$ and their mixes (D_{equ}/H_s = 0.1, D_{equ}/H_s = 0.118, D_{equ}/H_s = 0.125).

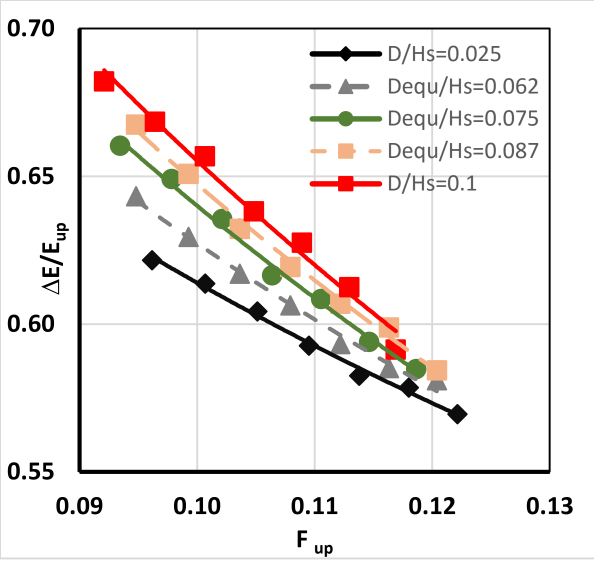

Figure 12 Relations between F_{up} and $\Delta E/E_{up}$ for relative particle sizes(D/H_s=0.025), (D/H_s=0.1) and their mixes (D_{equ}/H_s = 0.062, D_{equ}/H_s = 0.075, D_{equ}/H_s = 0.087).

Figures 13 and 14 show the relationship between the upstream Froude numbers (F_{up}) and the relative maximum scour depth (D_s/Y_{up}) and the relative maximum scour length (L_s/Y_{up}) for different relative particle sizes respectively. The figures showed that the relative maximum scour depth and length increased with the increase of Froude numbers (F_{up}), and decreased with the increase of the relative diameter of the particles (D/H_S).

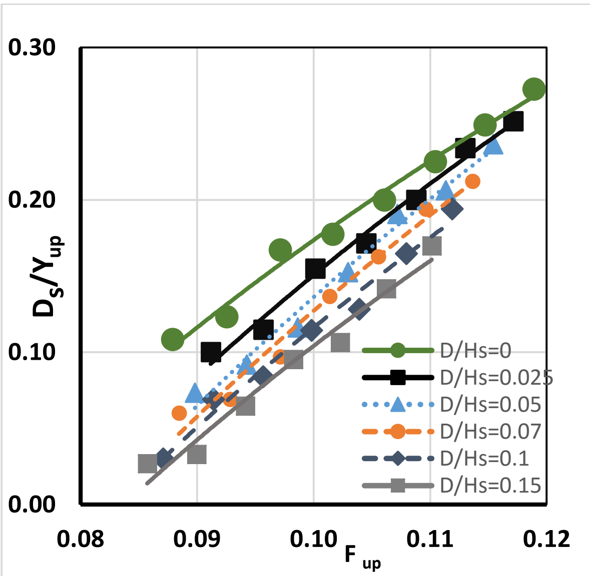

Figure 13 Relations between F_{up} and D_s/Y_{up} for different relative particle sizes.

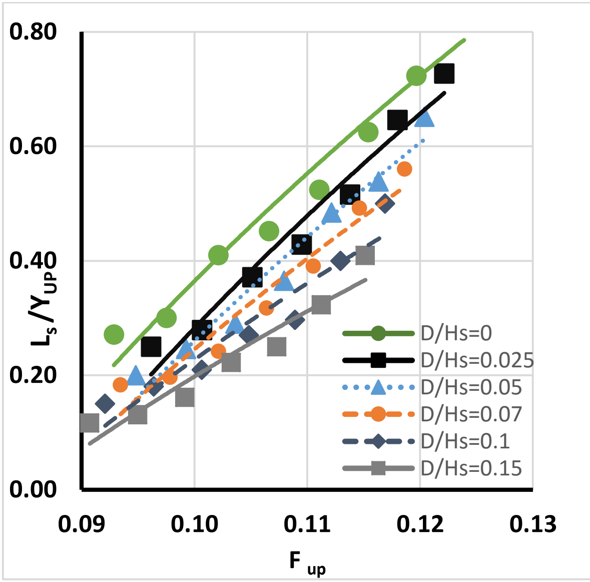

Figure 14 Relations between F_{up} and L_s/Y_{up} for different relative particle sizes .

It is shown that the relationship between energy dissipation and scour parameters is inverse, or in other words, as the energy dissipation increases, the relative depth and length of scour decrease. The convert of kinetic energy to potential energy complete with a certain length accompanied by energy loss. The energy loss increases as the amount of water passes through the gabion media increases. This happens when the relative uniform diameter increases, which explains that is why the maximum scour depth is reduced by gabion dam.

Mixing soil of different particle diameters results in an equivalent diameter value which equals a uniform soil diameter, for instance, in case of mixing 1cm and 3cm with the same ratio, the equivalent diameter is 2cm; the mix void ratio is less than the corresponding uniform diameter (2 cm). So the under passing discharge in the case of uniform diameter is more than the mix and hence the maximum scour depth and length are relatively less than the mix with the same equivalent diameter as shown in figures (15) and (16). For example, at Froude number =0.1 the mix of soil 1cm and 3cm with the same ratio 1:1 (equivalent D_{equ}=2 cm), the relative scour depth (D_s/Y_{up}) in this case is more than the corresponding soil uniform diameter = 2 cm by about 1 % and about 3 % for the relative maximum scour length (L_s/Y_{UP}). From results, it is shown that there is a negligible difference between the case of mixed particle sizes and the corresponding uniform size. in both cases the void ratio closes to each other but the void ratio in the mix is relatively smaller than the uniform particle which leading to relatively un effective increases in the under passing discharge consequently the results in the both cases gave approximately the same results.

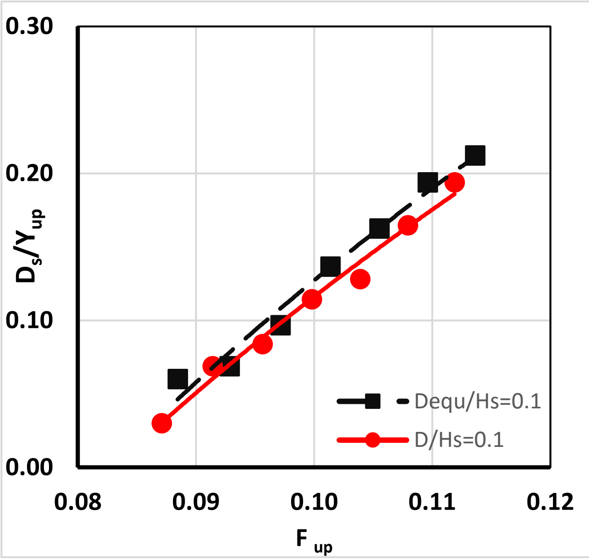

Figure 15 Relations between F_{up} and D_s/Y_{up} for the relative equivalent diameter for mix1 ($D_{equ}/H_s = 0.1$) and relative uniform diameter (D/H_s=0.1).

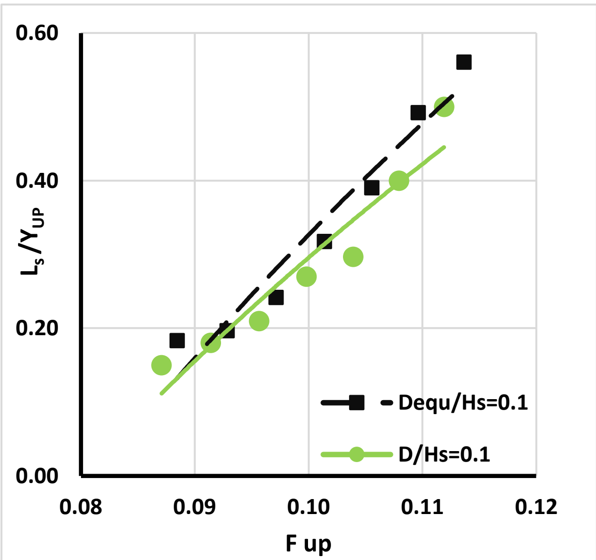

Figure 16 Relations between Fup and Ls/Yup for the relative equivalent diameter for mix1 (Dequ/Hs = 0.1) and relative uniform diameter (D/Hs=0.1).

4. Design guide

The obtained results can be used to determine the range of diameters of filling gravel in the gabion boxes relative to the designed spillway height, within the limits of the existing discharges at the site according to the following equation (eq.3) using the obtained charts of this study according to its limits.

$$\frac{D_s}{Y_{up}} = f\left(F_{up}, \frac{D_{equ}}{H_s}\right) \qquad \textbf{Eq.(3)}$$

for example, Figure (12) shows the relative scour depth. for small discharges with Froude number equals 0.09, scour will range from 3% to 12% relative to upstream water depth, while relative scour will increase from approximately 17% to 24% when the Froude number reaches 0.11.

Therefore, the designers must determine the value of Froude number in the spillway first, and the safe tolerance of scour, then choose the suitable relative diameter that gives scour less than the permissible. In the same way, it is possible to determine the suitable diameters for energy dissipation and the relative depth, and to choose the diameter that achieve all the requirements within the limits of the current study.

5. Conclusions

From the results of the present study, the following conclusions can be introduced. When the Froude number increases, the relative maximum scour depth and the relative maximum scour length increase at the same particle size. the increase in relative diameter in single size and mixed models increases energy dissipation and decreases scour. The case of relative diameter equal 0.15 is the best of all with reduction of, Y_2/Y_{up}, D_s/Y_{up} by about 9.69%, and 40.19 %, respectively and increase in $\Delta E/E_{up}$ by 11.7% compared to the solid spillway model. The scour parameters and jump characteristics for a mixture with a certain equivalent diameter are near to the single size model which has diameter near to this mixture equivalent diameter.

6. Recommendations

Studying different numbers of steps and different slops for the gabion spillway and their effect on scour and improving the performance of structures to resist the higher pressures at the upstream.

Notation

B	Width of the canal
D	The uniform particle diameter
D_{equ}	The equivalent particle diameter of the mix
d_{50}	Median Diameter of Sand sample of movable bed
D_s	Maximum depth of the scour hole
g	Gravitational acceleration
H_s	Dam height
L_s	Length of the scour hole
V	The water velocity
Y_1	Initial water depth
Y_2	The sequent depth of hydraulic jump
Y_{up}	Upstream water depth
ΔE	Energy loss between upstream the dam and the end of jump
E_{up}	Energy upstream the dam

References

[1] Shafai-Bajestan, M., & Kazemi-Nasaban, G., "Prediction Of Scour Depth Downstream Of Gabion Stepped Spillway", In Proceedings 2nd International Conference on Scour and Erosion (ICSE-2), Singapore, 2004.

[2] Hunt, S., & Kadavy, K., "The Effect Of Step Height On Energy Dissipation In Stepped Spillways", Paper Presented At The World Environmental And Water Resources Congress Great Rivers, 2009.

[3] Salmasi, F., Chamani, M. R., & FARSADI, Z. D., "Experimental study of energy dissipation over stepped gabion spillways with low heights", 2012.

[4] Vicari, M., "Application and Feedbacks Of Gabion Structures In Flood Storage Projects For The Protection Of Urban Areas And Infrastructures", 2-11, 34th Dam days Appl 2014.

[5] Elnikhely, E. A., "Minimizing scour downstream of spillways using curved vertical sill", International Water Technology Journal, 6(3), 2016.

[6] Taebi, H., & Fathi-Moghadam, M., "Scouring control of the eroded stilling basin: Case study, Namrood Dam", African Journal of Water Conservation and Sustainability ISSN, 5(3), 183-190, 2017.

[7] Elnikhely, E. A., "Investigation and analysis of scour downstream of a spillway", Ain Shams Engineering Journal, 9(4), 2275-2282, 2018.

[8] Awad, A. S., Nasr-Allah, T. H., Mohamed, Y. A., & Abdel-Aal, G. M., "Minimizing scour of contraction stepped spillways", Journal of Engineering Research and Reports, 1(1), 1-11, 2018.

[9] Aal, G. M. A., Fahmy, M. R., Elnikhely, E. A., & El-Tohamy, E., "Energy dissipation and discharge coefficient over stepped gabion and buttress gabion spillway", Technology, 10(4), 260-267, 2019.

[10] Shariq, A., Hussain, A., & Ahmad, Z., "Discharge equation for the gabion weir under through flow condition", Flow Measurement and Instrumentation, 74, 101769, 2020.

[11] Zuhaira, A. A., Al-Hamd, R. K. S., Alzabeebee, S., & Cunningham, L. S., "Numerical investigation of skimming flow characteristics over non-uniform gabion-stepped spillways", Innovative Infrastructure Solutions, 6(4), 1-19, 2021.

[12] Daneshfaraz, R., Bagherzadeh, M., Ghaderi, A., Di Francesco, S., & Asl, M. M., "Experimental investigation of gabion inclined drops as a sustainable solution for hydraulic energy loss", Ain Shams Engineering Journal, 12(4), 3451-3459, 2021. .

[13] Salmasi, F., Sabahi, N., & Abraham, J., "Discharge coefficients for rectangular broad-crested gabion weirs: experimental study", Journal of Irrigation and Drainage Engineering, 147(3), 04021001, 2021.

[14] Aamir, M., Ahmad, Z., Pandey, M., Khan, M. A., Aldrees, A., & Mohamed, A., "The effect of rough rigid apron on scour downstream of sluice gates", Water, 14(14), 2223, 2022.

[15] Nasralla, T. H.,"Experimental and numerical investigation of scour downstream contracted spillways", Journal of Water and Land Development, 53-59, 2022.