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Stability of A-Jack concrete block armors protecting the riverbeds

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ABSTRACT

Flip buckets are among one of the most common types of energy dissipaters, especially for dams. The scouring phenomenon occurs when falling jets hit the river bed, and A-Jack concrete block armors can be used as an effective way to control such a phenomenon. The main purpose of this study is to investigate the stability of sediment particles using A-Jack concrete block armors. In this regard, the general form of the incipient motion and incipient failure of A-Jack armor were extracted based on dimensional analysis and particle stability analysis. In these analyses, the dimensionless parameter of stability number denoted by SN is a function of other variables. The results of different physical models for different hydraulic conditions and sediment sizes are evaluated. Variability of SN related to each variable is considered, and linear and non-linear models for prediction of breakage conditions of the A-Jack block are derived. Using the experimental results, several empirical relations were developed to predict the incipient motion and incipient failure for different protection alternatives under different conditions of A-Jack block. By defining the bed scour as a criterion for the stability of A-Jack block, a design relation was also proposed to determine the required block size. Other topics investigated and discussed in this paper include effects of size and type of A-jacks as well as criteria for a gravel filter.

1. Introduction

Energy dissipater structures in spillways are employed to dissipate kinetic energy for dam safety and protection. The excess water of dam reservoirs is drawn to the river downstream through a kinetic energy dissipation system. There are different methods to release floodwater from dams. One of the most common types is to release water as free jets to mix with air and subsequently dissipate its energy [1]. The main concern is to convey flood flow and falling jets to the downstream of the structure without scouring or with the least amount of scouring. In most of the large dams, a spillway is drawn to the downstream as free falling jets conveying a large amount of energy. Falling jets can wash the bed materials and make scour holes and may consequently lead to dam failure [2,3]. Regarding wide applications of flip buckets (ski-jump) in chute spillways of large dams (concrete dams and earth-fill dams), examination and designation of a protective system such as energy dissipater structures for downstream beds are of great importance and necessity [4].

Efficient designing of protective structures against erosion to minimize the scouring process is a critical issue. Generally, the protection plans of a river from a structural view are classified into two groups of direct and indirect methods. In direct protection methods, some structures are constructed on bed or banks of the rivers to protect the river bed and the river banks from erosion and to scour phenomena. Impermeable liners are recommended to facilitate water seepage in bed and to prevent fine particle movements [5-8]. Permeability of liners makes them a suitable proxy to increase the stability of the structure because they serve as a rigid body during floods. In general, flexible and permeable protective structures for direct methods are more suitable as they get naturally consolidated with the sediments. Some of these liners are gravel lining, concrete lining (mattress or single block), stone lining, asphalt, and vegetation liners [9,10]. In some areas,

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Notation

The following symbols are used in this article:

ACI	American Concrete Institute
AJ1-AJ5	Type of A-Jacks
b	jet thickness at the lip of the flip bucket (m)
C	generic coefficients
D	diameter of the pipe outlets (m)
D_{AJ}	equivalent diameters (mm)
d_s	particle diameter (mm)
g	gravitational acceleration (m/s^2)
H	falling height or water height in the reservoir from tail-water (m)
"if" subscripts	incipient failure (if) here is defined when the first displacement or movement of the A-jack armor is observed
Ls	horizontal distance from flip bucket to center of scour hole (m).
M_{AJ}	armor mass (kg)
P_L	penetration length (m)
q	discharge per unit width (m^2/s)
q_c	critical discharge per unit width for the failure threshold of A-Jack armors (m^2/s)
R	radius of flip bucket (m)
R^2	coefficient of determination
R_c	hydraulic radius (m)
S_s	the ratio of specific gravity of the sediment particle to the specific gravity of the fluid ρ_s/ρ_w
USBR	United States Bureau of Reclamation
V_b	jet velocity at the lip of the flip bucket (m/s)
μ	absolute viscosity of water (N.s/m^2)
ρ_s	density of the bed materials (kg/m^3)
ρ_w	water density (kg/m^3)
ρ_{AJ}	density of A-Jack armor (kg/m^3)
ϕ	angle of flip bucket
θ	angle of jet at entry point to downstream pool
υ	kinematic viscosity of water (m^2/s)

construction cost is drastically high due to the long distance from the rock resource to be brought to the site. Considering such problems, other materials as an alternative to rocks should be taken into consideration. Using armors or concrete liners designed and constructed in several shapes and dimensions can be an appropriate option. A-Jack armors are innovative armors for bed protection against erosion, where their application and performance in many hydraulic structures have been tested and confirmed [11-13]. Also, in literature, Palermo and Pagliara (2018) analyzed the effect on the maximum scour depth of the inflow conditions. This means the analysis was conducted in the presence of both stepped gabion weirs and rock sills [14].

In recent years, various ideas have been taken into consideration in the field of flip buckets. For example, in Wu et al. (2018), a type of circular-shaped flip bucket with a slot, called the slot-type flip bucket, is proposed [15]. In Li et al. (2019), the FLOW-3D computational fluids software (Khalifehei et al., 2018) was combined with experiments to simulate overflow over a flip bucket with dovetail slits under four working conditions [16-19]. It could be seen that when the discharge flow was large, the energy dissipation scheme of a dovetail-shaped slit could cause the water nappe to stretch fully along the river course. The outer edge of the water nappe, however, would be closer to the riverbank slope. Theingi et al. and Rebollo et al. (2019) focused on the experimental analysis of aeration in supercritical and fully turbulent flows. The boundary conditions and the large scale selected for the experimental process ensure the accuracy of the test. Obtained results show that aeration plays the main role in energy dissipation in open channel flows under these conditions [20-22]. Pagliara et al. (2019) indicated that the equilibrium sediment scours morphology is affected by the curvature of the canal, the tail-water depth, and the approaching flow conditions. In this studies, based on a detailed dimensional analysis, a useful empirical relationship was derived to estimate the sediment scour depth [23]. Changing some of the hydraulic parameters can reduce the scour in the relaxation basin by energy dissipation. AlTalib et al. (2019) indicated that energy dissipation increased at hydraulic jump forming downstream stepped weir when increasing the Froude number and hydraulic jump length [24].

A-Jacks concrete blocks, designed with six legs, come to an integrated unit by locking the bases together and are lower in weight than rip rap structures. On the other hand, roughness and features of the bases divide the jets into smaller parts, and more importantly, the roughness increases the shear force and energy dissipation. Meanwhile, the jets partially percolate in beds and elements which make bed scouring. Thus, the number of armor layers affects the process. Fig. 1 illustrates a sample of A-Jack armor layouts and its application in the river and hydraulic engineering.

In recent years, A-Jack armors have been used in marine structures, such as breakwaters, and for the coastal lining. Apart from their wide application in marine structures, their performance for erosion control for river banks has recently attracted the attention of many researchers (Thornton et al., 1999) [26]. Available hydraulic studies about A-Jacks are mainly related to their application in coastal protection, riverbanks, bridge piers, and bridge abutments. One of the most important studies was conducted by Breusers and Raudviki (1999) to investigate the torsion of elements under static vertical loads [27]. Stability of A-Jack armors against waves, the study of the applied forces and their physical and numerical simulations are among the other hydraulic studies which were carried out for six-legged elements and their applications in marine structures [27-31]. The two-step report conducted by the Soil and Water Conservation Bureau of the United States at Manly Hydraulics Laboratory (2003) can be cited as another study which compares six-legged armors with the other types of breakwaters experimentally [32,33]. Also, there are some reports about the application of this type of structure employed to control the scour depth around bridge piers in sandy beds. The results indicate a decrease in scours depth by 70 to 95 percent for a six-legged structure. It was recommended to employ such structures with geotextile filters or placing them in rocks [26]. Bejestan et al. (2017) showed that using A-Jacks armors can reduce the scour of trapezoidal crest up to 100% [34]. There are comprehensive studies carried out at Chamran University, applying six-legged components for bed lining of stilling basins. The results imply that appropriate settings of the elements can decrease the length of the stilling basin and the conjugated depth, and they can also decrease the scour depth at the downstream of the basin [35-38].

Considering the advantages of six-legged elements, such as the interlocked feature, the suitable weight, flexibility and efficiency, applicability for regions lacking enough rock resources, the possibility for vegetation growth, etc., it appears that the reported studies have rarely investigated their application for scouring control at downstream of dam basins like flip buckets. Therefore, in

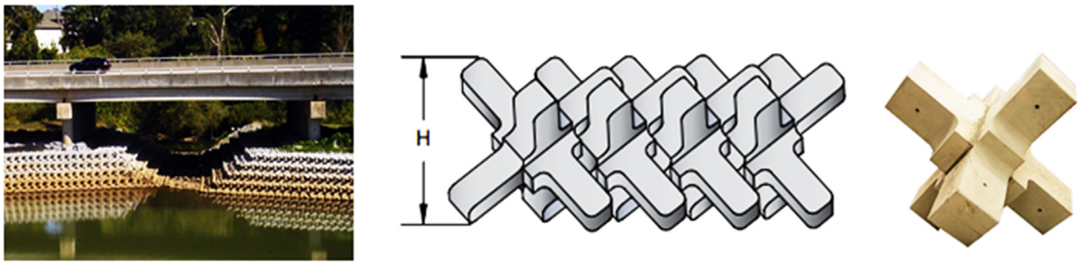

Fig. 1. An example of A-Jack armors with an interlocked system, and its application, (Source: Channel Lining and Pier Scour Design Manual, A-Jacks Armor Units [25]).

this study, the efficiency of the A-Jacks armors at downstream of flip buckets as a proxy to control the scouring phenomenon as a new subject with the possibility of wide applications in hydraulic engineering has been taken into consideration. The fact that so far no studies and research have been conducted to investigate this issue emphasizes the necessity of the present study conducted.

2. Theoretical approach

2.1. Particle stability

The particle stability analysis of a non-cohesive sediment in a scour defines equilibrium conditions between the particle weight and the hydrodynamic force generated by the diffused jet velocity [39-41]. A complete three-dimensional (3D) analysis of the forces and moments exerted on a single particle has been presented by Stevens and Simons (1971) [42]. When the incipient condition of uniform sediment in a streambed exceeds, the particles start to move. However, the entrainment development of a single particle in a non-uniform sediment bed is complex. The resistance to single particle motion is a function of shape, size and relative density of the particle. Schmidt and Gintz (1995) stated that Platy shaped particles have a lesser possibility to be entrained than more compacted sediments. In addition, resistance to particle movement is also affected by the exposure and hiding effects in non-uniform sediments [43,44].

2.2. Dimensional analysis

Fig. 2 presents a schematic layout of the research. Several variables for particle stability problem under flip bucket jets are effective including discharge per unit width (q), the density of the bed materials (ρ_s), water density ρ_w, particle diameter (d_s), viscosity (μ), penetration length (P_L), jet thickness (b), falling height (H) or water height in the reservoir from tailwater, radius of flip bucket (R), angle of flip bucket (ϕ) and angle of jet at entry point to downstream pool (θ). Thus, the expression can be written as Equation (1):

$$f(q, \rho_s, \rho_w, P_L, d_s, g, b, H, R, \theta, \phi, \mu) = 0 \tag{1}$$

Selecting three repetitive variables discharge per unit width(q), water density (ρ_w) and penetration length (P_L) and using Buckingham's theorem, the Equation (2) is obtained:

$$f\left(\frac{Vb}{\upsilon}, \frac{\rho_s}{\rho_w}, \frac{q}{\sqrt{gP_L^3}}, \frac{P_L}{d_s}, \frac{P_L}{H}, \frac{P_L}{R}, \frac{P_L}{b}\theta, \phi\right) = 0 \tag{2}$$

The driving force that causes movement and displacement of the particle is a combination of drag and lift forces. On the basis of the works of Einstein and E1-Samni (1949) and Gessler (1971), the following equation can be derived [45,46]: $\frac{V_b^2}{g(S_s-1)d_s} = C$.

Where S_s = the ratio of specific gravity of the sediment particle to the specific gravity of the fluid ρ_s/ρ_w; and C = a coefficient that has a constant value. For a given bed material, if the flow condition is such that C is larger than a critical value, the particles are in motion; for lower than the critical value, the bed is stable. The parameter on the left side of ($\frac{V_b^2}{g(S_s-1)d_s}$) is the same as the densimetric Froude number developed by Rajaratnam and Beltaos (1977) [36], mainly by dimensional reasoning. The same parameter was developed by Carstens (1966) and Mih and Kabir (1983) by taking the same procedure and was called a sediment number and an impingement number, respectively [47,48]. Since this study is more concerned with the A_Jacks stability and since it has been

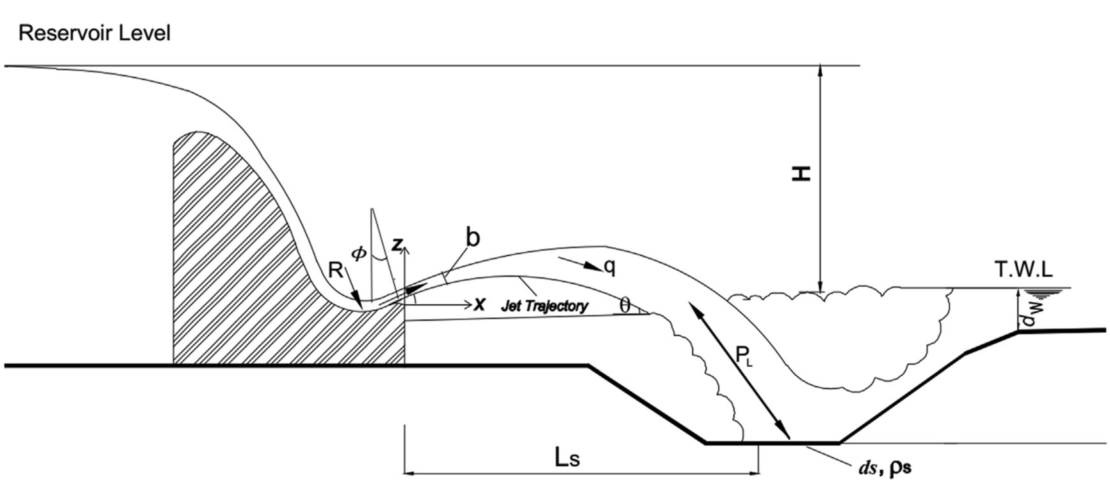

Fig. 2. Schematic of the jet on flip buckets and scouring hole at downstream of the stilling basin.

shown that the stability of A_Jacks is more likely to be a function of: $\frac{V_b}{\sqrt{g(S_s-1)d_s}} = Stability\ \ Number(SN)$.

The dimensionless variable of $\frac{V_b}{\sqrt{g(S_s-1)d_s}}$ is obtained from a combination of variables $\frac{\rho_s}{\rho_w}, \frac{q}{\sqrt{gP_L^3}}, \frac{P_L}{d_s},\ \ and\ \ \frac{P_L}{b}$, in which V represents the velocity of the jet. This velocity can refer to jet velocity in the bucket, or jet velocity when percolating downstream or jet velocity near the bed. The variable is considered as the particle Froude number if it has been written in the form of $\frac{V_b}{\sqrt{g(S_s-1)d_s}}$. This number has already been extracted using stability analysis of the sediment particles. The variable $\frac{V_b}{\upsilon}$ is the Reynolds number, which is not an effective parameter for this study because of the turbulent flow. The variables of $R, \theta,$ and ϕ have constant values for our cases, and they are ignored. Thus, the following function can be defined for the dimensionless variables (Equation (3)):

$$\frac{V_b}{\sqrt{g(S_s-1)d_s}} = f\left(\frac{q}{\sqrt{gP_L^3}}, \frac{P_L}{d_s}, \frac{P_L}{b}, \frac{P_L}{H}\right) \quad (3)$$

The stability number $\frac{V_b}{\sqrt{g(S_s-1)d_s}}$ denoted by SN can be considered as a function of dimensionless variables under special conditions of particle motion. In this research, these conditions are defined in two forms. First, the motion threshold condition, where A-Jack armors shake but still have no movement, and the second one is the damage threshold. In other words, it is the condition in which the first A-Jack armor and its materials move, and bed scouring is initiated.

The A-Jack armor design using Equation (3) requires estimation of V_b. On the other hand, applying the discharge per unit width for projectile place instead of V_b is easier in some conditions. Therefore, Equation (4) can be presented:

$$\frac{q_c}{b\sqrt{g(S_s-1)d_s}} = f\left(\frac{q_c}{\sqrt{gP_L^3}}, \frac{P_L}{d_s}, \frac{P_L}{b}, \frac{P_L}{H}\right) \quad (4)$$

Where q_c is the critical discharge per unit width for the failure threshold of A-Jack armors. It is noteworthy that in this study, the particle median diameter is considered as the particle size representative (d_s).

3. Materials and methods

To investigate damage threshold conditions and bed scouring initiation when A-Jack concrete blocks are used downstream of the flip buckets of dam spillways, a physical model has been designed and constructed (Fig. 3).

In this study, all the experiments have been conducted in a flume with a length of 7.5 m, a width of 0.56 m, a depth of 0.6 m, and a longitudinal slope of 0.0028. Under all conditions, the bed channel is rigid. The experiments were carried out at the hydraulic laboratory of Water and Energy Institute of Shahid Chamran University of Ahwaz in Iran. The lateral walls of this flat

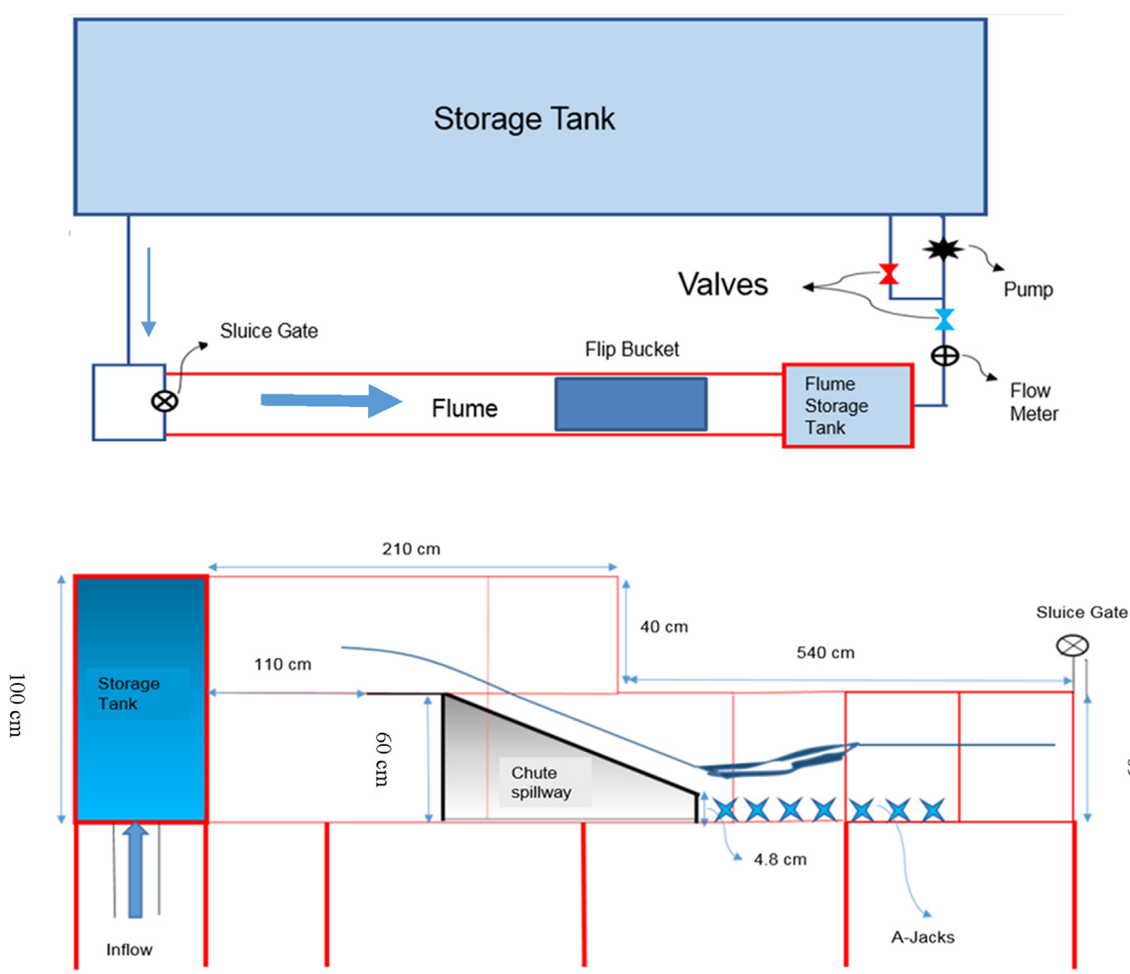

Fig. 3. Geometric and hydraulic characteristics of the physical model.

flume were made of clear plexiglass so that during the experiments, variation procedures could be recorded and monitored using the installed cameras and other measuring devices. At upstream of the flume, an ogee spillway connects the reservoir to a galvanized flip bucket with a radius of 0.16 m through a chute. The water is pumping from the source to the reservoir via a 6–inch-long steel pipe. Also, a 6-inch-long valve is installed on the pipe to control the flow. The spillway was designed according to the United States Bureau of Reclamation (USBR, 1976). The water level at downstream of the basin is controlled using a sliding gate. The water level downstream of the gate is increased in order to reduce the energy load on the gate. The flow discharge for this experimental model changes in a range between 5 and 20 L/s. Fig. 4 provides details of the physical model, experimental setup and the laboratory flume.

A-Jack armors are designed and constructed in 5 different types of names as AJ1-AJ5 with equivalent diameters of (D_{AJ}). The equation $D_{AJ} = \left(\frac{M_{AJ}}{\rho_{AJ}}\right)^{1/3}$ was used to compute equivalent diameters of the armors and is defined as the ratio of armor mass M_{AJ} to the density of A-Jack armor (Muttray and Reedijk 2009) [49]. The frames were designed using SolidWorks, and the designed template shell was constructed by a 3D printer so as to construct A-Jack concrete block armors. Afterwards, different samples of concrete blocks have been constructed using different mixing ratios of water, cement, sand, gravel and additional materials. Finally, a digital balance with an accuracy of 0.01 gr was employed to find the best concrete mixture according to standards of ACI 318-05 (ACI Committee, 2005) [50]. During the construction process, to block degradation, concrete dough was added to the vibrating frame when required. Moreover, all procedures were taken into consideration to cure the concrete accordingly. The geometric characteristics of the armors for protection of the flip bucket downstream, the schematic model, and the constructed sample for the physical model are presented in Fig. 5.

In the physical model, three types of non-uniform granular materials specified with names A, B, and C are used, and their particle size distribution curves are given in Fig. 6. The other characteristics of the bed materials are presented in Table 1, where σ_g is the geometric standard deviation and G_s is the specific weight of the particle.

A 15-to-20-centimeter thickness layer of bed materials with the mentioned characteristics of A, B, and C in the flume bed is placed underneath the materials. Its surface is smoothed with a trowel, and it is compressed to some extent. Then a layer of A-Jack concrete blocks is placed on the previous layer.

Slow flow is then maintained by closing the gate. The flume is filled with water until the tailwater depth in the basin increases to prevent the sudden motion of the bed particles. The control valve is used to set the desired discharge, and subsequently, the flow is running in the flume. The tailwater depth is gradually decreased when it is assured that the discharge is set accordingly. In this regard, the downstream gate is gradually and with time intervals opened, and after each decrease in the tailwater depth, the flow conditions are kept constant for a while, and the sediment particle motions are monitored. The decrease in the tailwater depth continues to reach the motion threshold and to observe the breaking of the threshold of particles. Simultaneously, with the damage of the liners, the bed materials are washed, and the flow in the flume becomes muddy. Water elevations for damage and motion thresholds are recorded, and with the aim of measuring the jet incident angle with the tail water, digital photos with high resolution are prepared from the experiments. These photos are transferred to the photo analysis software, and, with the software capabilities, the jet incident angle with the tailwater is measured. For practical applications, this angle is drawn from a tangent on the curve of the jet path or a trajectory on the tailwater.

4. Results and discussion

The important observation in all tests was the path of the jet through the tailwater. After entering the tailwater, the jet tended to follow a straight line inclined from the water surface to the

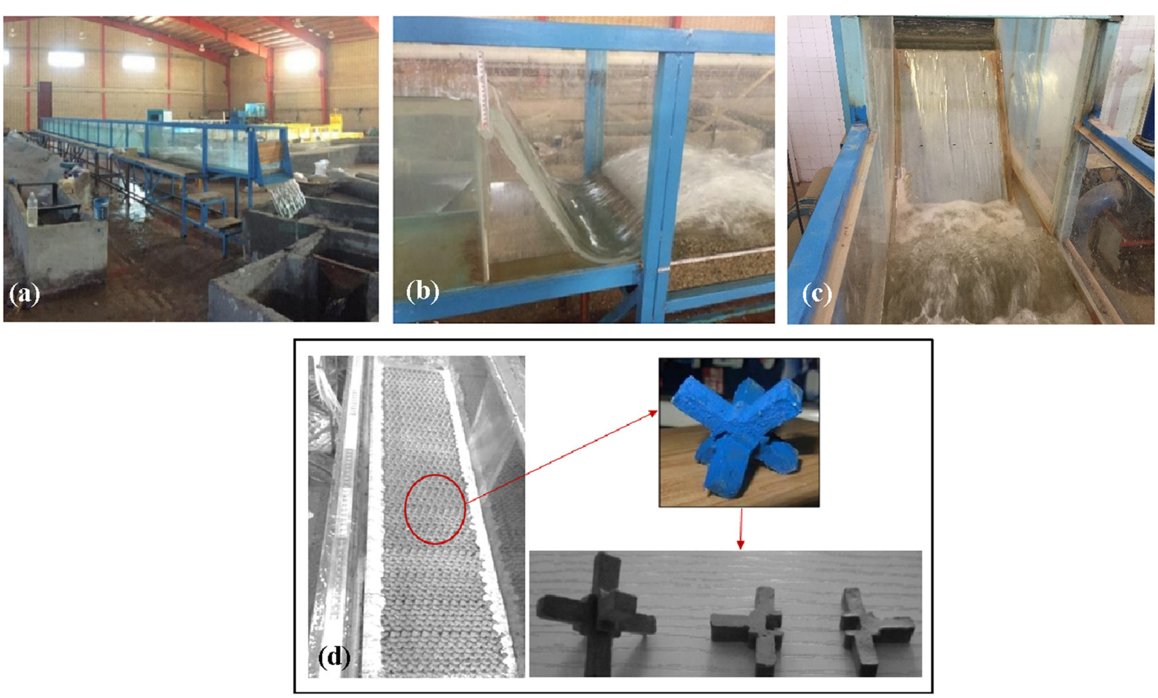

Fig. 4. Details of the physical model, experimental setup; (a) View of the experimental flume; (b) Physical model from the ogee spillway and flip bucket; (c) Physical model from the front view; (d) Placement of A-Jacks units for bed scour protection and A-Jack elements before and after connection.

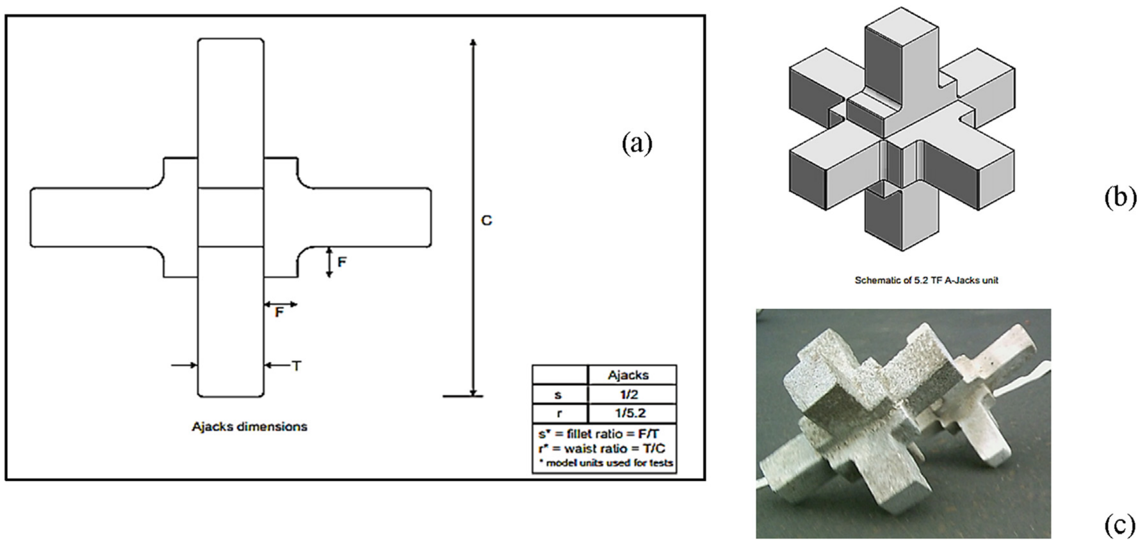

Fig. 5. (a) Geometric characteristics of the armors for protection of the flip bucket downstream, (b) the schematic model of A-Jack and (c) the constructed sample for the physical model.

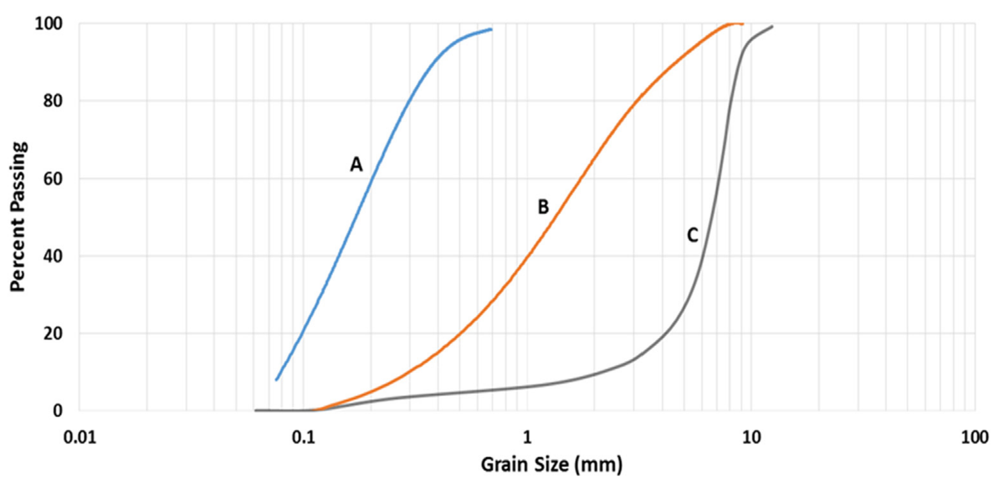

Fig. 6. Particle size distribution curves of erodible materials at downstream of the flip bucket in the physical model.

Table 1
Characteristics of the bed materials.

Material type	σ_g	$d_s(mm)$	S_s
Type A	1.97	0.18	2.73
Type B	2.95	1.5	2.74
Type C	1.45	7.5	2.62

σ_g : Geometric standard deviation (non-uniformity constant) of the bed material size $\sigma_g = \frac{D_{84}}{D_{16}}$.
S_s: Specific gravity.

bed surface with an angle of to the tailwater surface rather than the freefall trajectory that existed before entering the tailwater. This observation reveals that in the analysis of sediment movement below flip bucket, penetration length (the length of the path of the jet after it strikes the pool) should be used instead of the tailwater depth as it was in the past. This observation was also reported by Johnson (1974) but has not been used by others in the analysis of scour below a flip bucket. The main purpose of this study is to develop a A-Jacks armor sizing method to be used in protecting the riverbeds at the downstream area of dams. The theoretical analysis indicated that the criterion for the beginning of A-Jacks armor movement can be expressed in the form of (Eq. (4)). Such a relationship can be developed for both incipient motion and incipient failure of the A-Jacks armor as follows:

4.1. Scatter plots for dimensionless variables of $\frac{q}{\sqrt{gP_{Lif}^3}}, \frac{P_{Lif}}{d_s}, \frac{P_{Lif}}{b}$, and $\frac{P_{Lif}}{H_{if}}$ versus SN_{if}

The results of different experiments for several different conditions described in the previous sections are analyzed and presented in this section. The "if" subscripts are used in the parameters related to this section, which refers to incipient failure. Incipient failure (if) here is defined when the first displacement or movement of the A-jack armor is observed. Regarding the results obtained from the hydraulic model, the scatter plot of each dimensionless variable, including $\frac{q}{\sqrt{gP_{Lif}^3}}, \frac{P_{Lif}}{d_s}, \frac{P_{Lif}}{b}$, and $\frac{P_{Lif}}{H_{if}}$ versus SN_{if} (the stability number at damage time of concrete block armors), for different types of A-Jack concrete block are illustrated in Fig. 7. It is noticeable that for a specific type of AJ1 lining, no damage has happened for any experimental conditions. Therefore, the results are presented for AJ2- AJ5 types.

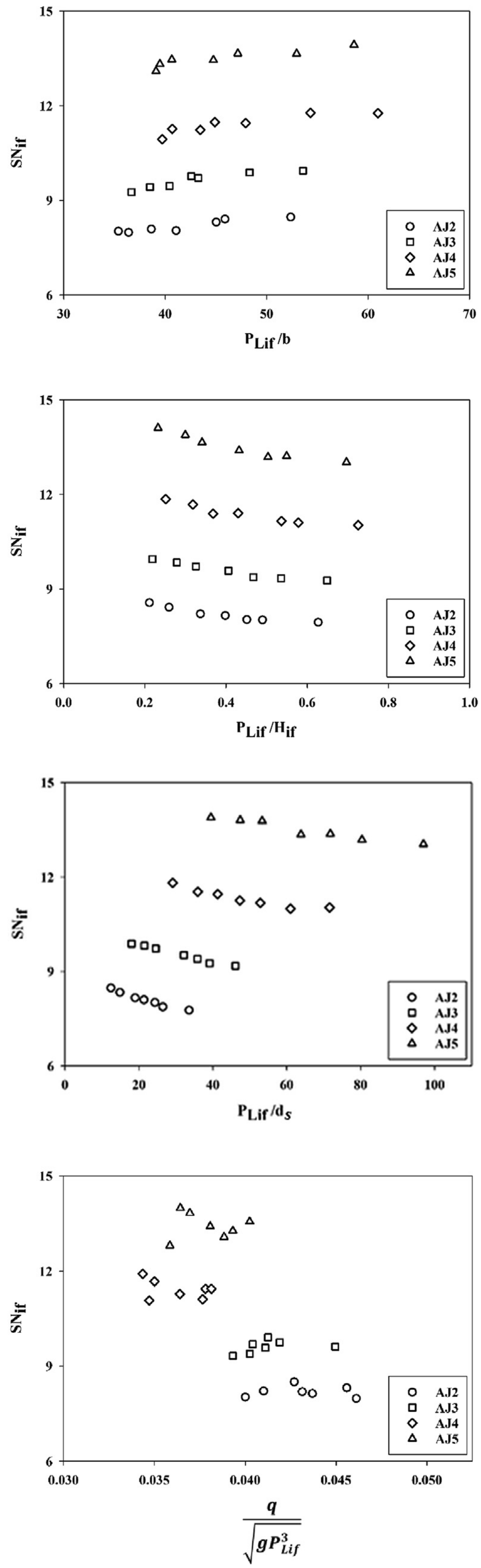

Fig. 7. Scatter plots of SNif versus dimensionless variables.

Figure (7) shows a scatter plot for two variables (SN_{if}) *vs*. $\left(\frac{q}{\sqrt{gP_{Lif}^3}}, \frac{P_{Lif}}{d_s}, \frac{P_{Lif}}{b}, \text{ and } \frac{P_{Lif}}{H_{if}}\right)$ that have a strongly linear relationship between them, also for variable ($\frac{q}{\sqrt{gP_{Lif}^3}}$), the scatter is slightly more. As can be seen in Fig. 7, the Stability Number (SN_{if}) is strictly dependent on the size of the A-Jacks armor. In all variables ($\frac{q}{\sqrt{gP_{Lif}^3}}, \frac{P_{Lif}}{d_s}, \frac{P_{Lif}}{b}$, and $\frac{P_{Lif}}{H_{if}}$), the change in the size of the A-Jacks armor changes the Stability Number (SN_{if}), indicating that the use of single variable models is not appropriate.

Moreover, the single variable models obtained for the variables do not cover effective parameters completely. In this regard, multivariate models are considered for SN prediction. Table 2 shows the correlation coefficient between SN_{if} and the other variables. The presented results in the table indicate an insignificant relationship between SN_{if} and the other variables.

4.2. Predicting models for damage condition of A-Jack armors based on the experimental results

To investigate damage condition for A-Jack protection based on the experimental results, different linear and non-linear regression models are analyzed in Sigmaplot statistical software. Among them, the following models are chosen due to their better fit (Equations (5) and (6)):

$$SN_{if} = 14.734 + 0.113\left(\frac{P_{Lif}}{d_s}\right) - 12.384\left(\frac{P_{Lif}}{H_{if}}\right) - 139.15\left(\frac{q}{\sqrt{gP_{Lif}^3}}\right) \quad R^2 = 0.941 \tag{5}$$

$$SN_{if} = 0.173 \times \left(\frac{P_{Lif}}{d_s}\right)^{0.316} \times \left(\frac{P_{Lif}}{b}\right)^{0.569} \quad R^2 = 0.937 \tag{6}$$

Results of the prediction models in Equations (5) and (6) against those of the experimental models are presented in Fig. 8. As it can be observed, both linear and non-linear models for prediction of damage conditions provide accurate results, and there is a good agreement with the results of the experimental models. With consideration of linear and nonlinear predicting models, it is obtained that these relationships use different variables. Using different variables in the linear model does not lead to suitable results when employed in a non-linear model. However, Equations (5) and (6) can be employed for designing these types of lining to illustrate damage conditions of A-Jack armors. These relationships are also useful to control and check the available structures so that the flow condition and the geometric characteristics of the projectile and sediment material satisfy Equations (5) and (6). The materials are subject to erosion. Therefore, coarser materials should be used, and further actions have to be taken into considerations to attenuate the damage.

4.3. The predicting model for the critical flow of a projectile for A-Jack linings in damage threshold

Regarding the abovementioned points, V_b can be substituted by discharge per unit width at the projectile location. In this case, different models using experimental data have been taken into account, and finally, the best model has been derived as Equation (7):

$$\frac{q_c}{b\sqrt{g(S_s - 1)d_s}} = 7.43 + 0.106\left(\frac{P_{Lif}}{d_s}\right) - 6.518\left(\frac{P_{Lif}}{H_{if}}\right) \quad R^2 = 0.932 \tag{7}$$

It was found that A-Jack cover will be damaged if the flow discharge in a projectile is of higher values than those of the computed flow discharge. Application of Equation (7) is also similar

Table 2
Correlation coefficients between SN_{if} and dimensionless variables.

Type A-Jack	Stability Number	$\frac{P_{Lif}}{b}$	$\frac{P_{Lif}}{d_s}$	$\frac{q}{\sqrt{gP_{Lif}^3}}$	$\frac{P_{Lif}}{H_{if}}$
AJ2	SN_{if}	0.96	0.94	0.78	0.92
AJ3	SN_{if}	0.94	0.97	0.88	0.95
AJ4	SN_{if}	0.96	0.98	0.62	0.98
AJ5	SN_{if}	0.98	0.97	0.57	0.96

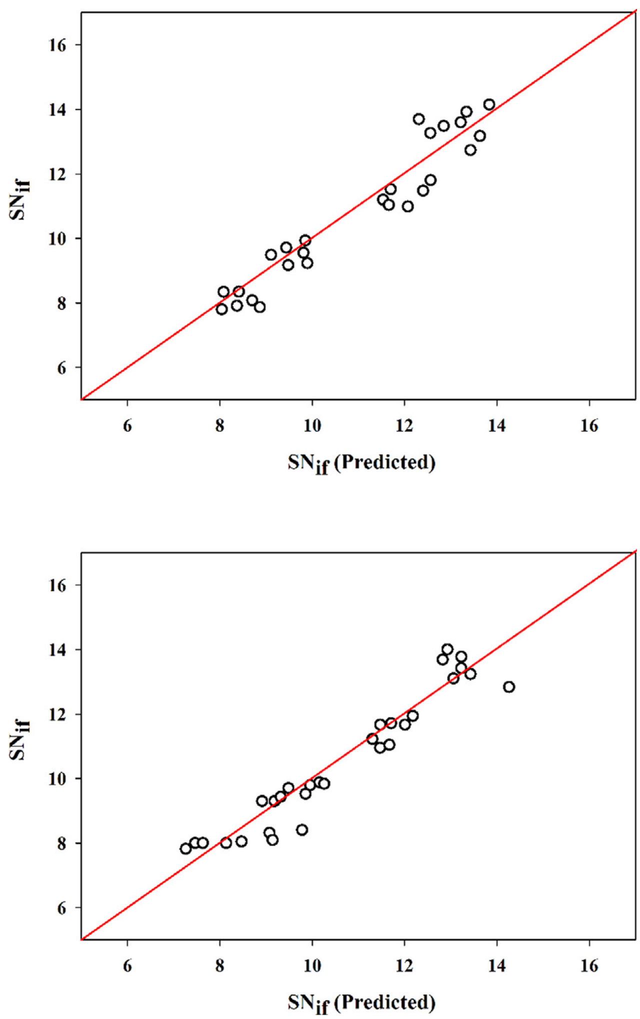

Fig. 8. Comparing linear and non-linear predicting models for damage conditions of A-Jack concrete block linings.

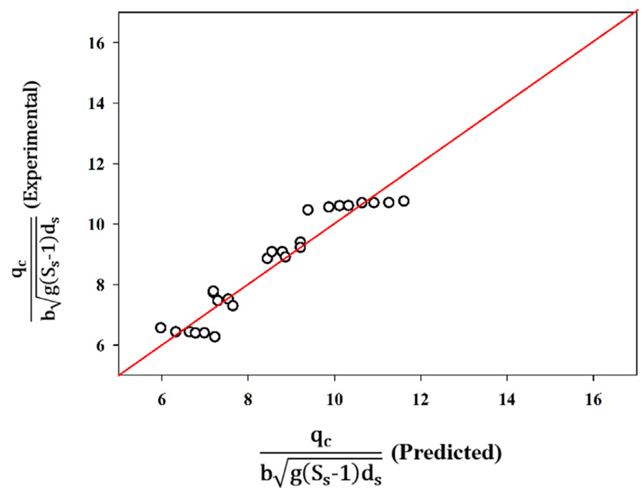

Fig. 9. Comparison between predicted critical discharges and experimental data.

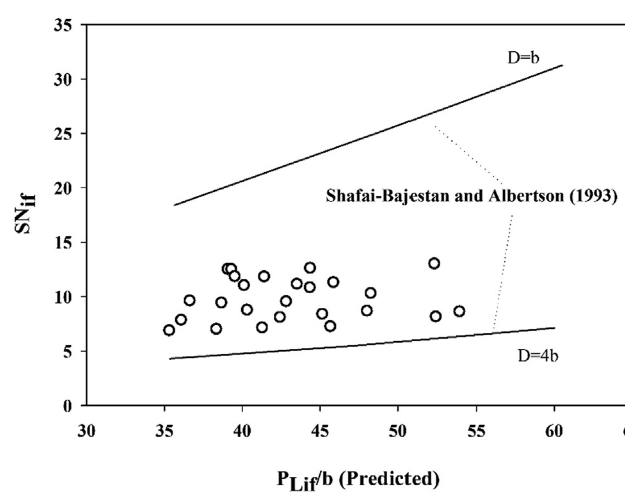

Fig. 10. Comparison between the results of the experimental model and those presented by Shafai-Bajestan and Albertson (1993).

to those of 5 and 6 with the difference that this equation can consider bed sediment materials and geometric conditions of a projectile to determine the maximum discharge per unit width of the projectile; while, if the discharge exceeds its value, bed materials are subject to erosion and A-Jack lining is required. Fig. 9 gives predictions of Equation (7) versus experimental observations.

In studies carried out by Shafai-Bajestan and Albertson (1993), Equation (8) for damage condition of riprap lining under circular jets is presented. It can be used to evaluate the performance of the equations in this study.

$$SN_{if} = 0.525\left(\frac{P_{Lif}}{D}\right) \quad R^2 = 0.82 \tag{8}$$

In studies Shafai-Bajestan and Albertson (1993) [36], parameter D is the diameter of the pipe outlets. Pipe outlets are used on many watershed-protection and flood-prevention dams. Fig. 10 illustrates the predicted results with Equation (8). The predictions are obtained from Equation (6), and $\frac{P_{Lif}}{b}$, as the geometric characteristic of the jet, is applied in Equation (8) instead of $\frac{P_{Lif}}{D}$.

As observed in both cases, the stability number is increased with an increase in $\frac{P_{Lif}}{b}$; however, the circular jets provide higher values of stability number, the fact which can reflect the difference in the geometric features of the jet applied for this research and also the substitution of parameter b for D. The hydraulic radius can be assumed equal to the flow depth since in spillways the depth is relatively small compared with the flow width. Because $D = 4R_c$ in open channels, where R_c is the hydraulic radius, D = 4b is assumed in Equation (8), which was depicted in Fig. 10.

Table 3
Values of $\frac{D_{(\text{A-Jack})}}{d_{85}(bed\ \ matrial)}$ and outlet materials for different combinations of A-Jack lining and bed materials.

A − Jack	Bed Material ($\frac{D_{(\text{A-Jack})}}{d_{85}(bed\ matrial)}$)			Description
	Type A	Type B	Type C	
AJ1	77 Bed materials exit	6.75 Bed materials exit	3.4 Bed materials exit	If the required size of A-Jacks is relatively large compared to the bed material size, more than one layer of filter may be needed. The thickness of each gravel-filter layer should be one-half that of the A-Jacks layer. For a graded A-Jacks in which the ratio $\left(\frac{D_{(\text{A-Jack})}}{d_{85}(bed\ matrial)}\right) < 2$, there is no need for a gravel filter. (yellow) No need for a gravel filter; (green) Need for a gravel filter; (blue) More than one layer of filter.
AJ2	57 Bed materials exit	5 Bed materials exit	2.5 Bed materials exit	
AJ3	36 Bed materials exit	3.1 Bed materials exit	1.6 Bed materials do not exit	
AJ4	28 Bed materials exit	3.1 Bed materials exit	1.3 Bed materials do not exit	
AJ5	18 Bed materials exit	1.57 Bed materials do not exit	0.78 Bed materials do not exit	

The illustration reveals that the experimental results are between the two cases mentioned above.

4.4. A qualitative investigation of the performance of A-Jack linings after damage

In this study, the experiments have been continued with lower water depth to have a qualitative evaluation of A-Jack linings. Further release of bed materials and the motion of A-Jack elements due to greater energy expand the downstream hill. The hill is a mixture of bed materials and A-Jack unit, which indicates better resistance against motion and washing compared to the concrete block with no cover or lining. Subsequently, it can help control the scouring phenomenon. Therefore, the role of A-Jack lining in scouring after the damage is still important. Also, it is effective for stabilizing the downstream hill, increasing the tailwater depth, and dissipating energy. By increasing the flow discharge, the jet collision is shifted downstream, where the jet is crashing the hill. As the hills are a mixture of fine bed materials and coarse materials of concrete blocks, they have more resistance against scouring. Thus, fewer materials are transported downstream, and less erosion is expected when compared to the case of no lining. This condition is maintained for real applications when a flood with a large discharge varying in time is running.

4.5. Presentation of A-Jack lining plan for bed materials without scouring

According to the content mentioned in the previous section, the size of A-Jack lining has usually been designed much larger than the bed materials. Therefore, A-Jack lining may remain stable at its place, but finer materials run away from A-Jack lining due to its porosity, causing erosion holes and damage over the lining. It is necessary to use a filter layer with a specific size distribution of materials to fill the space between the two layers in order to prevent such a problem. For this purpose, separate experiments have been conducted in this study.

Values of $\frac{D_{(\text{A-Jack})}}{d_{85}(bed\ \ matrial)}$ for different combinations have been computed and presented in Table 3. Here, $D_{(\text{A-Jack})}$ means the granulation materials place' underneath the A-Jack lining. Considering the numbers in the table, the criterion $\frac{D_{(\text{A-Jack})}}{d_{85}(bed\ \ matrial)} \leq 2$ is met for designing A-Jack lining without bed material scouring. The criterion is the same for circular jets (Shafai-Bajestan and Albertson 1993).

Comparing with open channels in which the criterion for them is less than 5, it is concluded that A-Jack lining dimensions under jets should be closer to the dimensions of the materials in the layer beneath so that if the ration of dimensions is greater than 2, it is essential to determine the dimensions of the middle layer considering this criterion. This issue can be addressed as A-Jack lining is divided into smaller pieces due to jet collision. These secondary jets have the power to pass from the porosity of A-Jack unit, reach the bed materials, and affect them. Consequently, the bed materials move from their place and leave A-Jack lining pieces. Compared with open channels, in which they flow over the materials, here the decomposed forces of the jet are imposed in different directions to bed materials. These forces can make the materials unstable and move them from their place.

5. Conclusions

One of the common ways of dissipating the excess kinetic energy at downstream of dam spillways is the use of flip-buckets. Usually, a scour hole is created on the river bed at the point of jet impingement, which may cause damage to the structures. A-Jack armor can be used to stabilize the river bed. The main purpose of this study is to develop design criteria for A-Jack armors. To reach such a goal, first, general relations were developed at the point of the incipient motion and failure condition for A-Jack armors. These relations were developed based on the stability criteria of A-Jack armors using dimensional analysis. Then extensive experimental tests were conducted in a physical flume. Five different sizes of A-Jack armors were tested under different flow conditions. The best fit relations were developed and presented by analyzing many linear and non-linear equations. Other tests were also conducted to establish the filter criteria, which must be placed beneath A-Jack armors to prevent escaping of fine materials. Main findings of this study can be expressed as follows:

- Particle motion under jets is a function of the ratio expressing total active forces on total resistant forces (SN). If this ratio exceeds the limitation, the particles are in motion.
- Stability number (SN) is investigated as a function of dimensionless variables, including normalized flow discharge ($\frac{q_c}{\sqrt{gP_L^3}}$), normalized penetration length ($\frac{P_L}{d_s}, \frac{P_L}{b}, \frac{P_L}{H}$). Flow intensity, jet thickness, and falling height are effective in available energy for motion, and the particle size affects the resistance against motion.

- The univariate model is not suitable for predicting the damage condition because it does not cover effective parameters completely. Multivariate linear and nonlinear models showed great capability for predicting the damage condition of A-Jack lining pieces.
- To investigate the damage condition for A-Jack protection based on the experimental results, different linear and non-linear regression models are analyzed in Sigmaplot statistical software. Among them, two models ($SN_{if} = 14.734 + 0.113\left(\frac{P_{Lif}}{d_s}\right) - 12.384\left(\frac{P_{Lif}}{H_{if}}\right) - 139.15\left(\frac{q}{\sqrt{gP_{Lif}^3}}\right)$) and ($SN_{if} = 0.173\times\left(\frac{P_{Lif}}{d_s}\right)^{0.316}\times\left(\frac{P_{Lif}}{b}\right)^{0.569}$) have been introduced with the best regression coefficients of $R^2 = 0.941$ *and* $R^2 = 0.937$, respectively.
- According to the linear model for predicting critical discharge in a projectile, if the flow in a projectile exceeds the computed critical flow, A-Jack lining damage will occur.
- Investigation of A-Jack part settlement due to bed materials exit from A-Jack lining leads to the criterion $\frac{d_{(A-Jack)}}{d_{85}(bed\ \ material)} \leq 2$ for bed materials near A-Jack unit lining.
- The performance of A-Jack linings in controlling scouring does not end when it has been damaged, and its secondary role of stabilizing the downstream hill, increasing the tailwater depth and energy dissipation, decreasing the scouring range, and decreasing the sediment transport downstream will be still remarkable.

Author contributions

G.A. is the article supervisor; K.K. designed and carried out the experimental analysis; M.S. edited the manuscript; and all authors read and approved the final manuscript.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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