Protection of embankment dam toe and abutments under overtopping conditions

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Abstract

This article is primarily intended to introduce the theoretical and practical significance of the downstream toe and abutments of embankment dams. Further, summary of previous empirical and experimental research works carried out in the field of embankment dam protection under overtopping conditions is presented. Relationships for sizing of dumped riprap stones at embankment toe are proposed based on key findings from the research areas of design of dumped ripraps and embankment dam toe. The proposed criteria are tested with available experimental data. The paper also aims at bringing to the fore, possibilities for further research.

1 Introduction

Embankment dams are vulnerable to extreme flood events in turn leading to accidental overtopping of the dam core or even the dam crest as the dam structure is mainly composed of pervious and erodible materials. ICOLD statistics (ICOLD, 1995) state overtopping as the main cause of failure of earth dams, appearing as the main factor in 31% of the total number of failures, and also involved in another 18% of failures as a secondary agent (Toledo and Morera, 2015). During the last decades, there has been a significant increment of social demand on dam safety standards, especially in the most developed countries. This has led to new, and more demanding dam regulations and guidelines (Moran, 2015).

Over the decades, a number of investigations have been carried out to study the stability of dumped ripraps under overtopping conditions. These studies have given rise to multitude of empirical stone sizing criteria for dumped ripraps, widely used in present engineering practice. Although a large number of stone sizing criteria are available for sizing dumped riprap stones on embankment side slopes, the applicability of these criteria for sizing dumped riprap stones at dam toe needs to be further evaluated as the dam toe could be considered a key component of the embankment dam overtopping protection system. Also, impact of abutment shape on downstream toe stability has seldom been discussed.

In this article, an introduction of the theoretical and practical significance of the downstream toe and abutments of embankment dams is presented. This is followed by a summary of the previous empirical and experimental research works carried out in the field of embankment dam toe protection under overtopping conditions. Further, empirical relationships for sizing of dumped riprap stones at an embankment dam toe based on key conclusions from the research areas of design of dumped ripraps and embankment dam toes are proposed and the validity of these criteria is tested with available experimental data.

Further, some recent investigations (e.g. Hiller et al., 2017) have investigated placed riprap technology as this is attributed to higher stability compared to randomly dumped riprap. Possibilities for future research are introduced discussing incorporation of state of the art in placed riprap technology in the area of embankment dam toe protection.

It should be noted that the terms 'riprap stability' and 'toe stability' employed on several occasions within this article refer to 'erosion resistance' of riprap/toe stones when exposed to overtopping flows. Consideration of mass sliding caused by pore pressure build up is beyond the scope of the present study.

2 Significance of embankment dam toe and abutments

Under normal operational conditions of embankment dams, seepage water through the dam core enters the downstream embankment structure. This seepage water needs to be effectively drained as retained water within the downstream embankment can raise pore pressures within the embankment structure leading to reduced slope stability. Hence, the downstream toe of embankment dams composed of rockfill needs to act as a drain for seepage discharges (generally of low magnitude).

Under overtopping conditions, excessive flow entering the downstream embankment structure poses major challenges concerning downstream slope stability. Considering throughflow conditions (overtopping of dam core), highly turbulent flow within the embankment structure can result in erosion of filter material and also destabilize the downstream embankment due to dynamic pore pressure generation (Figure 1). In highly permeable downstream shells, the turbulent throughflow may develop high seepage velocities. Therefore, the risk of internal erosion due to particle dragging from the inside of the dam body is high (Moran, 2015).

Further, flow concentration can be very high at the dam toe as seepage water is discharged through a relatively small cross section area at the dam toe leading to convergence of stream lines (Section 2 in Figure 1). Hence, the downstream toe should drain leakage flow efficiently in order to maintain embankment stability. It has to also act as a filter to capture fine materials transported from within the downstream embankment structure.

Under overflow conditions (overtopping of dam crest), the downstream slope is inundated with highly turbulent flow and this results in generation of dynamic forces within the riprap structure. The forces on the downstream toe are further magnified as in addition to the erosive forces discussed earlier, the dam toe has to deal with dynamic forces transferred by the overlying riprap layer. Under such scenarios, removal of stones from the dam toe can lead to unraveling failure of the entire downstream slope. The destabilizing effects of overtopping on dam toe stability are further amplified in case of steep downstream embankments.

Numerous past investigations looking into the stability of embankment dams with steep downstream slopes ($S > 0.5$) under overtopping situations have suggested that the probability of initiation of failure at the toe of embankment dams can be significant. Pertinent findings in this regard from select publications are stated herein.

Marulanda and Pinto (2000) studied the behavior of rockfill dams under throughflow conditions and stated that the instability of rockfill slopes initiates by rattling of rocks producing shallow slides at the emerging zone of the seepage water. The phenomenon tends to intensify with time as flow concentrates in the initially scoured area. Steeper slopes are formed and thus deeper slides occur. The instability propagates upstream, reaching the crest of the fill and eventually causing the breaching of the dam (Marulanda and Pinto, 2000).

Cruz et al. (2009) carried out a literature review of case studies on large rockfill dam failures under overtopping conditions and suggested that any description of failures observed in rockfill dams during throughflow always mentions that dams failed by progressive sliding and removal of stones from the toe up to the crest (Cruz et al., 2009). A case study of failure of the Hell Hole Dam (California, 1964) suggested that the dam

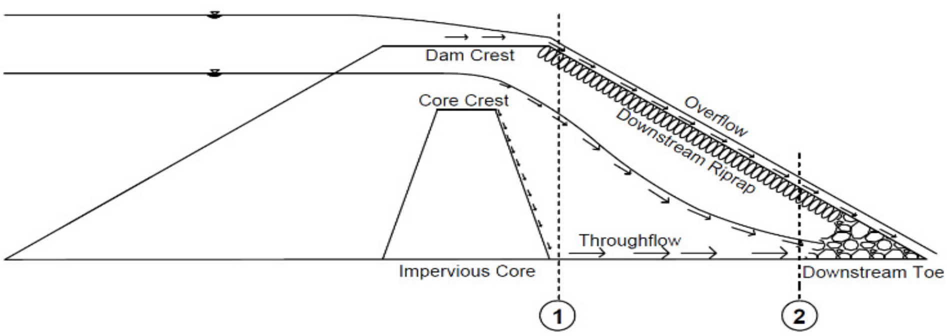

Figure 1: Throughflow and overflow scenarios in embankment dams

failed by progressive sliding and by removal of stones from the toe all the way up to the crest (Cruz et al., 2009).

Siddiqua et al. (2013) evaluated the behavior of full-scale rockfill dams under overtopping conditions. It was stated that the downstream seepage face is a critical design consideration as this is the most likely location where initiation of particle movements take place due to high exit gradients that can drive high flow velocities (Siddiqua et al., 2013).

The abutments of embankment dams play a key role in providing the dam structure with stability against sliding due to the frictional resistive forces set up at the contact points (Figure 2). Further, the abutments also help preserve the impervious nature of the reservoir by inhibiting excess seepage. It is essential to comprehend the influence of abutment shape on the stability of the dam toe.

As previously described, the flow intensity is highest at the dam toe under overtopping flow conditions. This effect is magnified when the dam is constructed in constricted cross-sections as for instance in narrow-valleys. To illustrate this effect, a conceptual rockfill dam (in Figure 1) is considered as built in a narrow valley cross-section depicted in Figure 2.

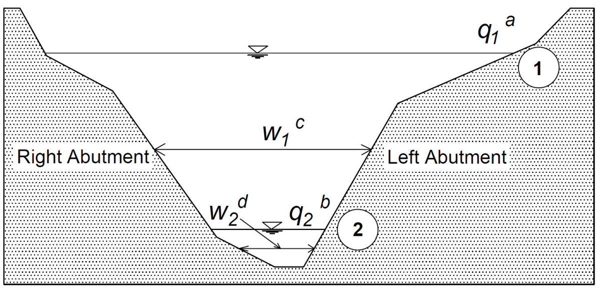

Figure 2: Depiction of flow concentration effect

[a] Unit discharge for water level at Section 1; [b] Unit discharge for water level at Section 2; [c] Mean width of flow channel for water level at Section 1; [d] Mean width of flow channel for water level at Section 2.

In case of overtopping, the flow per unit width would be much higher at the dam toe (Section 2) in comparison with Section 1 due to constricted channel width. Assuming constant discharge (Q_1 = Q_2), applying continuity equation between Sections 1 and 2 results in Eq 1 and 2.

$$q_1 w_1 = q_2 w_2 \quad [1]$$

$$q_2 = \frac{w_1}{w_2} q_1 = C_c q_1 \quad [2]$$

where the term 'w_1/w_2' could be termed the flow concentration coefficient 'C_c' between Sections 1 and 2. This implies that 'C_c' would be higher for a narrow-valley cross-section ($w_1 > w_2$) in comparison with a rectangular channel ($w_1 \approx w_2$).

The steep abutment profile results in flow concentration as the flownet is forced to converge onto the dam toe due to constriction of channel width. These conditions can result in high velocity flow with significant destabilizing potential. In Eq 1, the flow intensity is assumed uniform at a given cross-section. But, this can be significantly higher at the abutments due to generation of multidirectional flows. So, riprap stones along abutment slopes are less stable when compared with riprap stones in other sections of the riprap. Furthermore, abutment side slope can be steeper than the embankment slope, further influencing riprap stability.

Hence, the dam toe design criteria should incorporate details of abutment shape as this can have significant impact on toe stability.

3 Available literature on dam toe design and relation to riprap

A brief overview of the available literature on the design of embankment dam toe is presented in the following discussions.

Solvik (1991) conducted physical modeling investigations to study stability problems in rockfill dams exposed to exceptional loads. Solvik (1991) stated that special care should be paid to the last row of stones, which constitutes the toe of the dam. These stones are keystones and may cause instability to the next row of stones when removed. A total dam breach may therefore be the final result of such removal of key stones (Solvik, 1991). A design chart for sizing of key stones based on his investigation results was proposed by Solvik (1991). The proposed design chart was intended for sizing toe stones of dumped ripraps (ripraps constructed with randomly dumped stones).

Recent investigations into the design of rockfill dam toes with the primary objective of developing design criteria of cost-effective rockfill dam protection to avoid failure due to overtopping was carried out by Moran (2015) and Moran and Toledo (2011). Their findings suggested that rockfill toes may be used as an effective protection in rockfill dams against throughflow caused by either overtopping or a high leakage within the impervious element of such a dam (Moran and Toledo, 2011). The design methodology proposed by Moran (2015) was intended at dimensioning of rockfill toes and does not explicitly consider sizing of toe stones as a design outcome. However, the study findings demonstrate the importance of rockfill toes as a component of the rockfill dam overtopping protection system.

Perhaps the most pertinent investigation into the design of the toe of embankment slopes was carried out by Abt et al. (1998). A near prototype, pilot flume study was performed where flow overtopped an embankment with a mild side slope of $S = 0.2$ and transitioned into a toe structure comprised of 90, 130 and 200 mm stones (median stone diameter).

Abt et al. (1998) documented results from their investigations on stability of embankment toes. They recorded critical discharge values for stone movements at the side slope and the toe sections of dumped ripraps as presented in Table 1. A direct observation from the values presented in Table 1 is that the critical discharge values for toe stone movement were significantly lower compared to that of the stones on the side slopes for dumped ripraps suggesting considerably lower stability for toe stones under overtopping flow conditions.

The investigation results further indicated that the stone size required to stabilize the dumped riprap layer at the embankment toe needs to be approximately 100% larger than the dumped riprap stone size required to stabilize embankment side slopes (Abt et al., 1998).

Table 1. Experimental test results from Abt et al., (1998)

D_{50} [a] (mm)	q_{RR} [b] ($m^3/s/m$)	q_T [c] ($m^3/s/m$)
200	0.54	0.26
130	0.36	0.09
90	0.26	0.08

[a] Median stone size (mm); [b] Unit discharge for riprap stone movement at the side slope; [c] Unit discharge at toe stone movement.

Further, a criterion was developed for sizing toe stones of dumped ripraps with parameterization as embankment slope and unit discharge (Eq 3) (Abt et al., 1998).

$$D_{50(\min),T} = S^{0.43}\,(C_f q_f)^{0.56} \qquad [3]$$

where, '$D_{50(min),T}$' is the minimum median size requirement for riprap stones at the toe section (m). 'S' is the design slope and 'q_f' is the design critical unit discharge ($m^3/s/m$). 'C_f' is a flow concentration coefficient to consider flow channelization on uniformly graded slopes (Abt et al., 1998).

Eq 3 for sizing toe stones was derived based on the stone sizing criterion developed by Abt et al., (1991) for dumped ripraps given as Eq 4.

$$D_{50(min),RR} = 0.5\,S^{0.43}\,(q_f)^{0.56} \qquad [4]$$

with '$D_{50(min),RR}$' as the minimum median size requirement for dumped riprap stones on embankment side slopes (m) and other notations consistent with Eq 3. Physical validity of Eq 3 and 4 was confirmed over the boundary conditions $S < 0.2$, $D_{50(min),RR} < 152$ mm and $S < 0.2$, $D_{50(min),RR} < 198$ mm respectively.

As can be inferred, Eq 3 (for toe stones) was obtained by doubling Eq 4 (for riprap stones) in accordance with the findings of Abt et al. (1998).

i.e., $$D_{50(\min),T} = 2\,D_{50(\min),RR} \qquad [5]$$

Eq 4 for '$D_{50(min),RR}$' was derived based on near prototype flume studies conducted by Abt et al. (1991) in which embankments protected with dumped ripraps were subjected to overtopping flows. Since then, the state of the art in riprap stone sizing has advanced. At present times, 24 disparate riprap stone sizing criteria have been formulated for sizing dumped riprap stones (Abt and Thornton, 2014). The majority of these criteria were developed for sizing of riprap stones on mild embankment slopes ($0.2 < S < 0.4$) and few were designed for steeper slopes of $S > 0.5$.

The subsequent discussions presented in this article are aimed at combining the state of the art on sizing of dumped riprap stones with the finding of Abt et al. (1998) (Eq 5) to discern the ability of recently developed dumped riprap stone sizing criteria to predict the experimental data documented by Abt et al. (1998) (Table 1).

4 Recent dumped riprap stone sizing criteria used as a basis for toe stone sizing

The research area of downstream slope protection has advanced since its inception with the work of Isbash (1936). This paper is not focused on listing individual empirical relationships available for the purpose of sizing dumped riprap stones as this is already available in multiple review articles (e.g., Abt and Thornton (2014) and Abt et al., 2013). Instead, emphasis is laid on identification of best performing design criteria among available international literature.

Ravindra et al., (2018) compiled findings from disparate performance-based empirical evaluations on dumped riprap sizing criteria carried out by Abt and Thornton (2014), Abt et al. (2013), Khan and Ahmad (2011) and Thornton et al. (2014). Ability to predict documented results from large number of physical modeling investigations was assumed as the measure for performance.

The review (Ravindra et al. (2018)) brings forth that the Thornton et al., (2014) and Khan and Ahmad (2011) approaches for sizing of dumped riprap stones best predicted the physical modeling test results obtained from numerous past investigations. The performance of Thornton et al. (2014) approach was stated as being marginally better in comparison with the Khan and Ahmad (2011) approach. Hence, it could be concluded that the Thornton et al. (2014) and the Khan and Ahmad (2011) represent the best performing dumped riprap stone sizing criteria among international literature. It is recognized that the experimental setups, testing procedures and data-acquisition procedures for all the data sets employed for obtaining these relationships were similar (Thornton et al., 2014 and Khan and Ahmad, 2011).

As per the Khan and Ahmad (2011) approach, the minimum size requirement for the riprap stones is determined by employing Eq 6.

$$D_{50(min),RR} = 0.37\, n^{1.38} S^{0.52} C_u^{-1.07} q_f^{0.52} \quad [6]$$

where, '$D_{50(min),RR}$' is the minimum median size requirement for dumped riprap stones on embankment side slopes (m). 'C_u' is the coefficient of uniformity (D_{60}/D_{10}). 'n' is representative of the thickness of the riprap layer which can be considered as the number of stone layers in which the riprap has been placed on the sloping bed. 'S' is the design slope and 'q_f' is the design critical unit discharge (m^3/s/m). Eq 6 was stated as valid over the boundary conditions of $S < 0.4$, $D_{50(min),RR} < 278$ mm.

Further, as per the Thornton et al. (2014) approach, the minimum stone size requirement for riprap stones on embankment side slopes is determined by employing Eq 7.

$$D_{50(min),RR} = 0.23\, n^{1.63} S^{0.53} C_u^{-0.74} q_f^{0.55} \left[1.48/(SG-1)^{0.79}\right] \quad [7]$$

with 'SG' as the specific gravity of construction material and other notations consistent with Eq 6. Eq 7 was stated as valid over the boundary conditions of $S < 0.5$, $D_{50(min),RR} < 655$ mm.

As stated in Section 3 of this article, the proposed criteria for sizing of dumped riprap stones at dam toe intends to combine two separate findings from the available literature on the state of the art on embankment dam overtopping protections.

As per multiple review publications, Thornton et al. (2014) and Khan and Ahmad (2011) approaches best describe the stone sizing requirements for dumped riprap in comparison with 24 design criteria, including Abt et al. (1991) (Eq 4).

Further, findings of Abt et al. (1998) suggests that the minimum stone size required to stabilize the dumped riprap layer at the embankment toe needs to be approximately 100% larger than the dumped riprap stone size required to stabilize embankment side slopes (i.e., $D_{50(min),T} = 2\, D_{50(min),RR}$).

Consequently, doubling the Khan and Ahmad (2011) (Eq 6) and the Thornton et al. (2014) (Eq 7) criteria could potentially provide preliminary empirical relationships for sizing toe stones of dumped ripraps.

Modified Khan and Ahmad (2011) approach for sizing toe stones of dumped riprap is presented as Eq 8 (notations consistent with Eq 6).

$$D_{50(min),T} = 2\, D_{50(min),RR} = 0.74\, n^{1.38} S^{0.52} C_u^{-1.07} (C_C q_f)^{0.52} \quad [8]$$

Further, the significance of the abutment shape on flow concentration at the dam toe was introduced in Section 2. To incorporate this effect in the design criteria, a coefficient of concentration (C_C) was introduced in Eq 8.

Also, modified Thornton et al. (2014) approach for sizing of dumped riprap stones at dam toe is presented as Eq 9 (notations consistent with Eq 7).

$$D_{50(\min),T} = 2\, D_{50(\min),RR} = 0.46\, n^{1.63} S^{0.53} C_u{}^{-0.74} (C_C q_f)^{0.55} [1.48/(SG-1)^{0.79}] \qquad [9]$$

Advantages offered by the proposed stone sizing criteria (Eq 8 and 9) over the criteria recommended by Abt et al. (1998) (Eq 3) are listed as follows:

i. The proposed criteria (Eq 8 and 9) incorporate material and site-specific properties such as the coefficient of uniformity (based on particle size distribution), specific gravity (based on the type of construction material) and riprap thickness parameter, which were absent in Eq 3 proposed by Abt et al. (1998).

ii. As stated previously, performance of Khan and Ahmad (2011) (Eq 6) and the Thornton (2014) (Eq 7) approaches were better in comparison with Abt et al. (1991) (Eq 4) which serves as the basis for Eq 3 (Abt et al., 1998). Hence, state of the art in dumped riprap design is incorporated within the proposed criteria for sizing of toe stones of dumped ripraps. This could improve confidence for practical applicability.

iii. Validity of Eq 4 (Abt et al., 1991) was confirmed over the boundary conditions $S < 0.2$ and $D_{50(min),RR} <$ 152 mm. However, the Thornton et al., (2014) (Eq 6) and the Khan and Ahmad (2011) (Eq 7) approaches were validated over much broader boundary conditions of $S < 0.5$, $D_{50(min),RR} <$ 655 mm and $S < 0.4$, $D_{50(min),RR} <$ 278 mm respectively (Ravindra et al., 2018). This can address scaling issues related with design.

A disclaimer to the usage of the proposed empirical design criteria (Eq 8 and 9) could be in relation to its exact nature. Finding of Abt et al. (1998) which serves as the basis for the proposed criteria was based on limited data collected from experiments conducted on small scale test embankments on mild slopes (S = 0.2). Hence, further investigation of validity of the stone sizing criteria is strongly recommended on steeper slopes. Albeit the numerical values for the coefficients and the exponents include uncertainties, the parameterization of the design criteria should offer information regarding factors influencing toe stability.

$$D_{50}(T) = K\ \ n^a\ S^b\ C_u{}^c\ (C_c q_f)^d (SG)^e \qquad [10]$$

As can be inferred from Eq 10, toe stone sizing could be primarily influenced by the thickness of the riprap layer, side slope of the downstream embankment, particle size distribution, design unit discharge and properties of material employed for construction and shape of abutments.

Investigating physical validity of the proposed design criteria for toe stone sizing and assigning values to the flow concentration coefficient based on different abutment shapes is part of an ongoing research project at NTNU.

Influence of other parameters such as frictional resistance offered by the foundation and side walls, exit location of the phreatic surface on the downstream slope, permeability of toe, dimensioning of the toe

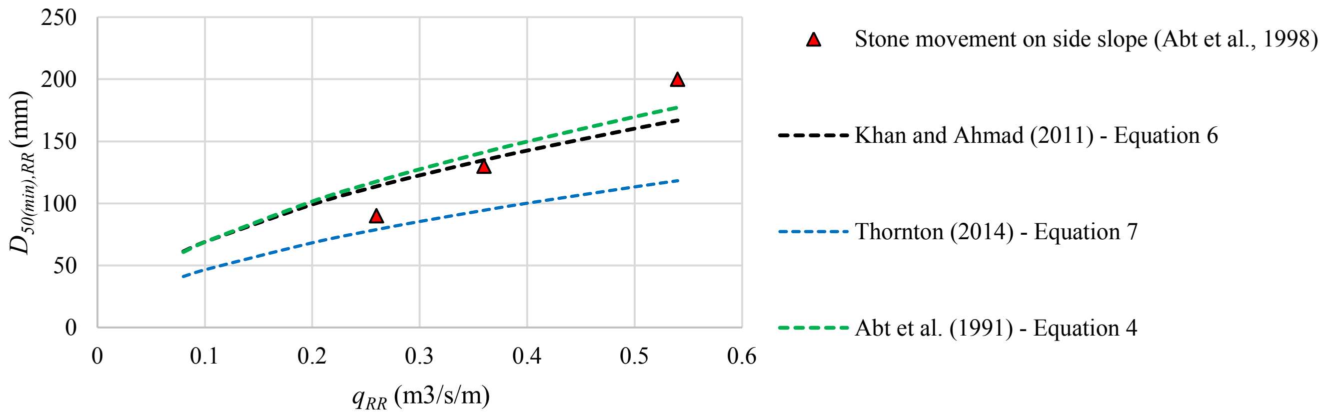

Figure 3: Empirical evaluation of Eq 4, 6 and 7 for stone movement on embankment side slope

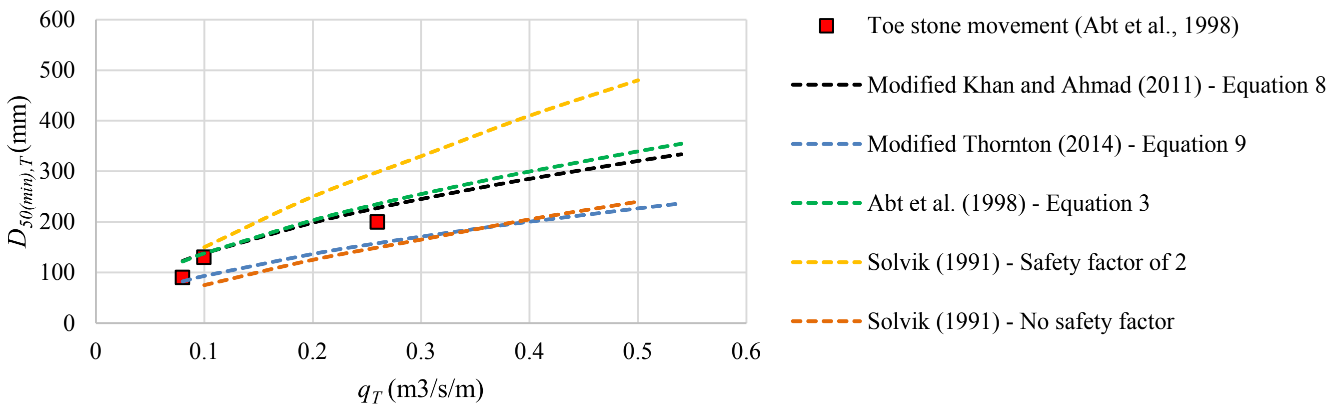

Figure 4: Empirical evaluation of toe stone sizing criteria

structure and stability of toe stones on steep abutments on embankment stability need to be incorporated in the design considerations. These are being looked into as part of the ongoing research project at NTNU.

5 Stone sizing criteria compared to available data

The proposed stone sizing criteria (Eq 8 and 9) can be tested by investigating their ability to predict experimental test results in Table 1 documented by Abt et al. (1998).

Eq 4, 6 and 7 were originally devised for sizing dumped riprap stones on embankment side-slopes. Hence, a test of these relationships against the experimental observations for stone movement on riprap side slope has been carried out in this article. The experimental setup employed by Abt et al. (1998) consisted of an embankment with side slope of $S = 0.2$. Average coefficient of uniformity of riprap stones was C_u = 1.20. Specific gravity of riprap stones was $SG = 2.63$ and the test ripraps were constructed with a thickness of 1.5 times the median riprap stone size ($n = 1.5$). Finally, the value for the flow concentration coefficient was assumed as unity ($C_C = 1$) since the experiments were conducted in a rectangular flume. So, the flow intensity could be assumed as uniform in all sections of the embankment.

These values were employed in Eq 4, 6 and 7 to predict the required sizing of riprap stones on embankment side slope at the recorded critical unit discharges for stone movements and the obtained results are presented in Figure 3. It could be observed that the computed values were overall in fair agreement with recorded measurements. However, with underestimation from Eq 7 in general, but only for the higher flows from Eq 4 and 6. Underestimation of the size requirement for riprap stones could be due to development of the design criterion with different definition of the term 'riprap failure' as riprap failure could be defined as either the complete destruction of riprap or as riprap stone movement. Design of ripraps for stone movement would require larger size stones in comparison with ripraps designed for total failure.

Further, Eq 3, 8 and 9 were employed to predict the required size of toe stones at the recorded critical unit discharges for toe stone movements with similar parameterization as employed for the previous computations and the results from the analysis are presented in Figure 4. The performance of proposed criteria in predicting the minimum required toe stone size could be considered satisfactory. Consistent underestimation for median stone size was observed on the part of Eq 9 (modified Thornton et al., 2014). Further, the predictions obtained from Eq 3 (Abt et al., 1998) and Eq 8 (modified Khan and Ahmad (2011)) demonstrated best fit with observations among the tested criteria.

As stated earlier, as per multiple review publications, Thornton et al. (2014) and Khan and Ahmad (2011) approaches best describe the stone sizing requirements for dumped riprap with the Thornton et al. (2014) approach demonstrating marginally better performance. However, the findings of this study (from Figure 3 and 4) suggest that the predictions obtained from the Khan and Ahmad (2011) approach had considerably better correspondence with observed data in comparison with the Thornton et al. (2014) approach. Furthermore, the results obtained from Thornton et al. (2014) criteria cannot be considered conservative for design purposes as this would cause stone movements.

Finally, design charts recommended by Solvik (1991) for toe stone sizing was overlaid in Figure 4 both with and without a safety factor of 2.0. An interesting observation was that the obtained results from the design chart of Solvik (1991) were in good agreement with the experimental results although the recommendations were based on limited experimental data. The design chart for Solvik (1991) with a safety factor of 2.0 was conservative especially for higher discharges. This suggest that the safety factor of 2.0 suggested by Solvik (1991) could be high and optimization of the same could be looked into.

6 Possibilities for future research

The discussions presented in this article are intended for sizing of dumped riprap stones. However, some investigations (e.g., Knauss (1979) and Hiller et al., 2017) have focused on investigation of placed riprap technology (riprap stones arranged in a specific pattern) as dam safety regulations in Norway prescribe construction of placed ripraps or ripraps built with an interlocking pattern and the stones placed with their longest axes inclined towards the dam.

This is attributed to the fact that placing stones in an interlocking pattern could result in five times higher stability (in terms of capability to withstand overtopping critical discharges) compared to randomly dumped riprap (Hiller et al., 2017).

With an objective of coupling state of the art on placed riprap technology with embankment dam toe design, a research project with the working title ‘Embankment Dam Safety Under Extreme Loading Conditions’ was initiated by HydroCen, Norway at NTNU in 2017.

The study aims at taking into account the modern state of the art on the design of placed ripraps to generate new knowledge on the stability of dam toe and abutments of rockfill dams to enhance dam safety measures. The objective of the study is arriving at criteria for design of toe section of placed ripraps.

Factors influencing rockfill dam toe stability such as the geotechnical properties of rockfill, hydraulics of turbulent flow through rockfill and abutment shape are being investigated. Physical modeling investigations in this regard are currently underway in the Hydraulics laboratory at NTNU and large-scale field tests are being planned for validation of physical modeling test results.

7 Conclusions

Preliminary criteria for sizing of stones comprising the toe of dumped ripraps for embankment dams are proposed coupling key findings from the research areas of design of dumped ripraps and embankment dam toe. The advantage offered by the proposed criteria are that they incorporate material properties and site specific properties in the computations in addition to the critical overtopping unit discharge and embankment side slope. Also, they broaden the boundary condition for applicability addressing scaling issues. However, it is communicated that the proposal is based on very limited experimental observations.

The proposed dumped riprap toe stone sizing criteria were tested using the available data demonstrating good fit with observations. Further validation of the criteria is recommended in future studies. Also, influence of other parameters such as frictional resistance offered by the foundation, stone interlocking, phreatic surface exit location on the downstream slope, permeability of toe, dimensioning and location of toe on embankment dam toe stability need to be incorporated in the design considerations and further research is recommended in this regard.

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