

Modelling Energy Dissipation Over Stepped-gabion Weirs by Artificial Intelligence

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Abstract The hydraulics of energy dissipation over stepped-gabion weirs is investigated by carrying out a series of laboratory experiments, building models to explain the experimental data, and testing their robustness by using the data reported by other researchers. The experiments comprise: six different stepped-gabion weirs tested in a horizontal laboratory flume, a wide range of discharge values, two weir slopes ($V:H$): 1:1 and 1:2, and gabion filling material gravel size (porosity equal to 38 %, 40 % and 42 %). These experimental setups were selected to ensure the development of both the nappe and skimming flow regimes within the measured dataset. The models developed for computing energy dissipation over stepped-gabion weirs comprise: multiple regression equations based on dimensional analysis theory, Artificial Neural Network (ANN) and Gene Expression Programming (GEP). The analysis shows that the measured data capture both flow regimes and the transition in between them and above all, and by using all of the data, it may be possible to identify the range of each regime. Energy dissipation modelled by the ANN formulation is successful and may be recommended for reliable estimates but those by GEP and regression analysis can still serve for rough-and-ready estimates in engineering applications.

Keywords Stepped-gabion weir · Energy dissipation · Artificial intelligence · Nappe · Skimming and transition regimes

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Notation

b	Weir/Spillway width
E_1	Energy at the downstream of spillway before hydraulic jump
E_0	Total energy at the upstream of Weir/spillway
$\Delta E = E_0 - E_1$	Energy difference between upstream and downstream of Weir/spillway
F_r	Froude number = $V_1 / \sqrt{g y_1}$
g	Acceleration due to gravity
h	Each step height
H_w	The height of the crest of Weir/spillway from flume bed
l	Each step length
K	Relative energy dissipation defined as $K = (E_0 - E_1) / H_w$
n	Stone porosity filled in gabion
q	Discharge per unit width
Q	Discharge
R_e	Reynolds number = $V_1 y / \nu$
S	Weir/spillway slope ($V: H$)
V_α	Approach velocity = q / y
V_1	Velocity at the toe of the spillway
y_0	Depth of flow about 0.60 m upstream of the spillway above its crest
y_1	Depth before hydraulic jump at the Weir/spillway toe
y_2	Depth after hydraulic jump, and
α	Weir/spillway angle (degree) with horizontal line.

1 Introduction

The case for research on a better understanding of the hydraulics of flow over stepped-gabion weirs is still strong, as it depends on the complexity of flow regimes, physical characteristics and various hydraulic effects such as turbulence and flow through porous media. In contrast, the hydraulics of conventional weirs is well understood, which typically consists of an impermeable body of concrete construction functioning primarily by water backing up to regulate flows. These two engineering measures are quite different and Markovic (2012) argues that “structural solutions may lead to environmental degradation, i.e. alteration of physical-chemical and structural characteristics of the natural components of the environment, decrease of diversity and biological productivity of natural and anthropogenic ecosystems, impacts on the ecological balance and quality of life.” Stepped-gabion weirs overcome such impacts as the individual stones are restrained significantly by wire meshes within their gabion baskets so that their motion is not of concern. This difference is important because gabions used as weirs reduce much of the above impacts.

Stepped-gabion weirs have become increasingly popular engineering measures implemented as stepped chutes/spillways, which cope intrinsically with flood releases through them. There are further reasons for this popularity including: (i) an ability to increase significantly the rate of energy dissipation taking place on the spillway face; (ii) to reduce the size of the required downstream energy dissipation basin; (iii) as noted by Chanson (1993), to lower additional costs of gabion construction techniques owing to their compatibility with Roller Compacted Concrete (RCC); and as noted by (Mohamed, 2010), stepped-gabion weirs offer an alternative design adopted for flash flood mitigation. An investigation for a better insight into the hydraulics of stepped-gabion weirs are focus of this paper, especially their energy dissipation and differentiate among flow regimes.

Many studies have been carried out to investigate discharge through stepped weirs and spillways but the hydraulics of through-flows of gabion constructions is complex due to flow patterns and resistance against impacts of flow on stone particles. The current understanding identifies the development of the following flow regimes over stepped weirs/spillways (see Fig. 1): (i) *nappe or jet flow regime*: the water flows as a succession of freefalling nappes at small discharges (Toombes and Chanson, 2008); (ii) *skimming flow regime*: stepped spillways normally operate at large discharges and under the right conditions the water forms a pseudo-bottom (i.e. not solid bottom) for a coherent stream formed by step edges, during which significant energy is dissipated by form losses and momentum transfer from the main stream to the recirculation zones (e.g. see: Chanson and Toombes, 2004; Chamani and Rajaratnam, 1999; Rajaratnam, 1990); and (iii) *transition flow regime*: for an intermediate range of flow rates, a transition flow regime is observed between the above two regimes. Also, as noted by Peyras et al. (1992), the nappe flow regime may be divided into partial and fully developed nappe regimes but this distinction is simplified in this paper.

This paper is focused on the study of energy dissipation over stepped weirs/spillways of gabion construction and not on deriving discharge equations. The quantitative techniques include: (i) dimensional analysis, (ii) the derivation of homolog functions; (iii) Artificial Intelligence (AI) techniques including Artificial Neural Network (ANN) and Gene Expression Programming (GEP). The application of the first two methods is customary in traditional hydraulics but this paper also explores the latter two. The investigation on energy dissipation in the present study is based on reporting a set of experimental data conducted on low-height stepped-gabion weirs constructed in a basket. The experimental data comprises six physical models with the overall objective of investigating the effects of hydraulic and geometric properties of stepped weir of gabion baskets on energy dissipation. Tests encompass both the nappe and skimming regimes to understand weir porosity (n), weir slope (S) and other hydraulic parameters like Froude and Reynolds numbers. Furthermore, energy dissipation modelled by the ANN model is compared with that of the GEP model using these experimental data. Also this paper will not overlook techniques suitable for both rough-and-ready estimation of energy dissipation.

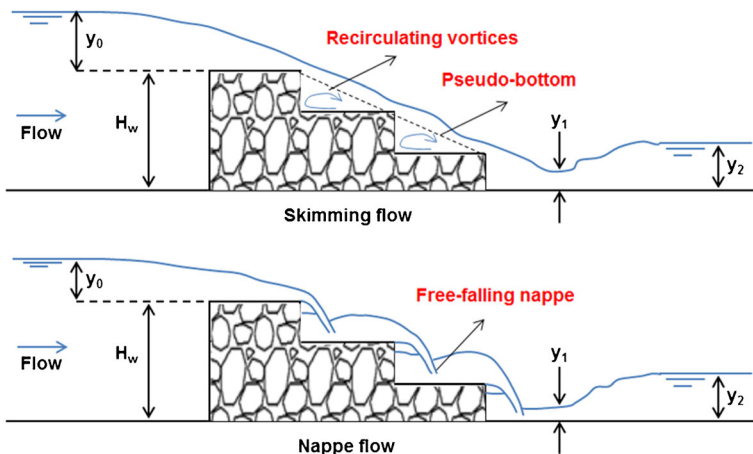


Fig. 1 Location for measured y_1 and y_2 depths at the downstream of weir

2 Literature Review

Gabion structures serve as water spreaders and drop structures to dissipate energy. Published experimental works provide database for studying energy dissipation and discharge formula for stepped weirs built on gabion stones either with baskets penetrating to natural bases or with mattresses sitting on solid steps. Table 1 captures the salient features of the relevant experimental-empirical studies reported by Stephenson (1979), Peyras et al. (1992), Kells (1994) and Chinnarasri et al. (2008). There are also other reported experimental works concerning stepped weirs, e.g. Chanson (1993) and Chanson and Toombes (2004), but they are concerned with solid constructions and not with gabion; likewise Mohamed (2010) investigates discharge coefficient through broad-crested gabion weirs but not energy dissipation.

In recent years, Artificial Neural Network (ANN) and Gene Expression Programming (GEP) models have attracted researchers in many disciplines of science and engineering, since they are capable of correlating large and complex datasets without any prior knowledge of the relationships among them. Application of these techniques to the problems in water aspects of control structures is topical, e.g. Kocabas et al. (2009) but this is not matched by research on stepped-gabions weirs. Salmasi (2010) applied ANNs modelling energy dissipation over stepped spillways using the data reported by Ohtsu et al. (2004) for large-size stepped spillways. The authors are not aware of the application of ANN and GEP to the gabion stepped spillways.

Based on the above review of experimental and mathematical approaches to stepped-gabion weirs, Table 1 also includes a gap analysis. As a result of the overview emerging from the table, it appears that the insight into the hydraulics of stepped-gabion weirs and their energy dissipation models are not fully supported by a set of experimental data covering both nappe and skimming regimes using gabion baskets. There is also a gap on the application of ANN/GEP artificial intelligence techniques for such experimental data. The challenge is taken on board in this paper by reporting the measured data of an experimental work, in which the porosity of gabion baskets and the slope of the stepped weir are selected to capture both regimes together including their transition.

3 Theorising and Modelling Stepped-Gabion Weirs

3.1 Experimental Setup

Gabion-weir test runs were carried out at the Hydraulic Laboratory of Water Engineering Department, Faculty of Agriculture, University of Tabriz. Plate 1 shows the section of the gabion-weir in these test runs installed in a flume, 0.25 m wide, 10 m long and 0.60 m high. All the physical tests had three steps, each with a height of 0.10 m. The spillway slopes selected were 1:1 and 1:2 ($V: H$).

A number of basic decisions had to be made before the experimental test runs. For instance, the size of gabion stones was decided by assuming a model scale of 1:10, which was a reasonable scale in hydraulic structures. This therefore led to determining gabion stone sizes to be 160 to 380 mm in the full scale gabion structures. The actual choice of gabion stones in this study was based on practical sizes normally found in prototypes. The gabion baskets were filled with three different stone diameter ranges of 16–19 mm, 19–25 mm, and 25–38 mm corresponding to three porosity levels of approximately 38, 40, and 42 %. Several earlier studies suggest that the porosity values between 30 to 40 % work well for stepped-gabion weirs (Stephenson, 1979; Kells, 1994).

Table 1 Overview of salient features of reported experimental works on gabion-stepped weirs

Research Works	Key Experimental Setup and Objectives	Key Findings
[1] Stephenson (1979)	<ul style="list-style-type: none"> • Basket gabions over 2–4 steps • Slopes ($V:H$): 1:1, 1:2, 1:3, 2:3 • Stone size: 10–40 mm; $n=40$ % • Measure relative energy dissipation, $\Delta E/H_w$, against different slopes 	<ul style="list-style-type: none"> • $\Delta E/H_w$ ranges from about 25 % to 85 %. • $\Delta E/H_w$ increases with the number of steps up to three, but reduces with more steps; • There may be an optimum number of steps for the greatest energy dissipation
[2] Peyras et al. (1992)	<ul style="list-style-type: none"> • Gabion Types: Plain gabion, end sills, impervious concrete slabs, horizontal impervious concrete slabs • Number of steps: 3–5 • Slopes ($V:H$): 1:1, 1:2, 1:3 • Stone size: 30–45 mm • Energy loss in stepped-gabion spillways • To establish stilling basin design criteria 	<ul style="list-style-type: none"> • Both nappe and skimming flows were observed during the tests • Relative energy dissipation, $\Delta E/H_w$, ranged from 25 % to 95 %
[3] Kells (1994)	<ul style="list-style-type: none"> • Basket gabions over 3 steps • Slopes ($V:H$): 1:1, 1:2 • Stone size: 15.6–19.1 mm; $n=38$ % • Relative energy dissipation, $\Delta E/E_0$ 	<ul style="list-style-type: none"> • Energy dissipation decreases with increasing critical flow depth (or discharge) but slopes have insignificant effect • Without overtopping: the increase in through-flow can be as much as 20 % and the total energy dissipation can be approx. 80 %–85 %;
[4] Chinnarasri et al. (2008)	<ul style="list-style-type: none"> • Mattress gabion over 4 solid steps • Weir slopes of 30°, 45°, and 60° • Void ratio: 0.27, 0.30, and 0.39 • Study flow patterns and energy loss, • Compare energy loss of horizontal steps and gabion-stepped weir 	<ul style="list-style-type: none"> • Energy loss ratios in stepped-gabions are greater than those in horizontal stepped weirs by approx. 7 %, 10 %, and 14 %, respectively • Energy dissipation is more sensitive to weir slope than the size and shape of stones in gabions • Average pressure difference is about 29 % as gabion stones absorb the fluid force acting on the step face by seepage of fluid to the lower void of meshes
Inter-comparison of existing studies	<p>Gaps in existing experimental setups</p> <ul style="list-style-type: none"> • Number of steps: from 2 to 5 • [1], [3] use basket gabions • [2], [4] use gabions with impervious base • [1], [2], [3] use one porosity but [4] uses 3 porosity values over impervious bases <p>GAP ANALYSIS</p> <ul style="list-style-type: none"> • Only [2] is likely to have produced measurements covering both nappe and skimming regime for basket gabions in stepped weirs but over impervious step bases, otherwise there seems to be no experimental data covering both regimes <p>Proposed experimental setup</p> <ul style="list-style-type: none"> • Basket stepped-gabions with 3 steps • Slopes ($V:H$): 1:1, 1:2 • Porosity: 38 %, 40 % and 42 % 	<p>Existing Capabilities</p> <ul style="list-style-type: none"> • Energy dissipation as a function of porosity, slope, number of steps <p>GAP ANALYSIS</p> <ul style="list-style-type: none"> • A clear understanding of the inception of nappe and skimming regimes • Energy dissipation models applicable to both nappe and skimming regimes and the transition in between <p>Proposed experimental setup</p> <ul style="list-style-type: none"> • To produce measurements capturing both nappe and skimming regimes and the transition in between • To capture the effects of porosity and slopes • To model energy dissipation across all the regimes

Plate 1 Gabion stepped spillway with a slope of 1:2 ($V: H$)



The flow through the flume was controlled at the end of the laboratory flume by a gate to form a hydraulic jump at the weir toe to enable flow measurements. Thus, discharge values were measured by a calibrated sharp triangle weir (53° angle) installed at the downstream of the flume. Discharge water was supplied by a pump (maximum value 50 l/s) ranging from 7 to 50 l/s with an accuracy level of ± 0.9 l/s.

The weir with step configuration is shown in Fig. 1. Water levels at the upstream were measured using a point gauge within ± 0.1 mm accuracy. All measurements were made along the centreline of the flume.

In each test run, water depth was measured 0.60 m upstream of the weir, y_0 , and downstream of the hydraulic jump, y_2 . This was due to the difficulty of measuring accurately the flow depth (y_1) due to air entrainment at the weir toe and the oscillation of water surface resulting from the impact of water jet on the bottom of the flume. Diez-Cascon et al. (1991), Tozzi (1992), Matos and Quintela (1994), and Pegram et al. (1999) calculated energy dissipation using the conjugate water depths of the hydraulic jump (y_2). In the present study, y_2 was measured with an accuracy level of ± 2 mm, where there were few bubbles and less undulation in the tail water.

3.2 Experimental Data

A total of 74 test runs were carried out with two different slopes, three different porosities (both specified in Section 3.1), and varying discharge rates and the measurements for each test run comprised discharge values and two values of water depth. The 74 datapoints are notably not timeseries and therefore dividing them into training data and prediction data has to employ a random procedure but reflect different test cases. A decision was made to use 80 % of these datapoints (58 data points) for training and 20 % of the total datapoints (16 point data) for testing the model in its prediction mode. The procedure for selecting training and prediction data was by plotting relative energy loss,

Gabion Number, Froude Number, Reynolds Number, slope, porosity against discharge and randomly selecting representative datapoints from the range involving high, medium and low values (note that these parameters are to be defined in Section 3.3). The measurement data are given in the Electronic Supplementary Material.

3.3 Dimensional Analysis

As illustrated in Fig. 1, upstream energy head (E_0), downstream energy head (E_1) and relative energy dissipation ($\Delta E/E_0$) are calculated as follows:

$$E_o = H_w + y_o + \frac{V_o^2}{2g} = H_w + y_o + \frac{q^2}{2g(H_w + y_o)^2} \tag{1.a}$$

$$E_1 = y_1 + \frac{V_1^2}{2g} = y_1 + \frac{q^2}{2gy_1^2} \tag{1.b}$$

$$\frac{\Delta E}{E_0} = \frac{E_0 - E_1}{E_0} = 1 - \frac{E_1}{E_0} \tag{1.c}$$

where, g is acceleration due to gravity; H_w is total gabion-weir height measured with a point gauge after the installation of the weir at the flume, y_0 is the depth of flow at a set distance upstream of the weir and above the weir crest and V_0 is the mean approach velocity, y_1 water depth and V_1 is mean velocity both at Section 1, and q is discharge per unit width of flume. Referring to Section 3.1, the depth, y_1 , is calculated using the conjugate depth (y_2) expressed by the following:

$$y_1 = \frac{y_2}{2} \left(\sqrt{1 + 8Fr_2^2} - 1 \right) \tag{1.d}$$

where, $Fr_2 = V_2/\sqrt{gy_2}$, V_2 and y_2 are mean velocity and water depth at Section 2 (after the hydraulic jump and the re-establishment of subcritical flow) respectively. Generally, energy dissipation depends on hydraulic and geometric variables expressed as:

$$\frac{\Delta E}{E_0} = f(q, l, h, H_w, g, n, \rho, \mu) \tag{1.e}$$

where, l is step length, h is step height, P is specific weight of water, μ is dynamic viscosity of water and n is porosity. In all tests, discharge was regulated in a way to form hydraulic jump at weir toe, so that supercritical flow at the downstream of the weir toe may occur ($Fr_r > 1$). Although depth values of y_1 and y_2 were both measured, energy dissipation was calculated by (1.a)-(1.d) by only using y_2 values.

The fundamental variables that are important in the hydraulics of gabion-stepped weirs are geometrical parameters like: total gabion-weir height (H_w), each step length (l), each step height (h), weir slope (S), stone size filled in gabion (d_{50}); and hydraulic parameters like: discharge per unit width (q), energy at upstream of weir (E_0) defined in (1.a), energy at downstream of weir (E_1) defined in (1.b), and material porosity (n). Using the Buckingham II-theorem, relative energy dissipation can be expressed as:

$$\frac{\Delta E}{E_0} = f \left(q^2/gH_w^3, h/l, n, R_{e1}, Fr_1 \right) \tag{1.f}$$

A more convenient way of expressing (1.f) is:

$$1/(1-K) = f(GN, S, n, R_{e1}, F_{r1}) \quad (2)$$

Where, $\Delta E/E_0$ is replaced with $1/(1-K)$, $GN=q^2/gH_w^3$, and $S=h/l$ is weir slope. The replacement of relative energy dissipation above has also been used by Peyras et al. (1992); the parameter GN is termed as Gabion Number, similar to drop number presented first by Rand (1955). Froude and Reynolds numbers at Section 1 are defined as: $F_{r1} = V_1/\sqrt{gy_1}$ and $R_{e1} = V_1y_1/\sqrt{\nu}$, where ν is water kinematic viscosity at 20°C. The average flow velocity at any section ($V=q/y$) was calculated as the measured flow rate per unit width ($q=Q/b$) where Q is total discharge, b is the weir width and y is depth of water at appropriate sections. Care is needed in using Inverse Relative Energy Dissipation (IRED) $1/(1-K)$ and the traditional Relative Energy Dissipation (RED), $\Delta E/E_0$, as when IRED values are high, their corresponding RED values are low and vice-versa.

3.4 ANN Modelling

The preliminary steps in any ANN model involve three basic steps: the generation of data for training, setting up a preliminary training ANN model, and the evaluation of the ANN configuration for the selection of an optimal configuration, which is then used in prediction. The ANN software program employed is Qnet2000 (Vesta Services, 2000), which is a back propagation neural modelling system. These steps for the development of the ANN model are outlined below:

- i. The parameters used for preparing the input data file are: (i) a measure of relative energy dissipation $1/(1-K)$, (ii) Gabion Number ($GN=q^2/gH_w^3$), (iii) material porosity (n), (iv) weir slope ($S=h/l$), (v) Froude number (F_{r1}) and (vi) Reynolds number (R_{e1}), where both the latter numbers are at Section 1 of the toe of the weir, shown in Fig. 1.
- ii. Implementation of an ANN model requires the selection of an optimum configuration and decisions to transform input data. The actual choices on configuration and functions are through trial-and-error procedure leading to an ANN model, ready for implementation.

3.5 Gene Expression Programming

Implementation of GEP models involves a number of preliminary decisions including the selection of a set of basic operators such as $\{+, -, \times, \sqrt{\quad}, \exp\}$. The GEP software applications provide operators like crossover and mutation to the “winners” (children or offspring) to emulate natural selection, in which crossovers are responsible for maintaining identical features from one generation to another but mutations cause random changes. The evolution starts from an initially selected random population of models, where the relationship, between the independent and dependent variables is often referred to as the “model,” the “program,” or the “solution.” The population is allowed to evolve from one generation to another by the virtue of a prescribed fitness criterion and new models replace the old ones in this evolutionary process by having demonstrably better performance.

The GEP model in this study was carried out using GeneXpro software application, (Ferreira, 2001a,b) and for more detail on the implementation of this model see Ghorbani et al. (2010 and 2012). In this study, the basic arithmetic operators ($*, /$) were used but addition

and subtraction operations were also tested. Input variables are the same as those for ANN. Large number of generations (5,000) were tested.

3.6 Performance Criteria

The two error measures are used to compare the performance of the various models: determination coefficient (R^2) and Root Mean Square Error (RMSE).

4 Results

4.1 Conceptualisation of Gabion Flow Regimes

Tables ESM.1 (in Electronic Supplementary Material) present experimental data for stepped-gabion weir for slopes 1:1 & 1:2 ($V:H$) respectively. These data are first used to conceptualise significant combinations of the parameters suggested by (2). GN-values are, in reality, ratios of actual flows, q , and potential flows suggested by the backwater caused by the gabion-weir configuration in terms of H_{w*} .

Figure 2 displays $1/(1-K)$ against GN using the above experimental data, according to which the experimental data are suggestive of capturing both the nappe and skimming regimes, as well as the transition region in between these regimes. The emerging insight is that GN-values are relatively low for the nappe regime but high for the skimming regime, as follows: (i) the transition is at $GN \approx 0.02$ but it is not easy to delineate the width of the zone (this is discussed later in the discussion section); (ii) the nappe regime prevails when $GN < 0.02$, at which values relative energy dissipation ($\Delta E/E_0$) is variable and low (but high $1/(1-K)$); and (iii) the skimming regime is when $GN > 0.02$, at which range, relative energy dissipation is high (i.e. low $1/(1-K)$) but remain insensitive to varying GN-values. Also, the difference between energy dissipation in slopes 1:1 and 1:2 is little but significant not to be ignored. These are to be discussed later.

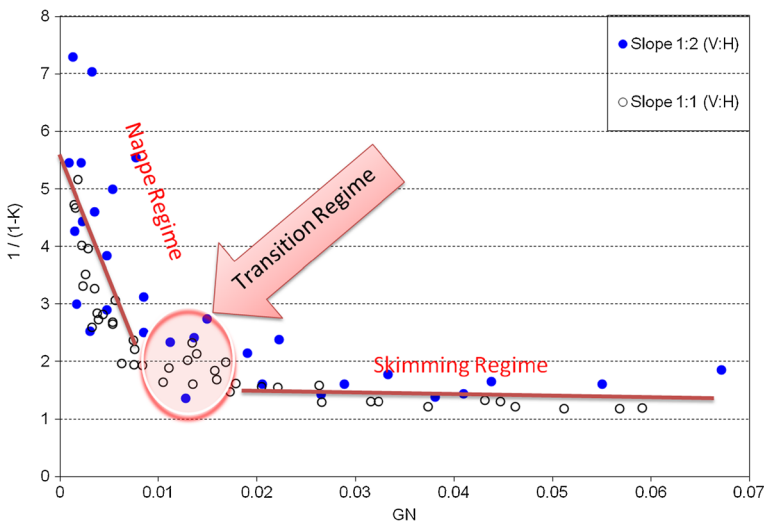


Fig. 2 Variation of Relative Energy Dissipation, $1/(1-K)$, against GN for Stepped-gabion weir – different slope and porosity

The above insight somewhat loses its clarity when the variation of relative energy dissipation is considered against F_{r1} and R_{e1} , as shown in Fig. 3, leading to the following salient points: (i) the test cases were all under the turbulent flow conditions and some were under subcritical condition but they were mostly supercritical; (ii) existence of nappe and skimming regimes are still visible but these are not sharp anymore; (iii) a greater scatter would be observed for datapoints above $F_{r1} > 3$ and $R_{e1} < 40,000$ under the skimming regime. This insight into the hydraulics of stepped-gabion weirs presented above conform to observations, although the regimes are not delineated rigorously but this is deemed acceptable for gaining an insight.

4.2 Regression Analysis

Multiple regression analysis was performed with different combinations of the dimensionless parameters in (2). Several linear and non-linear multiple regressions were conducted using the Statistical Package for Social Science (SPSS) software (SPSS, Version 17). The fitted equations are given by (3.a)–(3.e):

$$1/(1-K) = 0.417(GN)^{-0.359}(S)^{0.338} \quad R^2 = 0.732 \quad (3.a)$$

$$1/(1-K) = 0.312(n)^{0.079}(GN)^{-0.377} \quad R^2 = 0.683, \quad (3.b)$$

$$1/(1-K) = 0.001(S)^{0.302}(n)^{1.734}(GN)^{-0.346} \quad R^2 = 0.761, \quad (3.c)$$

$$1/(1-K) = 40.234(S)^{0.279}(n)^{-0.594}(GN)^{-0.188}(F_{r1})^{-1.254} \quad R^2 = 0.935 \quad (3.d)$$

$$1/(1-K) = 80670.763(S)^{0.298}(n)^{-0.479}(GN)^{0.109}(F_{r1})^{-1.279}(R_{e1})^{-0.611} \quad R^2 = 0.942 \quad (3.e)$$

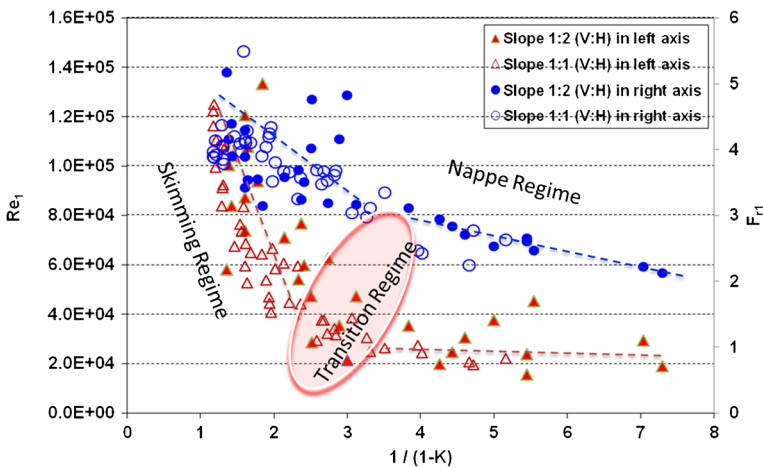


Fig. 3 Variation of F_{r1} and R_{e1} against $1/(1-K)$ for stepped-gabion weir – different slopes and porosity

The derived regression equations (3.a)–(3.e) provide ready tools for assessing energy dissipation across both nappe and skimming regimes, including the transition regime. In practice, even (3.a) can be helpful because it includes both weir geometry (slope and weir height, H_w) and weir hydraulics (discharge, q) as the designer can use it to calculate energy dissipation.

4.3 Artificial Intelligence Models

The challenge for modelling energy dissipation encompassing both nappe and skimming regimes is further taken by ANN and GEP, as the above regression equations show the room for improvement. The ANN model was implemented by identifying an optimal configuration by first fixing input layers to 5 neurons, with one neuron corresponding to each of the input parameters, and the output layer to one neuron. Further investigations included: (i) using various transfer functions; (ii) varying the number of neurons within hidden layer varied from 3 to 6 by using several configurations. Some of the results are given in Table 2, according to which ANN with one hidden layer was judged satisfactory. Thus, the architecture of 5-5-1 (input layer: 5 neurons, hidden layer: 1 layer with 5 neuron; output layer: 1 neuron) is selected for having minimum RMSE (a value of 0.024) and maximum, R^2 , (a value of 0.992) which is associated with *Hyperbolic secant* transfer function.

The GEP model was implemented by five options using different operators defined in Table 3, also showing the output results. Options 1–2 perform better than (3.a)–(3.d) in terms of R^2 (0.94 for Option 1) and RMSE (0.64 for Option 1). The equations derived by GEP are:

Option 1:

$$1/(1-K) = 910(n^{0.33})(S^{0.33})(F_r^{-1})(R_e^{-0.56}) \tag{4.a}$$

Option 2:

$$1/(1-K) = \frac{9.64 F_{r1}}{GN} - \frac{n^2}{R_{e1} - n^2} + \frac{11.91 + 5.95 S}{F_{r1}^2} + GN \frac{F_{r1}}{S} (F_{r1} - S) - n - S - F_{r1} \tag{4.b}$$

Both ANN and GEP models were trained and then employed to predict the data given in Table ESM.1. Their performances against their observed datapoints are given in Fig. 4. According to the figure, ANN is well capable of predicting the values of energy dissipation;

Table 2 Performance of Preliminary ANN Model

Transfer function	Hidden layers	Neurons/layer	Training		Test	
			RMSE	R^2	RMSE	R^2
Sigmoid	1	3	0.018	0.993	0.062	0.963
Gaussian	1	3	0.013	0.997	0.023	0.996
Hyperbolic, tanh(x)	1	3	0.014	0.996	0.046	0.972
Hyperbolic secant, sech(x)	1	3	0.012	0.997	0.027	0.991
Hyperbolic secant, sech(x)	1	4	0.010	0.998	0.015	0.999
Hyperbolic secant, sech(x)	1	5	0.005	0.9995	0.024	0.992
Hyperbolic secant, sech(x)	1	6	0.004	0.9996	0.028	0.991

Total datapoints are 74, of which 59 (80 %) are used for training and 15 (20 %) for testing

Table 3 Performance of the GEP model and their operators

Type	Operator	R ²	RMSE	
Option 1	{*,/}	0.93	0.64	See (4.a)
Option 2	{+, -, */}	0.94	0.49	See (4.b)
Option 3	{+, -, */, x}	0.66	1.35	Complex regression equations
Option 4	{+, -, */, x ² }	0.80	0.73	
Option 5	{+, -, */, Exp(x)}	0.89	0.55	
Option 6	{+, -, */, x, x ² , Exp(x)}	0.89	0.62	

whereas, the Option 1 of the GEP model performs as good as traditional regression equations suffering from undue errors, particularly at high values of energy dissipation values. The GEP model based on Options 2–6 resulted in a highly nonlinear relationship with some of unreported ones even performed better.

4.4 Comparison with Other Researchers

Figure 5 shows the experimental data reported by the present study using stone size of 25–38 mm and spillway slope of 1:1, 1:2 with the similar data reported by (i) Peyras et al. (1992) for a spillway slope of 1:1, 1:2, 1:3 and stone size of 30–45 mm; and (ii) Kells (1994) using stepped-gabion baskets with three steps, each with a height of 12.5 cm, an average porosity of 37.7 %, and two slopes of 1:1 and 1:2 (*V:H*). Figure 5 shows the data reported by Peyras et al. (1992) are likely to correspond to the skimming regime but such identification for the Kells (1994) data is not obvious. The figure shows a reasonable coincidence between the respective data.

5 Discussion

When the usual uniform dissipation of energy along natural riverbeds is hampered by embanking structures, the energy not dissipated is transformed into potential energy at the

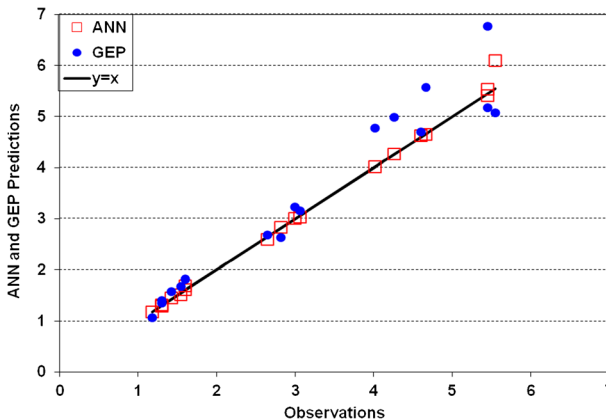


Fig. 4 Performance of ANN and GEP against observed datapoints

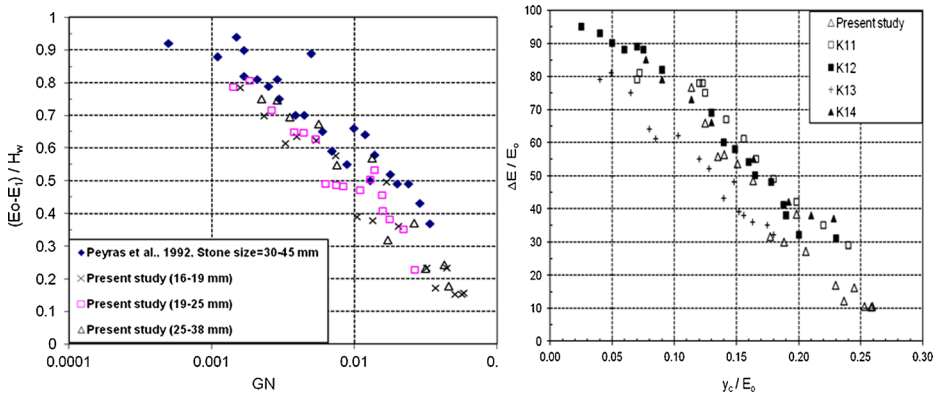


Fig. 5 Comparison of experimental data for a weir slope of 1:1 and 1:2 obtained in the present study with those of Peyras et al. (1992) and Kells (1994) - (K: Kell’s data points; K11: no barrier, no capping; K12: with barrier, no capping; K13: with barrier, with capping; and K14: no barrier, with capping)

upstream of the structures and this gives rise to the risk of erosion or scouring downstream of embankments. Said (2006), also discusses a program of impaired watercourses in Idaho State, USA, stemming from an imbalance of natural flows and in-stream and off-stream water uses in their study areas. Their study included a series of three gabion structures, which were installed to reduce successfully erosion at key points across an actively eroding meander section in the upper part of the watershed. As gabion weirs dissipate energy, their application aim to minimise erosion/scouring downstream of embankments and to maximise dissipated energy.

Dimensional analysis was used to conceptualise the hydraulics of energy dissipation through stepped-gabion weirs. The insight emerging from Fig. 2 is that stepped-gabion weirs are likely to have distinct nappe and skimming regimes with a transition zone at $GN = q^2 / gH_w^3 \approx 0.02$. Under the nappe regime, energy dissipation is likely to be insensitive to the design flow but energy dissipation is likely to be very sensitive to the conditions under the skimming regime. However, as per Fig. 3, increased energy dissipation is associated with high turbulence and supercritical flows and likely to encourage local scour/erosion. The regimes were delineated visually and this is deemed sufficient for gaining an insight into the problem. Further works are needed (i) to integrate knowledge on the subject; (ii) to identify the need for more experimental data; (iii) to assess the need for a quantitative delineation of the regimes; and (iv) to formulate a design procedure to maximise energy dissipation without encouraging scour/erosion.

The analysis of the experimental data was carried out by regression equations, ANN and GEP and their comparison by using scatter plots and error statistics, which reveals that both GEP model (4.a)–(4.b) and regression equations (3.a)–(3.b) have similar R^2 values, but the relationship derived by GEP needs management. Whilst (4.a) is parsimonious, (4.b) is complex and less revealing. A clear outcome of the study is that the ANN model performs generally better than both GEP and that better than the regression equations in terms of RMSE and R^2 . As the ANN model is trained by both regimes and their transition, it is likely to have captured the appropriate signal to cope with the two regimes; whereas the others are just regression equations and seemingly not at their best to capture the variability due to the regimes.

Formulating an ANN model, though not too difficult, takes time and expertise but sometimes engineering practices are in need of rough-and-ready estimates (i.e. first order estimates). For this,

regression equations can serve as a practical formula for calculating energy dissipation and even (3.a) can serve the purpose. A further improvement is offered by combining all the datapoints, as follows:

$$\left(\frac{E_0 - E_1}{E_w}\right) = 0.238(GN)^{-0.19}(S)^{0.175} \quad R^2 = 0.805 \quad (5)$$

The derivation of (5) involves the datapoints from the present study and those by Peyras et al. (1992), which improves R^2 from 0.732 to 0.805 but the datapoints reported by Kells (1994) could not be used, as their reported values of relative energy dissipation were in term of $\Delta E/E_0$.

6 Conclusion

This paper investigates the hydraulic problem of energy dissipation over stepped-gabion weirs by carrying out a series of laboratory experiments. It uses dimensional analysis to conceptualise the hydraulics of the problem and builds various models to explain the data. The robustness of the data is examined in the light of the data reported by other researchers. The paper applies Artificial Intelligence (AI) techniques to predict the energy dissipation, where the techniques selected are Artificial Neural Networks (ANN) and Gene Expression Programming (GEP) techniques. The ANN model was trained and used for prediction, with performance measures of R^2 and RMSE rendering the values of 0.992 and 0.024 respectively. The less successful GEP model and regression equations can still be used where rough-and-ready tools are needed. The models and equations are derived using the data from both the nappe and skimming regimes and therefore they should be robust.

The paper offers a set of experimental data encompassing both the nappe and skimming regimes and the transition in between them. The emerging insight is that these regimes can be delineated to aid the quantitative approaches to energy dissipation of stepped-gabion weirs of basket constructions. However, further works are needed to establish design procedures (i) to integrate knowledge on the subject; (ii) to identify the need for more experimental data; (iii) to assess the need for a quantitative delineation of the regimes; and (iv) to formulate a design procedure to maximise energy dissipation without encouraging scour/erosion.

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