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Investigation of Hydraulic Stability of Boulder Weir

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***Abstract*:** *The Himalayan Rivers are steep and are characterized by highly turbulent flow transporting a lot of bedload and boulders during floods. Conventional concrete diversion structures face continuous damage from rolling boulders, necessitating frequent repair. The risk of hydro-geomorphic disaster is increasing in the Himalayan region due to climate change effects. Boulder weirs, constructed from riverine boulders, emerge as a cost-effective and disaster-resilient alternative for small to medium hydropower projects. Boulders, abundant in Himalayan riverbeds, offer superior resistance to abrasion compared to concrete, and in case of damage, swift rehabilitation can be achieved using the riverbed materials. In Nepal, the Khimti-I Hydropower Plant pioneered the boulder weir as a diversion structure, demonstrating over two decades of successful operation with minimal maintenance. Design of the weir, including boulder stability were determined by physical model testing. Many hydropower projects have adopted the boulder weir design, relying on empirical experience from Khimti-I. Guidelines for design are available for rock ripraps using crushed stones and dumped rounded stones, and, packed angular stones in embankment dam overtopping situations. However, boulder weirs are constructed by packing boulders having smoother surface, in a single layer. So, this study employs flume experiments to investigate hydraulic stability criteria for boulder weirs, considering variations in downstream slope ranging from 12.5% to 25% and stone diameters of 30 mm, 35 mm, 40 mm and 50 mm. A relationship between the stone-related Froude number and downstream weir slope was established which can be potentially used to design boulder sizes for a given flood discharge and downstream slope of a weir.*

Keywords: *boulder weir, riprap, physical modelling, diversion structure, disaster resilience*

1. Introduction

Nepal is a landlocked country located in the central part of the Himalaya. It is rich in water resources, encompassing a network of 6000 rivers and rivulets (Sharma and Awal 2013), which collectively contribute to an annual runoff of 225 billion cubic meters (Upadhyay and Gaudel 2018). The topographic elevation changes rapidly from 8,848 m in the north to below 100 m in the south in a relatively short lateral distance of about 250 km (Hannah et al. 2005). High topographic relief combined with abundant water resources makes Nepal as one of the highest per capita hydropower potential country in the world (Hoes et al. 2017). The storage potential is limited to the middle and the lower reaches of major river systems and the potential at the upper reaches is dominated by the Run-of-River (RoR) projects (Shrestha 2016). Lower development cost of small and medium RoR projects compared to the storage projects, has even attracted private sector investments and local financing in hydropower sector in Nepal. More than 50% of the current hydro-electricity generation in Nepal is contributed from the private sector owned projects (NEA 2020).

The Himalayan Region was formed by the submergence of Indian plate into the Eurasian plate (Molnar and Tapponnier 1975) comprising mainly of young and fractured sedimentary and metamorphic rocks (Upreti 1999). The weak geology, steep terrain, frequent seismic activity, and heavy monsoon rainfall create a landscape prone to water induced events such as landslides and debris flows which contribute to very high bedload and boulder transport during the monsoon season. Multiple hazards and cascading hazards, resulting from the interaction of several hazards, are common in this region, compounding their impacts compared to a single hazard (Sharma et al. 2023). So, water resources infrastructures located in the Himalayan region have high risk of damage by these disasters. The Sunkoshi Small Hydropower Plant (Ojha 2018), Upper Bhote Koshi Hydroelectric Project (Shrestha et al. 2019) and Melamchi Water Supply headworks (Talchabhadel et al. 2023) have all experienced such instances of damage. The increase in hydrological extreme events, permafrost thaw and melting of glaciers in this region due to climate change is expected to increase the risk of the multiple hazards in the future (Sharma et al. 2023).

Conventional concrete weirs are so far the most common diversion structures implemented at the headworks of small and medium RoR hydropower projects in Nepal. These structures made up of concrete experience abrasion wear caused by sediment laden flow during flooding season, demanding regular repair and maintenance (Annandale et al.

2016). Similarly, the performance of trench weir implemented in small streams of Himalayan region in India have reported trapping of coarse sediments by the intake, clogging of the trash racks by bed load during the flooding season and necessitating frequent repair and maintenance (Arora and Kumar 2018). Additionally, in case of severe damage caused by disaster events, the rehabilitation works of conventional concrete structures would require an extended time period for site preparation and construction, involving a substantial need for skilled labour.

Boulder weirs can be potential alternatives to conventional concrete and trench weirs as diversion structures to run-of-river (ROR) headworks in steep Himalayan Rivers. It is constructed from a single layer of interlocked boulders above a filter layer (Figure 1). The elevated parts of the weir body, both upstream and downstream, are made using local alluvium material. The filter media serves as an intermediate, preventing the removal of the alluvium material from the voids of boulders due to piping. The weir is provided with cutoff walls at required locations to increase the seepage length. The upstream and downstream of the weir are enveloped with boulder lining for smooth transitioning of flow. A boulder weir is constructed using locally available boulders from the river, making it a more cost-effective alternative to concrete weirs. They also exhibit high resistance to abrasion and minor impacts from movement of bedload and boulders. The resilience can be attributed to how these rounded boulders are formed. The abrasion rate is mainly governed by the lithology (Shobe et al. 2021). The softer rock masses disintegrate and abrade during the fluvial transport, leaving behind the resilient boulders containing hard mineral in the riverbed. Boulder weirs offer an additional benefit- even if severely damaged by a disaster, they can undergo quick rehabilitation through simple procedures utilizing the ample boulders available in the river bed.

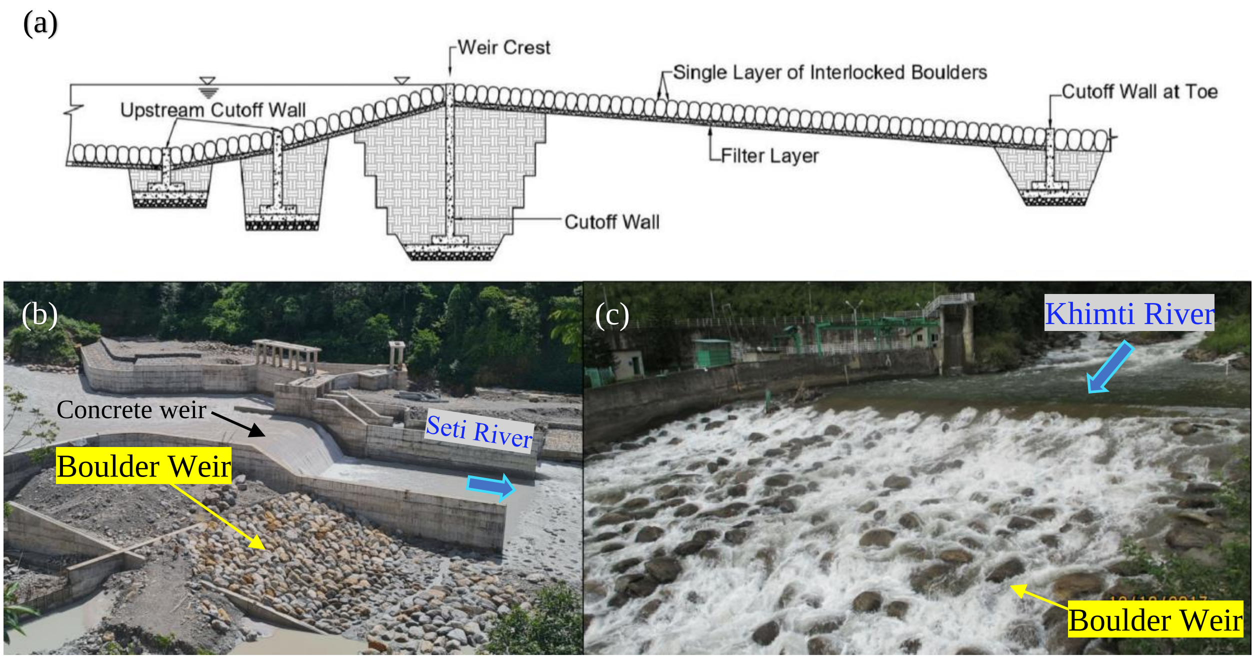

Figure 1. (a) Schematic diagram of a boulder weir (b) Boulder weir (under-construction) as a secondary weir for Seti Hydropower Project (c) Boulder weir of Khimti-I Hydropower Project

Boulder weir was first implemented in Nepal at Khimti-I Hydropower Project in the year 2000 (Bishwakarma 2020). The weir was designed by conducting scaled physical model tests at Hydro Lab in 1996. The weir structure has so far safely passed a debris flow and several floods with return periods ranging from 2 to 5 years, requiring minimal repairs and maintenance till date. The structure at Khimti-I hydropower project, proving to be cost effective and efficient, led it to be replicated by many other small hydropower projects. While empirical evidences speak in favour of boulder weir structures, there is a paucity of literatures regarding the stability of the same. Most studies on the stability of boulders are carried out for ripraps constructed using the dumped angular and rounded stones (Abt et al. 1988; Gallegos and Abt 2001; K.M. et al. 1998; Maynord 1988; Mishra 1998; Peirson et al. 2008; Ullmann and Abt 2000). The boulder weir is constructed from a single layer of placed rounded stones having a smoother surface. The studies conducted for placed stones (Hiller 2017; Hiller et al. 2018; Hiller and Ravindra 2020; Siebel 2007) are dedicated for accidental overtopping in embankment and rockfill dams using angular stones. The flooding scenarios in those tests haven't been considered. A boulder weir is overtopped with floods of various magnitudes during wet season. This indicates that there is a need to undertake further studies on the same to reach to a reliable conclusion in regard to the performance of round shaped boulder on different hydraulic conditions. This study therefore intends to investigate the hydraulic stability of boulder weirs constructed using rounded boulders at various downstream slopes of the weir.

2. Methodology and Experimental Setup

Experiments were conducted in a hydraulic flume of dimension 12 m x 0.4 m x 0.67 m (L x B x H) at Hydro Lab Pvt. Ltd. in Lalitpur, Nepal. The inlet of the flume consisted of a tank which collected water from a constant head regulating overhead tank which was connected to a centrifugal pump. The centrifugal pump supplied water to the overhead tank and necessary discharge was supplied through a 254 mm diameter pipe by operating a sluice gate valve connected to the overhead tank. To ensure tranquil and uniform flow in the flume, a perforated plate was positioned immediately after the inlet tank. A weir having a height of 0.30 m and top width of 0.10 m was fabricated using ply boards and placed at a distance of 3.20 m from the inlet tank of the flume. A 0.09 m high ply board was provided as a cutoff wall and support for the upstream filter and stones. Similarly, a triangular prism emulating the downstream cutoff was provided at the toe. The outlet facility of the flume consisted of a long canal fitted with a calibrated sharp crested weir at the end to measure the discharge. The rating curve for the sharp crested weir was established and the datum point was determined to facilitate the calculation of head over the crest for discharge measurement (Figure 2).

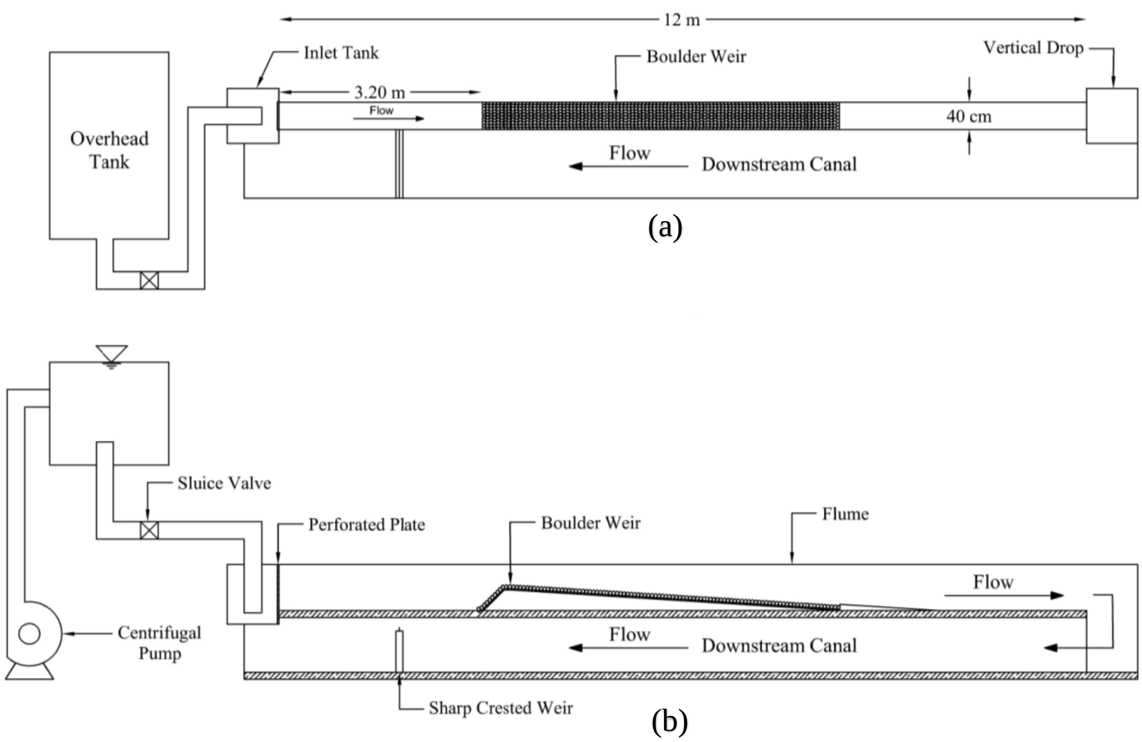

Figure 2. Details of experimental setup showing (a) plan view (b) side view

The rounded stones were collected from the natural reaches of rivers flowing through the Kathmandu valley. The tests were conducted using four stone sizes, 3 cm, 3.5 cm, 4 cm and 5 cm in diameter. The slopes for the tests ranged from 12.5% to 25% (Table 1). Stones within each size category were measured using vernier calliper and carefully selected for their uniformity, maintaining geometric similarity with nearly identical diameters and an elongation of approximately 50%. In addition, 7 tests were performed employing spherical stones with no elongation. The filter layer above which the stones were placed was designed adhering to the guidelines provided by (Keller 2003). The stones were then laid over the filter media orienting their longest axes at an angle of 60-70 degrees to the downstream slope. The stones were packed to minimize voids, ensuring that the gaps formed by two adjacent stones in the preceding row were filled by a third stone. This arrangement aimed to reduce void spaces, necessitating a higher quantity of stones to cover the same area. This configuration is akin to hexagonal close packing, where each stone supports six neighbouring stones at its periphery. For majority of tests, stones were chosen randomly; the one at hand was rotated to fit among preceding ones, simulating field placement using excavator buckets. The initial stone that came to hand wasn't discarded for a better fit, replicating real-world scenarios where placement adjustments are limited during construction (Figure 3). The packing factor has been defined as the number of stones of a given size contained in a unit squared area (Olivier 1967).

Table 1. Number of tests conducted for various slopes, sizes and shapes

S.N.	Stone Size (cm)	Shape	Slope (%)					
			25	22.5	20	17.5	15	12.5
1	3	Elongated	0	2	1	1	1	1
2	3.5		1	0	0	0	0	0
3	4		1	1	1	1	1	1
4	5		0	1	1	1	1	1
5	5	Spherical	2	1	1	1	1	1
Total			25					

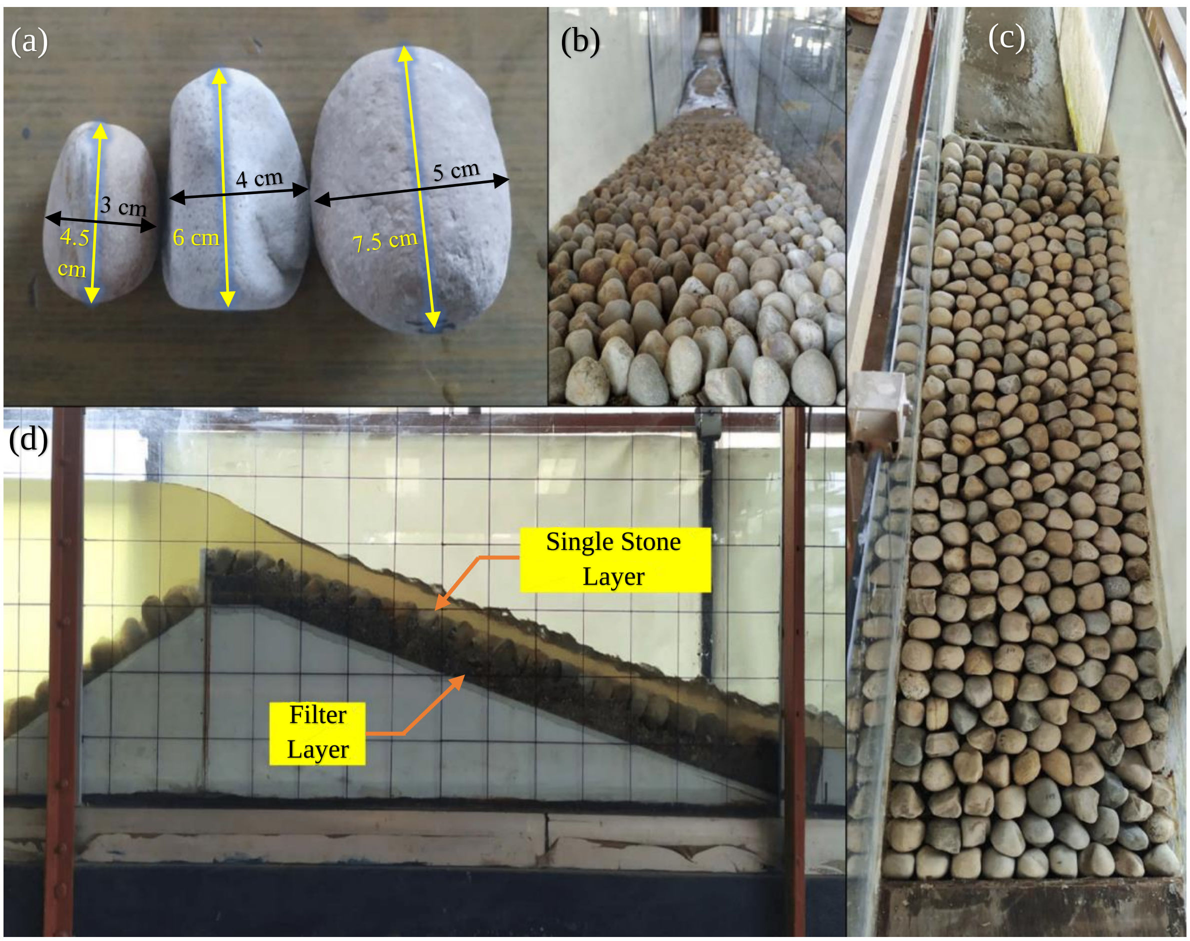

Figure 3. (a) Sample stone of each size (elongated) (b) downstream slope of the weir (c) top view of model weir (d) side view of model weir during experiment

To start the experiments, the inlet tank up to upstream of the weir was first filled gradually by water. The outlet of the constant head regulation tank was operated at a desired opening to supply discharge to the flume. The centrifugal pump was then operated to supply water to the constant head regulation tank. The water level at the sharp crested weir was measured to determine the discharge in the experiment. The outlet of the constant head regulating tank was adjusted, if required, to ensure desired discharge was supplied to the experiment. To implement a realistic duration of the experiments with reference to field cases, Froude similarity was used to scale the duration of experiments with respect to the size of stones used in different experiments. The scale was determined assuming that the stone size used in the experiment represented the boulder of size 1 m in the field. At each discharge, the experiment was carried out for a duration of 8 hours (in field scale). The discharge was gradually increased within 1 hour (in field scale) to next increment step (Figure 4). Flow increment rates for 4 and 5 cm stones were chosen in multiples of 10 l/s, while for 3 and 3.5 cm stones was selected in multiples of 5 l/s. Videos of the experiment were recorded from the side and top of the flume. At the end of each discharge, a visual inspection was conducted to determine the failure of stones. If the failure of stones were observed, the corresponding discharge was considered as the critical discharge for the stability of the stones.

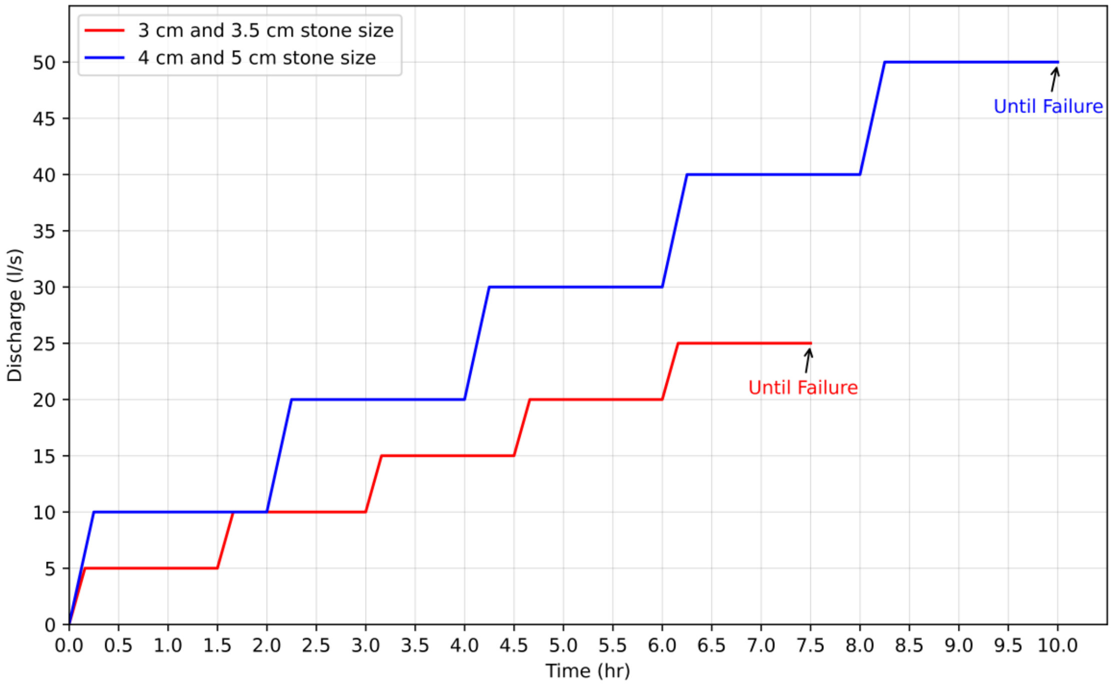

Figure 4. Hydrograph for various stone sizes

The stability of the boulder weir under various downstream slopes has been analyzed using the stone-related Froude number ($F_{s,s}$), which is associated with the dislodgement of the first stone in a dimensionless manner.

$$F_{s,s} = \frac{q_s}{\sqrt{gd^3}} \quad (1)$$

Where, q_s is the specific discharge leading to the dislodgement of the first stone; g is the acceleration due to gravity; d is the stone diameter.

3. Results

The stone-related Froude numbers associated with the dislodgement of the first stone ($F_{s,s}$) for various downstream slopes, as determined from the experiments are presented in Figure 5. The results of experiments with randomly packed elongated stones and spherical stones show a best-fit relation between the stone-related Froude number ($F_{s,s}$) and slope (S) through power regression equations Eq. (2) and Eq. (3) respectively. The predicted data using the derived relations and their corresponding observed data have been depicted in Figure 5 (b) and 5 (c) respectively for elongated and spherical stones.

$$F_{s,s} = 32.92 \times S^{-0.81} \tag{2}$$

$$F_{s,s} = 31.08 \times S^{-0.94} \tag{3}$$

Where, $F_{s,s}$ is the stone-related Froude number associated with the dislodgement of the first stone; S is the downstream slope of weir in %.

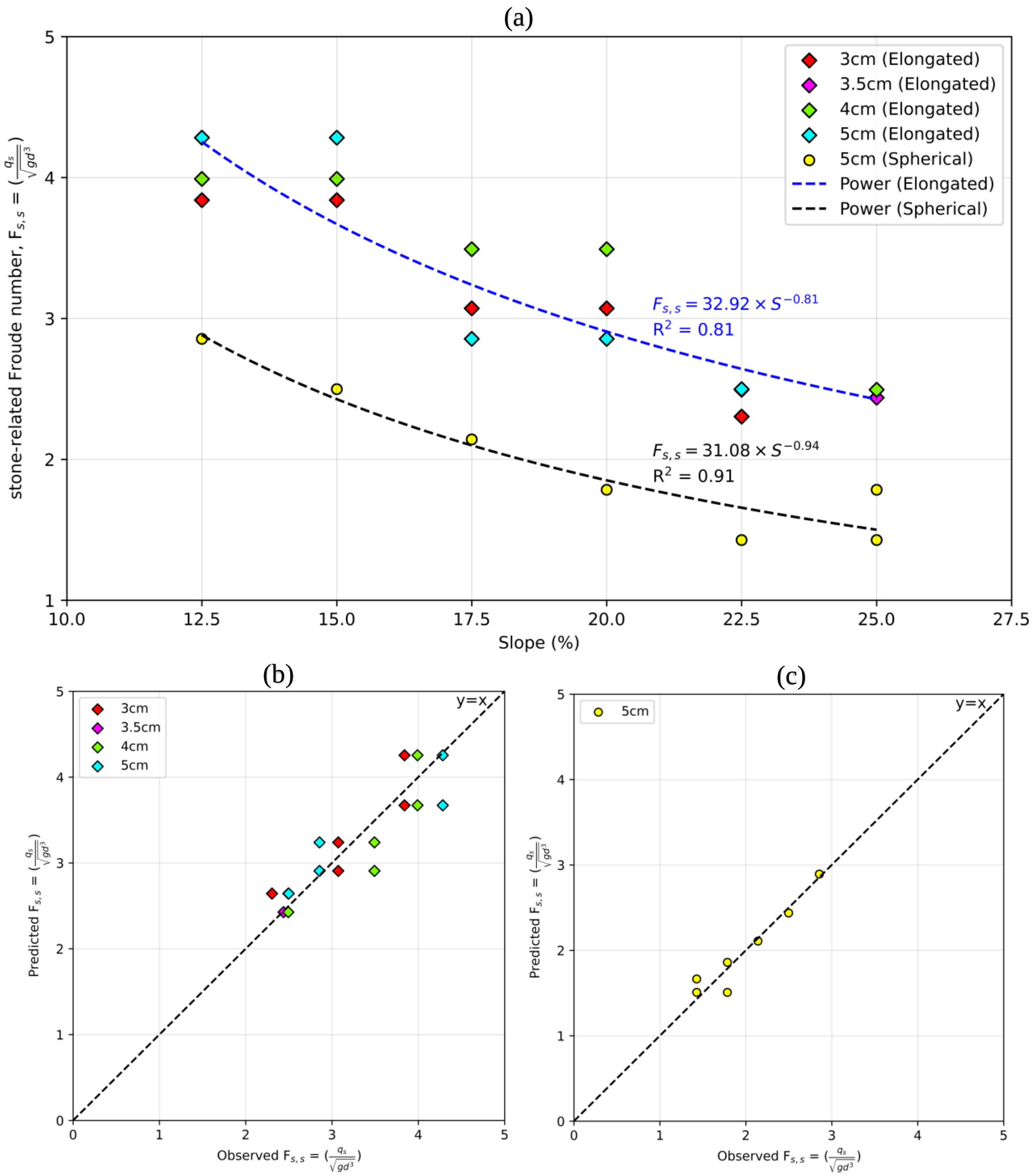

Figure 5. (a) Stone-related Froude number ($F_{s,s}$) vs downstream slope of weir for randomly packed spherical and elongated stones (b) Predicted vs observed data for elongated stones (c) Predicted vs observed data for spherical stones

The stone-related Froude number ($F_{s,s}$) for the elongated stones were observed to be higher than that for spherical stones, indicating greater stability in elongated stones as compared to spherical ones. In the experiments with spherical stones, failure of multiple stones occurred immediately after the dislodgement of the first stone. The spherical stones have a tendency to roll due to their uniform mass distribution. The consequence is that the dislodgement of a single stone can trigger a cascading failure of multiple stones, leading to the failure of the weir. However, in the experiments with the elongated stones, the failure of a single stone did not lead to an immediate failure of multiple stones. The elongated stones, with their longer axis placed perpendicular to the downstream slope, exhibited greater stability as they lack uniform mass distribution about that axis. The stability of elongated stones can also be attributed to increased contact points, due to increased surface area, that increases the frictional resistance between the interlocked stones. The stone-related Froude number for the failure of multiple stones were observed to be higher than that of the failure of the first stone for elongated ones. Therefore, the selection between spherical and elongated stones plays a pivotal role in the stability and resilience of the boulder weir structure.

4. Discussion

The relationships, Eq. (2) and Eq. (3), derived for elongated and spherical stones respectively are plotted for slopes ranging from 12.5 to 25%. The stability criteria reported in the literatures (Abt et al. 1988, 2008; Ullmann and Abt 2000) for stone ripraps constructed from dumped rounded stones is shown in Table 2. The stone-related Froude number for the slopes between 12.5 and 25% were derived based on the same stability criteria. The value of coefficient of uniformity was assumed to be 1.2 when employing stability criteria (Abt et al. 2008). This was the average value found in most of the tests (Gallegos and Abt 2001; Ullmann and Abt 2000) that were evaluated to derive the relationship. The graph depicting the current findings and established riprap stability criteria (Abt et al. 1988, 2008; Ullmann and Abt 2000) using stone-related Froude number for the aforementioned slopes is shown in Figure 6.

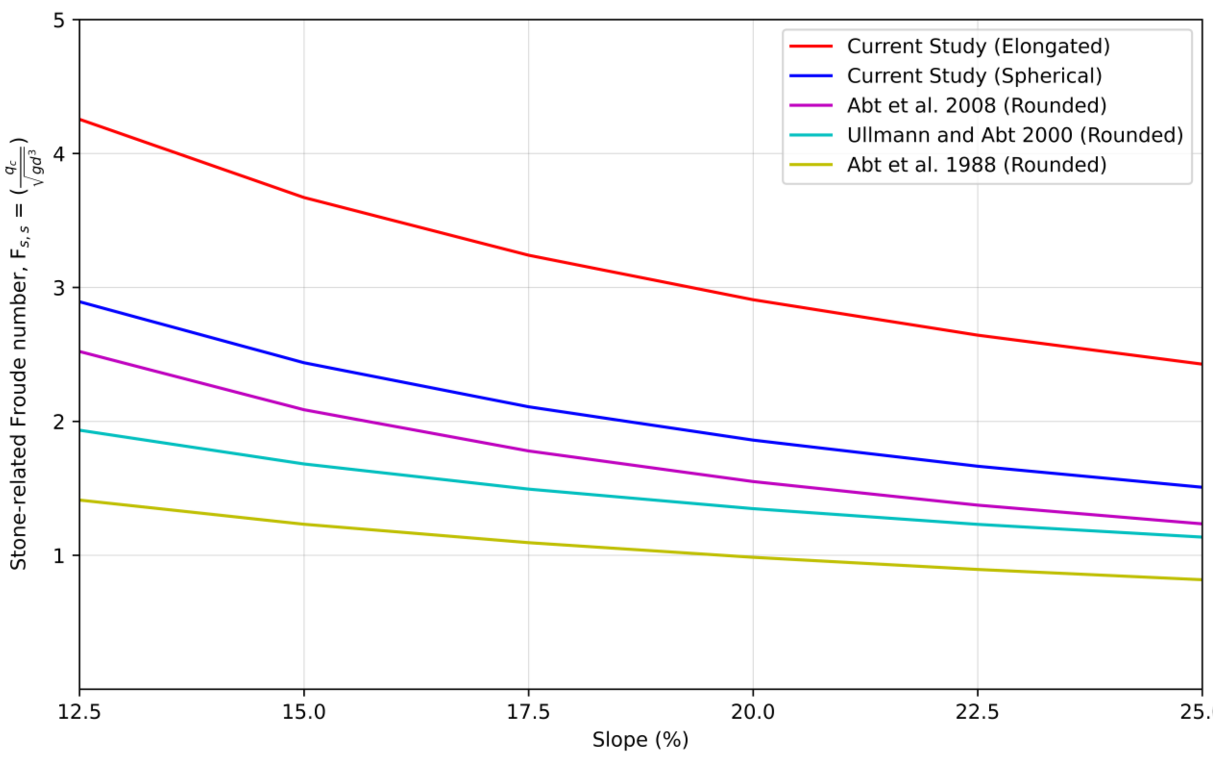

Figure 6. Stone-related Froude number vs downstream slope for dumped ripraps and placed stones

Table 2. Established stability criteria for dumped riprap design

S.N.	Stability Criteria	Reference
1	$D_{50}= 8.16\ S^{0.43}\ q^{0.56} - 0.2897$	Abt et al. 1988 (Rounded)
2	$D_{50}= 7.24\ S^{0.43}\ q^{0.56} - 0.5353$	Ullmann and Abt 2000 (Rounded)
3	$D_{50}= 7.66\ C_u^{0.70}\ S^{0.70}\ q_f^{0.68}$	Abt et al. 2008 (Rounded)

During their experiments on dumped ripraps using rounded stones, (Abt et al. 1988, 2008; Ullmann and Abt 2000) observed that ripraps using rounded stones demonstrated approximately 40% lower resistance to failure discharge as compared to angular ones. The boulder weir constructed using filter material and packing of a single layer of boulders appear to be more stable than stone ripraps constructed from dumped rounded stones. Spherical stones, when packed, exhibited higher resistance to failure discharge, approximately 50% more compared to dumped rounded stones. The results also demonstrate that packed elongated stones saw an approximately 2.5- and 1.70-fold increase in failure discharge compared to dumped rounded stones used as a riprap (Abt et al. 1988, 2008; Ullmann and Abt 2000).

5. Conclusion

The study aimed to evaluate the hydraulic stability of boulder weir through flume experiments, considering downstream slopes ranging from 12.5% to 25%. 25 tests were undertaken. Rounded elongated stones measuring 3 cm, 3.5 cm, 4 cm and 5 cm in diameter were used. Spherical stones measured 5 cm in diameter. A relationship between stone-related Froude number associated with the dislodgement of the first stone and downstream slope was derived for spherical and elongated stones. The study showed that the shape of boulders significantly influences the stability of the boulder weir. Spherical stones are inferior in terms of stability as compared to elongated ones due to their tendency to roll, and that the failure of a single stone can lead to mass failure of the weir. Nevertheless, packed spherical stones offer higher stability compared to dumped rounded ones. Elongated stones were found to be the most effective. Increased elongation of stones was observed reduce mass distribution and enhance interlocking between stones, resulting in greater stability. Therefore, design of boulder weir should be approached with careful consideration of elongation of boulders, given the crucial role it plays in ensuring the stability.

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