Block ramps for stream power attenuation in gravel-bed streams: a review
Rakesh Kumar Chaudhary, Nayan Sharma and Zulfequar Ahmad

ABSTRACT
Application of block ramp technique in steep gradient streams for energy dissipation as well as to maintain river stability finds increasing favor amongst researchers and practitioners in river engineering. This paper dwells on a comprehensive state-of-the-art review of flow resistance, energy dissipation, flow characteristics, stability, and drag force on block ramp by various investigators in the past. The forms and equations for each type are thoroughly discussed with the objective of finding the grey areas and gaps. While, more research is warranted further to improve the equations, essential for design analysis. Block ramps can be a promising simple technique to achieve reasonable attenuation of devastating fluvial forces unleashed in gravel-bed streams during cloud bursts.

Key words | block ramp, drag force, energy dissipation, flow resistance, stability

HIGHLIGHTS
- It discussed on critical review of recent advancement in flow resistance, energy dissipation, stability and drag forces on block ramps.
- Highlights on the grey area and gaps.
- The major research gaps are on 3D turbulence study.
- Flow characteristics.
- Formulation of block ramp are based on steady flow assumption but in reality flows are highly turbulent with unsteady flow in mountain streams.

INTRODUCTION
Block ramp is a short section of steep channel, produces large scale roughness in form of boulder which allows passing flow from a higher elevation to lower elevation by dissipating energy (Aberle & Smart 2003; Pagliara & Chiavaccini 2006a; Ahmad et al. 2009). It is used in mountain rivers and are made of blocks having mean diameters ranging between 0.3 m and 1.5 m, disposed on a steep bed. Block ramps can serve very best in the restoration of rivers and maintain the ecological balance of river system as well as attenuate stream power.

It serves as corridors for fish migration by creating favorable flow velocity (Weibel & Peter 2013; Tamagni et al. 2014a, 2014b). It attenuates shear velocity and turbulent bursts adjacent to bed which prevents large boulder movement during flood. Moreover, protruding boulders provide suitable conditions for oviposition also.

Flow resistance, flow velocity and water depth can be estimated using flow resistance Equations which have been proposed by many investigators in terms of Manning’s n and Darcy-Weisbach friction factor f (Hey 1979; Griffiths 1985; Jarret 1984; Bathurst 1985; Abt et al. 1988; Rice et al. 1988; Ferro 1999). Aberle & Smart (2003) studied the effect of roughness on flow resistance on steep slopes. They found that standard deviation of bed elevation is more appropriate parameter for bed roughness than characteristics gran size of bed and used this parameter in flow
resistance equation. Similarly, Habibzadeh & Omid (2009) studied the bed load resistance in supercritical flow and found that bed load transport increases friction factors by 90 and 60% in smooth and rough bed respectively. Pagliara & Chiavaccini (2006a, 2006b, 2006c) proposed flow resistance and energy dissipation Equations for block ramps.

Similarly, stability of block ramp has been investigated by different investigators (Whittaker & Jäggi 1986; Robinson et al. 1995; Weichert 2006; Pagliara 2007a; Tamagni et al. 2008; Pagliara & Palermo 2011; Weitbrecht et al. 2017). Their findings are discussed in subsequent topics on stability of block ramp. Study on scour at the toe of the block ramp and its protection have been done by Pagliara & Hager 2004; Pagliara 2007b; Pagliara & Palermo 2006; Oertel & Schlenkhoff 2012b. They have developed empirical formula for estimation of maximum scour depth and maximum scour length for uniform and non-uniform sand. Moreover, they found that rock sill performed better than other types of sills for scour minimization. Besides this sediment transport over block ramp has also effect on bed morphology and energy dissipation which was later investigated by Pagliara et al. (2009a, 2009b).

It is very much effective for dissipating energy downstream of trench weir, overflow weir, spillway etc. due to large roughness. Ghare et al. (2010) proposed mathematical model for computation of size of base material of block ramps which is correlated with step chute height ratio. Similarly, Pagliara et al. (2019) found that equilibrium scour morphology is affected by channel bends, tail water depth and approach flow conditions. Increase in channel curvature increases scour depth and rise in tail water depth decreases scour depth. They also developed empirical equation for estimation of maximum scour depth in curve channel. Artur et al. (2018) measured the hydrodynamic parameters of flood impacted unstructured block ramp in prototype and found that displaced boulder due to flood functions well as before occurrence of flood.

**CLASSIFICATION OF BLOCK RAMP**

Depending on the morphological structure and configuration of macro roughness elements, block ramps are classified into two groups, i.e., type A (block carpet) and type B (block cluster). Type A consists of tightly packed blocks covering the entire width of the river. It may be one layer or more than one layer. One layer of blocks interlocked with each other leading to a compact form called as interlocked block ramp. When blocks are arranged in two or more than two layers leading to heavier and more heterogeneous construction then such block ramp is known as dumped blocks. With both types of block ramps, a filter layer should be provided against washout effects (DWA 2010). Block carpet can be provided up to slope S = 10% (Bezzola 2010). However, they are investigated up to bed slope S = 40% slope (Robinson et al. 1995). Type B is characterized by dispersed configuration leading to more natural condition. In this, blocks are either arranged in row and arches (systematic way) or randomly placed. It consists of three types of block ramps. They are Structured blocks, Unstructured blocks and self-structured blocks. Structured and unstructured blocks are isolated with each other. Structured blocks are characterized by systematic arrangements of blocks in row or staggered form and blocks are isolated with each other leading to more heterogeneous form. The maximum slope for structured block ramp is 6.7% (LUBW 2006) and maximum slope for unstructured block ramp (UBR) is 3% (Janisch 2007). Self-structured blocks ramps get formed due to natural hydraulic load occurring on the ramp after long time. The ramp slope ranges for self-structured block ramp is 5% to 13% (Lange 2007). The morphological and structural classification of block ramp is shown in Figure 1.

**FLOW RESISTANCE**

Knowledge of mean velocity is of primary importance in river engineering. Flow velocity can be directly measured by using velocity measuring instrument or using continuity Equation \( Q = UA \) for known discharge and cross-sectional area of flow. But velocity measurement is a tedious task and always not possible. So, there is a need of flow resistance Equation from which velocity can be determined by knowing other parameters such as flow depth, equivalent roughness height etc. Flow resistance Equation can be easily applied to any river reach of uniform section without calibration. The most commonly used flow resistance equation.
Equations are, The Chezy, the Manning’s and the Darcy’s Weisbach Equation and are as follows.

\[ U = C \sqrt{RS} = \frac{1}{n} R^{2/3} S^{1/2} = \sqrt{\frac{8gRS}{f}} \]  

(1)

where, \( U \) = Mean flow velocity, \( Q \) = flow rate (L\(^3\)/S), \( C \) = Chezy coefficient (L\(^{1/2}\)/S\(^{-1}\)), \( n \) = Mannings rugosity coefficient (L\(^{-1/3}\)/S\(^{-1}\)), \( f \) = Dimensionless Darcy Weisbach friction factor, \( S \) = slope of energy grade line and \( R \) = hydraulic radius (for narrow channel) and some times depth of flow \( h \) is used for wide channel instead of \( R \).

Several studies have been done to derive general Equation for flow resistance in terms of Darcy Weisbach dimensionless friction factor \( f \). Keulegan (1938) had derived a general form of flow resistance Equation for rough boundary channels by integrating the Prandtl-karman-Nikuradse logarithmic mean velocity profile Equation in the following form:

\[ \sqrt{\frac{8}{f}} = \frac{U}{u^*} = \frac{1}{k} \ln \frac{h}{k_s} + 6.25, \]  

(2)

where \( u^* \) is shear velocity = \( \sqrt{ghS} \), Keulegan (1938) proposed \( k_s \) by using it equivalent to median diameter (D\(_{50}\)). Several expressions have been given for values of \( k_s \) such as \( k_s = cD_x \) (where, \( 1 < c < 8 \)). Subscript \( x \) denotes percentage finer of \( D \). Weichert (1939) presented different definitions of \( k_s \) according to different studies. Bezzola (2010) suggested \( k_s = 2D_{90} \) for flat natural river bed without bed forms. In boulder stream, the irregular bed topography makes difficult to measure actual representative flow depth (\( h \)) and also \( D_{90} \) or \( k_s \) does not represent actual characteristic grain size. So, keeping this view, Aberle (2000) developed flow resistance Equation in terms of discharge and used \( \sigma_b \) as standard deviation of bed elevation rather than flow depth (\( h \)) and \( D_{90} \) as characteristic grain size. The equation suggested by Aberle (2000) is as follow,

\[ U = 0.81(\sin \alpha)^{0.18} q^{0.5}n_s^{-0.5} \left( \frac{1}{\sigma_b} \right)^{0.5} \left( \frac{1}{3n_a} \right). \]  

(3)

where \( n_a = 0.87(\sin \alpha)^{0.09} \) and \( \sin \alpha = \) bed slope, \( q = \) specific discharge, \( g = \) acceleration due gravity.

Whatever approach used to derive flow resistance Equation, It is found that flow resistance equation is more reliable on type of flow condition for which depth of flow

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Figure 1 | Morphological and structural classification of block ramps (adapted after Tamagni et al. 2008).
or hydraulic radius is larger compared to bed roughness. Bathurst et al. (1981) defined roughness in to three categories and proposed to classify flow according to relative flow depth. The large scale roughness \( h/D_{84} \leq 1.2 \) in which free surface gets affected by roughness features, intermediate scale roughness \( 1.2 < h/D_{84} \leq 4 \) and small scale roughness \( h/D_{84} < 4 \). They found that flow resistance increases as relative submergence decreases and vice versa. Various forms of expressions for relative submergence such as \( h/d_{84}, h/d_{50}, h_{\text{mean}}/D_b \) etc. have been used in flow resistance equations by different investigators. It is difficult to model flow resistance for large and intermediate scale roughness since flow turbulence gets strongly affected by relatively large roughness and hence Equation (2) derived from law of wall is not valid more. It is valid for steep mountain river with step pool morphology and flow on block ramp is somehow similar to it. Therefore, the above approach have to be applied with caution.

There is another approach for the determination of flow resistance for UBR in which flow resistance is divided in two parts. First part resistance is offered by the roughness of bed material and second part is that of form drag, developed due to macro roughness element. Whittaker et al. (1988) used this approach to find flow resistance for UBR.

So, the flow resistance is given by the superposition of the two elements (Einstein & Banks 1950; Weichert 2007). With Chezy coefficients,

\[
C'' = \frac{U}{\sqrt{gR S'}} = 2.5 \ln \frac{12 R}{K''}
\]  

(4)

It is the flow resistance due to the bed material, i.e. bed roughness \( S' = \) slope of grain friction, \( K' = \) equivalent sand roughness for the bed material; and

\[
C'' = \frac{U}{\sqrt{gRS''}} = 2.5 \ln \frac{12 R}{K''}
\]  

(5)

For the flow resistance due to macro roughness element such as boulders, \( S' = \) slope of form friction, \( K'' = N_{b} D^5 (17.8, 0.47 \ h/D) = \) equivalent sand roughness for macro roughness element; the flow resistance can be calculated with

\[
C'' = \frac{1}{C^2} + \frac{1}{C'^2}
\]  

(6)

Thus, both the block diameter \( D \) and number of blocks \( N_b \) is considered. The application range is limited to \( 0.1\% < S < 5\% \), \( 0.5 < h/d < 4 \), and \( N_b D^2 < 0.15 \) per unit area. Whittaker et al., \(^{52}\) showed that submergence \( h/D \) has major influence on flow resistance.

In most of studies the influence of large scale roughness on flow resistance have been done but lacked the quantification of increase in flow resistance due to large roughness element. So, Pagliara & Chiavaccini (2006c) did experimental study on flow resistance of block ramps with protruding boulders placed in random and row arrangement. They combined friction factor \( f \) for rock chutes in base condition and increase in friction factor \( f_1 \) due to protruding boulders to get total friction factor and obtained following relation as,

\[
\sqrt{\frac{8}{f_{tot}}} = \frac{U}{\sqrt{(ghS)}} = 3.5 (1 + \Gamma)^5 S^{0.17} (h/d_{84})^{0.1}
\]  

(7)

or,

\[
\sqrt{\frac{8}{f_{tot}}} = \frac{C}{\sqrt{g}} = 3.5 (1 + \Gamma)^5 S^{0.17} (h/d_{84})^{0.1}
\]

where, \( U = C \sqrt{hS} \) (Chezys Equation) also the total Manning’s coefficient \( n_{tot} \),

\[
n_{tot} = 0.064 (1 + \Gamma) c \times (d_{50} S) 0.11
\]  

(8)

where, block concentration \( \Gamma = \frac{N_{b} \pi D^2}{4 WL} \), in which, \( N_b = \) number of blocks, \( D = \) block diameter, \( L = \) ramp length. Valid for range \( 0.8 < F < 2.9, 0 < \Gamma < 0.3 \) and \( 0.6 < h/d_{84} < 2.6 \). where \( F \) and \( h/d_{84} \) are Froude number and submergence ratio, respectively. \( c \) and \( e \) are coefficient derived from experimental measurements and observed data, whose values are listed in Table 2. Equation (7) obtained by Pagliara & Chiavaccini (2006c) for flow resistance estimation of block ramp with protruding boulders, considers the effect of slope as well as new term boulder concentration \( \Gamma \). This equation shows that Chezy coefficient can be expressed as a decreasing monotonic
function of the boulder concentration. It is in contrast with findings of author (Rouse 1995; Wohl & Ikeda 1998). According to Wohl & Ikeda (1998) study, it is reasonable that Chezy coefficient decreases with boulder concentration up to a certain range and then increases with boulder concentration for given geometrical and hydraulic conditions. Hence, Equation (7) is not valid for larger value of block concentration ($\Gamma > 30\% - 35\%$). Figure 2(b) depicts the range of validity and variation of chezy coefficient, $C$ with block concentration $\Gamma$. It follows previous research findings and valid up to range $\Gamma = 0.3$.

Equation (7) proposed by Pagliara & Chiavaccini (2006c) used $d_{84}$ of bed material in relative submergence ($h/d_{84}$) instead of considering protruding boulder mean diameter. The protruding boulders creates additional resistance to flow. So, it over estimates mean flow velocity on block ramp. Later on Weitbrecht et al. (2017) considered protruding boulder protrusion $P$ in Equation (7) and finally, they proposed the following relation.

$$\sqrt{\frac{8}{H_{tot}}} = \frac{U}{\sqrt{ghS}} = 1.9(1 + \Gamma)^{-0.5}S^{-0.21}(h/P)^{0.29}$$

Valid for $h/p < 3.5$, $0.15 < \Gamma < 0.25$.

The flow resistance Equation (9) is valid for a minimal range of block concentration, so it is necessary to find out a more generalized form of flow resistance equation that covers a larger range of block concentration. Several studies on finding the optimal value of block concentration $\Gamma$ have been done to achieve maximum flow resistance (Schlichting 1956; Loughlin & MacDonald 1964). Thus, one can determine flow resistance, flow velocities and flow depth using one of the standard flow resistance equations discussed below.

Some of the widely used flow resistance equations for block ramp is briefly presented in Table 1 with their application range.

### ENERGY DISSIPATION ON BLOCK RAMPS

The energy head at the ramp head is $H_1 = H + 1.5 h_c$, where $1.5 h_c$ is the specific energy at a critical depth (at the head of a ramp), and at toe is $H_2 = h + q^2/(2gh^2)$, specific energy at toe. So, the relative energy dissipation is given as $\Delta H_r = \Delta H/H_0 = H_1 - H_2/H_1$. Pagliara & Chiavaccini (2006a) studied the energy dissipation mechanism on smooth and ramp with a base material. They first studied on a smooth ramp and then on-ramp with blocks.

A smooth ramp is highly representative as chute in terms of hydraulic characteristics of flow. Chanson (1994) suggested the energy dissipation relation between inlet and

![Figure 2](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2020.339/787884/ws2020339.pdf)

**Figure 2** (a) Relationship between $\Gamma$ and $\alpha$ for given $e = (D_{25}/d_{50})$ values (Ferro 1999) and (b) Chezy coefficient $C$ as a function of macroroughness concentration $\Gamma$ for a transverse row disposition of macroroughness.
The toe of a smooth ramp chute as,

$$\Delta H_t = 1 - \left( \frac{h_u \cos \theta + h_c}{1.5h_c + H} \right)$$  \hspace{1cm} (15)

where $\Delta H_t$ is relative energy dissipation, $h_u$ = uniform flow depth at toe of ramp and $h_c$ = critical flow depth at the inlet as shown in Figure 3. Pagliara & Chiavaccini (2006a) suggested a relationship for smooth and ramp with base material as blocks in terms of Darcy-Weisbach friction factor $f$.

$$\Delta H_r = \frac{\Delta H}{H_1} = \frac{H_1 - H_2}{H_1} = [A + (1 - A)e^{(B + CS)(hc/H)}]$$  \hspace{1cm} (17)

A, B, C = Coefficients depending on the roughness scale ($hc/d_{50}$) and E, F = function of arrangement and roughness of blocks $hc$ = critical flow depth $d_{50}$ = median size of river bed material, $H$ = ramp height and $S$ = ramp slope.

Pagliara & Chiavaccini (2006a) found that the relative energy dissipation ($\Delta H_r$) increases with decrease in $hc/H$ for same discharge, same slope and same length of ramp. Thus, the height of the ramp is directly proportional to relative energy dissipation. Similarly, roughness of bed also has a significant effect on relative energy dissipation. Large scale roughness (LR) dissipates more energy than small scale roughness (SR) whereas intermediate scale roughness (IR) presents greater variability. It is shown in Figure 4(a), they...
also found that relative energy dissipation decreases with an increase in slope keeping roughness constant. So, Energy dissipation is also a function of the slope of ramp. Figure 4(b) shows relative energy dissipation as a function of $h_c/H$ obtained by various investigators.

Pagliara & Chiavaccini (2006b) extended the energy dissipation mechanism to structured and unstructured block ramps, and proposed a relation same as Equation (17) in which block concentration $\Gamma$ was introduced.

$$\Delta H_{rb} = \frac{\Delta H}{H_1} = \frac{H_1 - H_2}{H_1} = \left[A + (1 - A)e^{B + CS}(h_c/H)\right]\left(1 + \frac{\Gamma}{E + F1}\right)$$

$$\Gamma = \frac{N_B\pi D^2}{4WL},$$

where, $N_B$ = number of blocks, $D =$ block diameter, $W =$ ramp width and $L =$ ramp length. It can be
used for ramps without boulders by substituting $\Gamma = 0$. Here $E$ and $F$ are two parameters that are functions of arrangement and roughness of blocks which are given in Tables 3 and 4. Equation (18) is valid for $\Gamma < 0.33$; $0.08 < S < 0.33$; $1.75 < D/d_{50} < 19$ and for uniform flow condition.

Figure 5 depicts that rows arrangement of boulders dissipates more energy than random arrangement and it is higher for rough boulders than smooth (rounded) boulders. Rouse (1965) suggested optimum block concentration $\Gamma = 0.26$ using spheres. But for lower value of $\Gamma$, the maximum value of relative roughness and form drag doesn’t get achieved and whereas a higher value of $\Gamma$ leads to affect flow characteristics by single block to other neighbouring blocks so, flow separation cannot develop fully leading to reduced energy dissipation. Thus, at optimum value of block concentration $\Gamma$, each block offers maximum form drag to flow resistance.

Later on, Ahmad et al. (2009) found that the energy dissipation in staggered arrangement of boulder on ramp is higher than the random or row arrangement of boulders. They proposed a relationship based on extensive experimentation on staggered arrangement of hemispherical boulder on ramp. These values were validated with the experimental observations of authors within $\pm 5\%$ error line. Adopting the roughness parameter $E = 0.6$ and $F = 7.9 \left( \frac{D_b}{h_c} \right)^{0.9}$, keeping the original form of equation same as suggested by Pagliara & Chiavaccini (2006b)

\[
\frac{\Delta H}{H_1} = \frac{H_1 - H_2}{H_1} = \left[ A + (1 - A)e^{(B+CS)(h_c/H)} \right] 
\times \left( 1 + \frac{\Gamma}{0.6 + 7.9 \left( \frac{D_b}{h_c} \right)^{0.9}} \right)
\]

(19)

In this Equation $\Gamma$ varies from 0.074 to 0.21 and $D_b/h_c$ from 0.506 to 2.307

Though the Equation (19) proposed by Ahmad et al. (2009) is the outcome of the staggered arrangement of hemispherical boulder on ramp, but in nature, we mostly get irregular shape of boulder. So, further research can be extended on block ramp having irregular natural shape of boulder in staggered arrangement.

### Table 3 | Values of $A$, $B$, and $C$ for different roughness condition and ranges of $h_c/d_{50}$

<table>
<thead>
<tr>
<th>Roughness condition</th>
<th>$h_c/d_{50}$</th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large scale roughness</td>
<td>$h_c/d_{50} &lt; 2.5$</td>
<td>0.33</td>
<td>-1.3</td>
<td>-14.5</td>
</tr>
<tr>
<td>Intermediate scale roughness</td>
<td>$2.5 &lt; h_c/d_{50} &lt; 6.6$</td>
<td>0.25</td>
<td>-1.2</td>
<td>-12.0</td>
</tr>
<tr>
<td>Small scale roughness</td>
<td>$6.6 &lt; h_c/d_{50} &lt; 42$</td>
<td>0.15</td>
<td>-1.0</td>
<td>-11.5</td>
</tr>
<tr>
<td>Smooth ramp</td>
<td>$h_c/d_{50} &gt; 42$</td>
<td>0.02</td>
<td>-0.9</td>
<td>-25.0</td>
</tr>
</tbody>
</table>

### Table 4 | Values of $E$ and $F$ for different arrangement and roughness of boulder

<table>
<thead>
<tr>
<th>Arrangement and roughness of boulder</th>
<th>$E$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random disposition and rounded boulders (River stones)</td>
<td>0.6</td>
<td>13.3</td>
</tr>
<tr>
<td>Row disposition and rounded boulders</td>
<td>0.55</td>
<td>10.5</td>
</tr>
<tr>
<td>Random disposition and crushed boulder (Quarry stones)</td>
<td>0.55</td>
<td>9.1</td>
</tr>
<tr>
<td>Row disposition and crushed boulders</td>
<td>0.4</td>
<td>7.7</td>
</tr>
</tbody>
</table>

### Table 5 | Values of coefficient $a_1$, $a_2$, and $a_3$ for different values of $\Gamma$

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17–0.19</td>
<td>0.110</td>
<td>0.053</td>
<td>0.064</td>
</tr>
<tr>
<td>0.20–0.21</td>
<td>0.020</td>
<td>0.834</td>
<td>0.352</td>
</tr>
<tr>
<td>0.22–0.24</td>
<td>0.051</td>
<td>0.323</td>
<td>0.207</td>
</tr>
<tr>
<td>0.25–0.26</td>
<td>0.074</td>
<td>0.173</td>
<td>0.140</td>
</tr>
<tr>
<td>0.27–0.30</td>
<td>0.012</td>
<td>1.616</td>
<td>0.530</td>
</tr>
</tbody>
</table>
Similarly, Oertel & Schlenkhoff (2012a, 2012b) proposed Equation for energy dissipation for structured block ramp with crossbar as,

$$\frac{\Delta H}{H_1} = \frac{H_1 - H_2}{H_1} = a_1 + (1 - a_1)e \left[ \frac{h_c}{H} \right]$$

(20)

where, $a_1 = 0.17 - 0.0017/S$, $a_2 = -0.7 + 0.0073/S$, $a_3 = -4.9 - 0.26/S$. Equation (20) is valid for tested data range as of Equation (14).

Later on, Romeji et al. (2020) developed a generalized Equation for uniform and non uniform staggered arrangement of boulder block ramp based on experimental work as given by Equation (21).

$$\Delta E_r = L_R a_2 e^{\left( \frac{a_3 + \Gamma \left( \frac{h_c}{H} \right)}{H} \right)}$$

(21)

where, $L_R$ is length of ramp, $a_1$, $a_2$, $a_3$ are coefficient whose values are tabulated below and rest of all are same as discussed above. The above Equation is applicable for $\Gamma = 0.17 - 0.30$ and $0.05 < h_c/H < 0.29$.

For submerged flow condition, Pagliara et al. (2008) developed an Equation for energy dissipation on submerged block ramps and they identified the main parameters on which energy dissipation on block ramps in submerged condition depends.

They are $h_c/H$, ramp scale roughness and the ramp submergence condition. The effect of ramp slope can be considered negligible for relative energy dissipation for same scale roughness and ramp submergence condition ($L_j/L_R$) as shown in Figure 6.

$$\Delta H_{r2} = A + (1 - A)e^{B(h_c/H)}$$

(22)

Which is valid for range: $0 < L_j/L_R < 0.7$, $0.1 < h_c/H < 1.2$; ramp slope varying between $1 V:8H$ and $1 V:4H$ and roughness condition SR, IR and LR. The expression of coefficients of A and B are given in Table 6.

The equation proposed by Pagliara et al. (2008) for block ramp in submerged flow condition considers $h_c/H$ as main parameters in energy dissipation equation but when the flow is fully submerged, the parameters $h_c/H$ doesn’t clearly reflects the hydrodynamics of submerged flow. Instead of $h_c/H$ term, it would be better to use $h/d_84$ or $h/P$. So, further
research is needed for improvement of energy dissipation equation in submerged flow condition.

The details of the experimental setup and parameters used by various investigators in the past have been summarized in Table 7.

**FLOW CHARACTERISTICS**

Block ramp offers high resistance as a result of form drag, wake vortices, local hydraulic jump, and jetting flow between each block. Flow over block ramp or rock chutes shows two types of flow, such as nappe flow and Skimming flow. Nappe flow occurs for small discharge. In this, flow cascades over a boulder in a series of falls plunges from one boulder to another boulder in a thin layer that clings to the surface of each boulder and dissipates the energy of flowing water by breaking of a jet in air or jet impinging on a boulder, mixing of flow and by partial hydraulic jump. Skimming flow occurs at high discharge. In skimming flow, the water flows down the boulder surface as a coherent stream, skimming over the boulder edge and cushioned by the recirculating fluid trapped between them.

*Ahmad et al. (2013)* investigated the turbulence characteristics of flow over block carpet type block ramp. The findings from their research are as follows:

(a) Turbulent intensity and Reynolds stress distribution: Longitudinal Turbulence intensity $I_{T_{L}}$ increases first and then becomes constant after a certain distance. At the leading edge of the block ramp, the boundary layer was thin, and generated turbulence intensity was confined in it. This is due to the fact that initially, the thickness of the boundary layer was thin, and then it increased along downstream and became constant up to flow depth. So, turbulence intensity also increases along downstream of block ramp and becomes constant (*Ahmad et al. 2013*). Similar results were also obtained by Balachandar & Patel (2002) who studied development of boundary layer on roughened flat plate. However, transverse turbulent intensity decreases and then attains constant value after a certain distance downstream of the block ramp, and vertical turbulence intensity $I_{T_{V}}$ decreases gradually downstream, as shown in Figure 7(a). It might be due to the breaking of larger eddies into smaller eddies, which dampens the turbulence intensity $I_{T_{V}}$ production.

Similarly, *Ahmad et al. (2013)* found that Reynolds stress components $u'u'$ and $u'w'$ increases first and then attain an equilibrium value, whereas $v'w'$ increases linearly along the block ramp Figure 7(b) depicts it clearly. Also, turbulent Kinetic energy increases along the length of the block ramp linearly.

Flow characteristics of unstructured or structured block ramp is far more complex than other type. For this, Tamagni *et al. (2014a, 2014b)* carried out extensive experimentation on flow characteristics of unstructured block ramps under steady conditions for three different specific discharges with relative submergence such that $h < p$ (where $p$ is block protrusion.) i.e. blocks emerged, $h \approx p$ i.e., blocks just submerged and $h > p$ i.e.blocks fully submerged. They divided flow into different sublayers as suggested by Nikora *et al. (2001)* which is shown in Figure 8. Here they divided flow layers in to two major sub layers for small value of submergence $h/p < 1.5$ and impermeable bed layer. They are form induced sublayer and interfacial sublayer. The interfacial sublayer further consist of two sublayers where flow gets affected by macroroughness elements and lower sedimentary sublayer. The all layers thickness are denoted by $z$ with different subscripts. Here, $z_m$ is the mean bed level obtained by averaging the measured bed elevations without considering block protrusions, $\sigma_b$ is the standard deviation of measured bed elevations, $2 \sigma_b$ is the thickness of sedimentary sublayer, $z_c$, the zero plane defined as $z = z_m - \sigma_b$ and $Z_{MR}$, the boundary between macroroughness sublayer and sedimentary sublayer $Z_{MR} = z_m + \sigma_b$. Similarly, $z_c$ is the average of crest height of all blocks from which we get the thickness of macro roughness sublayer and $z_c$ defined as lowest trough level of bed.

The data were analyzed both with time-averaged and double averaged (in time and space) velocities, using measured Reynolds stress, form induced stress, and RMS values. From their study, they found that there exists a wide range of velocities variation regions, which is favorable for fish migration. On just lee side of block, time average local velocity is negative due to recirculation of flow. Similarly, just upstream and above the block, there is supercritical flow region having accelerated flow and also there is small velocity range because the accelerated overtopping flow does not occur over each block for $h_m/p = 0.6$. It also shows that flow velocity between two blocks...
**Table 7** A brief summary of the experimental setup and range of parameters used by various investigators

<table>
<thead>
<tr>
<th>Author</th>
<th>Type of block ramp</th>
<th>Flume Dimension (m)</th>
<th>Slope(s)</th>
<th>Block dia (mm)</th>
<th>Base material</th>
<th>F</th>
<th>σ, Cu</th>
<th>Q (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pagliara &amp; Chiavaccini (2006a)</td>
<td>Interlocked blocks (Type A)</td>
<td>3.5 0.25 0.3 1 V:4H-1 V:12H</td>
<td>......</td>
<td>1.0 2.0 10.0 20.0 88.0</td>
<td>Base material</td>
<td>1.4-4.3</td>
<td>1.2-1.5</td>
<td>0.001-0.025 for Flume 1, 2, 0.006-0.1 for Flume 3</td>
</tr>
<tr>
<td>Pagliara &amp; Chiavaccini (2006b)</td>
<td>Reinforced block ramp</td>
<td>3.5 0.25 0.3 0.08-0.33 29, 38, 42</td>
<td>2, 3.5, 12.3, 16.5, 21.7</td>
<td>0.95-3.9</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td></td>
</tr>
<tr>
<td>Pagliara et al. (2008)</td>
<td>Submerged block ramp</td>
<td>3.5 0.25 0.3 1 V:4H-1 V: 8H</td>
<td>......</td>
<td>1.0 2.0 10.0 20.0</td>
<td>Base material</td>
<td>1.1-1.3</td>
<td>(Cu)</td>
<td>0.002-0.008</td>
</tr>
<tr>
<td>Ahmad et al. (2009)</td>
<td>Block ramp with staggered boulder</td>
<td>4.12 0.3 … 1 V:4H</td>
<td>55, 65, 100</td>
<td>20</td>
<td>…</td>
<td>…</td>
<td>0.077-0.0297</td>
<td></td>
</tr>
<tr>
<td>Oertel &amp; Schlenkhoff (2012a, 2012b)</td>
<td>Cross bar block ramp</td>
<td>6 0.8 … 1 V:30H</td>
<td>60</td>
<td>2</td>
<td>…</td>
<td>…</td>
<td>0.001-0.05</td>
<td></td>
</tr>
<tr>
<td>Tamgani et al. (2014)</td>
<td>Unstructured block ramp</td>
<td>8 0.4 0.7 0.04 65</td>
<td>4.3</td>
<td>…</td>
<td>3.2 (σ)</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weitbrecht et al. (2017)</td>
<td>Unstructured block ramp</td>
<td>13.5 0.6 0.6 0.05 45, 57, 65</td>
<td>1.5 (FM) 3.1 (UM-FM) 4.3 (CM) 8.5 (UM-CM)</td>
<td>1.1-3.3 (σ)</td>
<td>…</td>
<td>…</td>
<td>0.00018-0.084</td>
<td></td>
</tr>
<tr>
<td>Romej et al. (2020)</td>
<td>Uniform and non uniform staggered boulder</td>
<td>4.0 0.3 0.45 1 V:5H-1 V:7H-1 V:9H</td>
<td>42-100</td>
<td>16-25</td>
<td>…</td>
<td>…</td>
<td>0.0073-0.0387</td>
<td></td>
</tr>
</tbody>
</table>
along ramp length is positive unless it gets retarded by downstream blocks. In this way there exists strong heterogeneous distributions of a wide range of local velocities. As larger the variation in local velocities, more will be possibilities of certain fish to find suitable conditions for migration of fish with respect to swimming capacity.

Over all the local time-averaged velocities are heterogeneously distributed on unstructured block ramp which leads to vary turbulence intensities heterogeneously. Zones that have high TI corresponds to two kinds of regions.

(i) The region having high-velocity variation, are directly influenced by blocks and where recirculation of flow occurs in the lee side of protruding boulder.

(ii) Those adjacent to the flow corridor with accelerated velocity.

Figure 7 | (a) Variations of longitudinal u', transverse v' and vertical w' turbulence intensity along length of ramp (Ahmad et al. 2013) (b) Variation of Reynolds Stress along length of block ramp (Ahmad et al. 2013).

Figure 8 | Proposed flow sub-divisions suggested by Tamagni et al. (2014a, 2014b) for lower submergence ratio and impermeable bed layer based on guidelines of Nikora et al. (2001).
So, there is variability in both turbulence intensity as well as time averaged velocity which is positive in terms of hydraulic heterogeneity and ecological aspects.

Though the time-averaged velocity were found to be heterogeneously distributed throughout the length of the ramp but the double averaged (averaged both in time and space) velocity $\bar{u}$ profile is found to be almost uniform distribution as shown in Figure 9.

For lower relative submergence, flow mainly occurs below boulder crest where the flow is influenced by form drag within the interfacial sublayer (macro roughness layer). Similarly, near bed level flow is dominated by form and viscous drag (sedimentary sublayer). The entire water column is affected by total roughness of bed material and boulder and due to this reason double averaged vertical velocity profile is uniform at higher relative submergence $h_m/p = 1.5$, it strongly varies and it tends to S-shape velocity profile similar to Bathurst (1985); Ferro (1999) and Baiamonte & Ferro (1997). Tamagni et al. (2014) compared S-shape vertical velocity profile distribution results with those of Ghisalberti & Nepf (2006) which is similar to their result as shown in Figure 9.

Similarly, They calculated normalized spatially averaged Reynolds shear stress, given as $\frac{-\bar{u'}w'}{u_I}$, where $u_I = (-\bar{u'}u_{max})^{0.5}$ in which $u'$, $w'$ are fluctuating components of instantaneous velocity $u$, $w$. Figure 10 shows comparison of vertical profile of spatially averaged Reynolds shear stress by Tamagni et al. (2014a, 2014b) and Ghisalberti & Nepf (2006) for $h_m/p = 1.5$ which has triangular shape with its maximum value at $Z \approx 0.83$ just below $Z_c$ at which the maximum momentum exchange occurs due to the maximum interaction between fluid at the form induced sublayer and the macro roughness sublayer. The shape of both profiles is similar. Similarly study on flow characteristics of staggered arrangement of boulder on rock ramp fish pass in relation to fish passage was done by Baki et al. (2014).

**BLOCK RAMP STABILITY**

Stability is another important aspect of block ramp for its proper functionality. It must withstand design flood discharge. Thus, it is important to estimate discharge at which block just fails and such discharge is known as critical discharge, usually expressed as critical specific discharge $q_{cr}$. A block resting on river bed remains stable unless until shear stress imposed by flowing water exceeds tractive shear stress of block. So, a critical flow parameter must be known. Generally, Shields (1936) method is used to estimate critical flow parameters, i.e. Shields dimensionless critical shear stress and dimensionless Reynolds number. But the Shields approach is valid for nearly horizontal bed in which component of gravity can be neglected. Chiew & Parker (1994) proposed a relationship for estimation of critical shear stress in streamwise bed slope by considering all the hydrodynamic forces (drag, lift,
buyout and gravity force) acting on sediment particle resting on streamwise bed slope given by,

$$\frac{\tau_{cw}}{\tau_{co}} = \cos \theta \left(1 + \frac{\tan \theta}{\tan \phi}\right)$$  \hspace{1cm} (23)

where, $\tau_{cw}$ is the critical shear stress on the sloping bed of angle $\theta$, $\tau_{co}$ = critical shear stress on horizontal bed and $\phi$ is friction angle of sediment. However, mountain stream is characterized by low value of relative submergence and steep bed slope of large scale roughness. So, Shields approach is not suitable for mountain streams. Later on Aguirre-Pe & Fuentes (1991) put forth their concept that critical shear stress doesn’t represent the condition for initiation of sediment motion in steep macro-roughness stream ($S \geq 0.005$ and $h/d \leq 10$). Aguirre-Pe et al. (2005) suggested a relationship for sediment entrainment in terms of critical particle densimetric Froude number given as,

$$F_{dc} = 0.9 + 0.5 \ln \frac{h}{D_{50}} + 1.3 \frac{d_{50}}{h}$$  \hspace{1cm} (24)

Which is valid for $0.02 < S < 0.065$ ; $0.02 < h/d_{50} < 30$.

But for field engineers it would be worth to express failure criteria in terms of critical specific design discharge rather than critical particle densimetric Froude number.

Whittaker & Jäggi (1986) investigated stability of block carpet type block ramp with different block diameter, bed material, characteristics grain size, bed slope and different ramp length.

They suggested a relationship between critical specific discharge $q_{cr}$, bed slope $S$ and block diameter $D_{65}$ for the determination of stability of block ramps of block carpet (type A) with dumped blocks.

$$q_{cr} = \frac{0.257}{S^{7/6}} \sqrt{g(G - 1)D_{65}^3}$$  \hspace{1cm} (25)

where $S$ = bed slope, $G$ = specific gravity of block $= \frac{\rho_s}{\rho_w} = 2.65$ and $D_{65}$ = block diameter for which 65% of mixture is finer, $\rho_s$ is density of block and $\rho_w$ is density of water.

Hartung and Scheuerlein, suggested a relationship for block ramp type A with interlocked blocks in terms of critical velocity $u_{cr}$:

$$u_{cr} = 1.2 \sqrt{2g(G - 1)D_B \cos \alpha}$$  \hspace{1cm} (26)

where $u_{cr}$ = critical flow velocity, $D_B$ = equivalent block diameter and other terms are same as defined above.

$$D_B = \sqrt{\frac{6m_B}{\pi \rho_s}}$$  \hspace{1cm} (27)

where $m_B$ = mass of block, $D_B = 1.06 D_{65}$

Robinson et al. (1995) investigated stability of rock chutes for slope ranging from 0.1 to 0.4 and suggested a relationship for estimation of critical specific discharge $q_{cr}$ at failure of blocks as

$$q_{cr} = (D_{50}S)^{0.40} \frac{0.215}{\sqrt{S}} \exp(-11.2 + 1.46/\sqrt{S})$$  \hspace{1cm} (28)

where, $D_{50}$ = is the median size of blocks, $S$ = slope of ramp. In this experiment, the investigated chutes were made of layers of thickness 2$D_{50}$ placed over geotextile as filter medium.

According to Aberle (2000) the stability of block cluster type is determined with

$$q_{cr} = 0.062 S - 1.11 \sqrt{g(G - 1)D_{65}^3}$$  \hspace{1cm} (29)

It has the same structure as Equation (25) but has a lower value of numerical coefficient and slightly lower power coefficient of the ramp slope $S$.

Pagliara & Chiavaccini (2007) investigated three boulder configurations (blocks in rows, random and arc configuration) and proposed a relationship for estimation of critical specific discharge

$$\frac{q_c}{q_{cr}} = (1 + 0.084 \Gamma)^{2.7}$$  \hspace{1cm} (30)

where $q_c$ is critical failure discharge of reinforced chutes and $q_{cr}$ is one for base chutes and $\Gamma$ is block concentration as discussed above.
Pagliara & Chiavaccini (2007) extended the investigation on stability of block ramps on failure mechanism of base and reinforced block ramps having different configurations such as random, row and arc disposition. They analyzed the stability of block ramps in terms of critical particle densimetric Froude number $F_{D}$ and evaluated the bed evolution of the rock chute up to its failure.

They defined three stages of failure based on their observation. They are as follows:

(a) Initial movement: Initial movement of the base material in which base material just starts to vibrate and transportation of some elements towards downstream occurs.

(b) Local failure: In this one or more than one base material starts to move from the original position and producing well defined circular or semicircular scour hole.

(c) Global failure: The global failure of the ramp in which many local failures occur. Many boulders and part of the layers of base material gets removed. Longitudinal scour holes get formed especially in the downstream part of the ramp.

They combined experimental results with Equation (7) (flow resistance estimation for block ramp with protruding boulders) and definition of densimetric Froude number, obtained following relation for critical particle densimetric Froude number as,

$$F_{DC} = 1.98 S^{0.18} \left( \frac{h}{D_{90}} \right)^{0.36} (1 + \Gamma)^{a_1}$$

(31)

where $a_1$ depends on blocks disposition: $a_1 = -2.2$ for rows, $a_1 = -2.0$ for random, $a_1 = -2.6$ for arc and $a_1 = -2.6$ and $-2.8$ for two different reinforced arc types configurations.

The dependency of Equation (30) on water depth $h$ makes it difficult to use. So they further modified Equation (30) to find out critical specific discharge $q_{cr}$

$$q_{c} = 1.8 S^{(-0.52-b_1)} D_{90}^{1.5} (1 + \Gamma)^{b_2}$$

(32)

where $q_{c}$ is in m$^2$/s and $D_{90}$ in m.

The coefficients $b_1$ and $b_2$ depends on block disposition:

- $b_1 = -0.2$ and $b_2 = 1.7$ for rows,
- $b_1 = -0.17$ and $b_2 = 1.2$ for arc,
- $b_1 = -0.27$ and $b_2 = 0.8$ for random,
- and $b_1 = -0.17$ or $-0.3$ and $b_2 = 1.2$ or $0.4$ for the two different reinforced arc types.

According to Raudkivi & Ettema (1982), the bimodal mixture of sediment on unstructured block ramp (UBR) consisting of random disposition of boulder of diameter $D$ laid on bed material of characteristic diameter $d_{xx}$, fails in two ways. (1) Overpassing of boulders and (2) Embedding of the boulders in to finer base. According to them the dimensionless parameter consisting of two mean diameters as $D/d_{xx}$ controls the stability. To avoid the above failure mechanism, they had given range of value for $D/d_{xx}$ as $6 < D/d_{xx} < 17$. Generally in mountain river, characteristics size of river bed material is taken as $d_{xx} = d_{90}$ (Janisch et al. 2007). For value of $D/d_{90} < 6$ boulder tends to move over base material and for value $D/d_{90} > 17$ boulder tends to sink in to base material causing to reduce dissipative properties of boulder. The equation suggested by Pagliara & Chiavaccini (2007) for estimation of critical densimetric Froude number and critical specific discharge does not considers the effect of $D/d_{xx}$.

Later on the effect of $D/d_{90}$ was considered by Weitbrecht et al. (2017) for UBR. They carried out experimental study on UBR consisting of protruding boulder of concentration $\Gamma$ laid on base material of characteristics diameter $d_{90}$. The parameters were bimodal mixture ratio $D/d_{90}$, block diameter $D$, block concentration $\Gamma$ and specific discharge $q$. The range of parameters for study was $4.9 < D/d_{90} < 18.6$; $0.15 < \Gamma < 0.25$. Finally the optimal range was $6.5 < D/d_{90} < 7.4$ for no ramp failure resulting in an equilibrium slope $S_e = 30\% - 50\%$ and $\Gamma = 0.15$.

They suggested a relationship for developed equilibrium slope after long run for design purpose based on result of extensive experimentation as,

$$S_e = \frac{11}{200} + q_{d^*}^{-1}, \quad \text{for} \quad q_{d^*} < 1700, \quad \text{Eqn. (33)}$$

where $q_{d^*} = \text{Dimensionless specific discharge}$, They also parametrized dimensionless specific discharge with $D/d_{90}$, $\Gamma$, $D$, and $q$ which is given as,

$$q_{d^*} = q/\sqrt{g(G-1)D^3\Gamma^{-1}(D/d_{90})^2} \quad \text{Eqn. (34)}$$
can be determined. Note all the mentioned approaches do not take into account the stabilizing and destabilizing effect of incoming bed load except the equation proposed by Weitbrecht et al. (2017). In their experiment, sediment supply as bed load showed stabilizing effect.

Generally we choose straight reach of streams for block ramp but sometimes it becomes necessary to provide block ramp in curve portion of streams. In that case the above discussed equations doesn’t give the stable parameters of block ramp.

**DRAG COEFFICIENT OF BOULDER ON BLOCK RAMP**

In steep mountain rivers with large scale roughness, flow resistance is dominated by form drag. Drag force is significant hydrodynamic force in gravel bed stream. Drag from channel form, bed form and immobile obstacles causes to slow down flow velocity by extracting momentum from flow. In block ramp, resistance is offered by mainly due to boulder drag, resulting increase in flow depth and decrease in flow velocity. Estimation of drag coefficients on block ramp is essential for drag force, mean velocity and mean flow depth calculation. Basically, hydrodynamic force consists of two components, drag and lift force.

The drag force depends on hydrodynamic pressure \( P = \rho \frac{U^2}{2} \), where \( \rho \) is medium fluid density, and \( U \) is mean flow velocity. Drag force \( F_D \) acting on projected area \( A_p \) of boulder, having coefficient of drag \( C_d \) is given as (Naudascher 1991)

\[
F_D = C_d \rho A_p \frac{U^2}{2}
\]

\[
C_d = \frac{2F_D}{\rho A_p U^2}
\]

Very few research have been done on drag coefficient estimation for block ramp, where each boulder influences drag coefficient of others. i.e. drag coefficient of single isolated boulder is different than boulder arranged in a group of particular pattern. Oertel et al. (2011) did experimental work on drag coefficient estimation for boulders on block ramp due to flow interaction process. They used sixteen different configuration of cubical as well as cylindrical boulders in row and column such as single block, double block in row, and maximum of six numbers of blocks arranged in three different rows as shown in Figure 11(a). The configuration was chosen in such a way to experience boulder interaction process to determine forces and drag coefficients. They related drag coefficient with Reynolds number. The variation of drag coefficient versus Reynolds number is shown in Figure 11(b).

For single boulder cube, \( C_d \) shows quasilinear dependency on the Reynolds number as shown in Figure 12.

---

**Figure 11**

(a) Photometric view of drag force measured by load cell (similar to Kothyari et al. 2009) for cubical blocks arranged in row and (b) Coefficient of drag as a function of Reynolds number for different configuration of boulders represented by equations. (Oertel et al. 2011).
represented by Equation (36). It shows coefficient of drag $C_d$ increases for decrease in Reynolds number.

\[
C_d = -4.0 \times 10^{-6} R + 2.1 \quad (36)
\]

Similarly, it follows for single cylindrical boulder shape but having lower drag coefficient than cube shape. In this case,

\[
C_d = -4.0 \times 10^{-6} R + 1.5 \quad (37)
\]

For three cubical boulders in different rows, the upstream boulder gets lower value of $C_d$ due to backwater effect offered by downstream boulders.

\[
C_d = -3.5 \times 10^{-6} R + 1.6 \quad (38)
\]

But for six boulder arranged in different row as shown in Figure 11(a) it shows, $C_d$ varies in a quadratic fashion with Reynolds number.

\[
C_d = -3.4 \times 10^{-11} R^2 + 8.0 \times 10^{-6} R + 1.4 \quad (39)
\]

\[
C_d = -4.9 \times 10^{-11} R^2 + 1.2 \times 10^{-5} R + 0.8 \quad (40)
\]

Equation (39) and (40) is for downstream outer and middle boulder in third row respectively. The variations of $C_d$ and $R$, both are shown in Figure 11(b). The drag coefficient for outer boulder of third row is higher than middle one boulder of same row. It is due to fact that the upstream boulder bifurcates main flow towards downstream outer boulder causing to increase in drag coefficient of outer boulder and decrease in drag coefficient for middle boulder. The interaction process decreases drag coefficient of upstream boulder. Interaction process becomes negligible when the distance between each boulder is increased causing to reduce drag coefficient as represented by Equation (41).

\[
C_d = 7.8 \times 10^{-12} R^2 + 8.0 \times 10^{-6} R + 2.7 \quad (41)
\]

Baki et al. (2016) studied the effect of submergence on drag coefficient for various simulations of Fish pass (staggered arrangement of boulders) such as flow variation, channel slope, boulder diameter, boulder longitudinal and transverse spacing and boulder disposition pattern. They found that boulder spacing (longitudinal and transverse) and disposition pattern have great influence on variation of drag coefficient ($C_d$ ranged from 0.5–3.0) with submergence ratio $(h/D)$ as depicted from Figure 12.

**FURTHER RESEARCH NEEDS**

A comprehensive review is presented on experimental studies relating to different configurations of block ramps covering various design aspects such as flow resistance, energy dissipation, stability and drag coefficient of block ramp as well as its flow characteristics done by various investigators in the past. The forms and equations for estimating each of these aspects are also presented in detail. While more research is warranted for further improving the equations essential for design analysis. The major grey areas and gaps which could enhance the future research are as follows.

- 3-Dimensional turbulence burst analysis using modified 3-D Reynolds Stress approach using all the three fluctuating instantaneous velocity components $u'$, $v'$, $w'$ around blocks to improve the understanding on internal mechanism of turbulent flow structure which is primarily responsible for energy dissipation. Present reported
research on turbulent analysis is based on 2-D Reynolds stress concept, where as in reality turbulent bursts occurrence is 3-Dimensional. The positive end product from this research foray will significantly enhance the prediction of residual energy from block ramps much more realistically leading to their better design.

- Even though block ramp technology is used mostly in mountainous torrents carrying highly non-uniform bed and suspended sediment load in episodic transport mode, hardly any research is reported on this vital issue. In this respect, innovative research design is awaited for a skillful interaction between the fluvial processes of 3-Dimensional turbulent bursts on ejection and sweep attributes with sediment transport modes of entrainment, transport and deposition for episodic flow regime.

- Since block ramp application in primarily hilly torrents is made in a highly turbulent flow conditions with rapidly varied unsteady flow regime, the present day formulations are based on assumption of steady flow condition. This steady flow assumption superimposed on 2-D Reynolds stress simplification has obviously introduces probably great deal of error with regard to actual energy loss estimation in the design of block ramps.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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