Toe support conditions for placed ripraps on rockfill dams – A field survey

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Summary

Riprap toe stabilization is of significance to ensure adequate overall stability of the riprap structure exposed to extreme overtopping conditions. From economical and stability points of view, it is of importance to investigate current state of toe support conditions for placed ripraps on rockfill dams. This article presents findings from field surveys investigating construction aspects of placed ripraps built on several Norwegian rockfill dams. Key parameters describing quality of placement of riprap and toe stones such as size, shape and inclination have been analysed as part of this study. Further, details concerning current state of riprap toes have been outlined. In addition, conformity of construction practices with Norwegian dam safety guidelines is also looked into. Study findings suggest that construction practices adopted for placed ripraps meet the requirements of Norwegian dam safety regulations. However, investigation outcomes also show that construction practices adopted at present do not prioritize on addressing additional recommendations put forward by the dam safety authorities with regards to placed riprap stability. Furthermore, detailed survey of riprap toe sections revealed that well-defined toe support measures stabilizing riprap toes are currently not implemented at any of the surveyed rockfill dams. Further experimental research in this regard to better understand failure mechanism of placed ripraps with realistic toe support conditions is recommended. Also, experimental investigations to arrive at methodologies to provide ideal toe support for placed ripraps on rockfill dams is recommended.

Sammendrag

Tåstøtte til plasting på steinfyllingsdammer – en feltstudie. Sikringstiltak ved damtå har betydning for stabilitet til plastring som blir utsatt for overtopping. Fra et økonomisk og stabilitetsmessig ståsted, er det viktig å studere hvordan tåstein faktisk er plassert på plastrede steinfyllingsdammer. Denne artikkelen presenterer funn fra feltkartlegging, gjennomført for å undersøke utforming av nedstrøms plastring og tå på eksisterende norske steinfyllingsdammer.

Ulike parametere som beskriver kvaliteten til plastringen, slik som størrelse, form og helning av tå- og plastringsstein, har blitt analysert som en del av denne studien. Videre blir detaljer vedrørende praksis for sikring av tåstein beskrevet. I tillegg blir samsvar mellom eksisterende fyllingsdammer og norsk regelverk for bygging av fyllingsdammer undersøkt. Funn fra studien antyder at plastring på eksisterende fyllingsdammer oppfyller kravene som er gitt i damsikkerhetsforskriften. Derimot viste resultatene fra kartleggingen at ytterligere anbefalinger for å sikre en stabil plastring, gitt i Veileder for fyllingsdammer, ikke er oppfylt. Dessuten viste studier av nedre del av skråningene at ingen av de kartlagte steinfyllingsdammene er bygd med ekstra sikringstiltak for tåstein. Videre studier anbefales for å bedre kunne forstå bruddmekanismene til plastring som ikke er sikret ved damtå. I tillegg anbefales det å utføre fysiske modell- og storskalaforsøk med et formål om å utvikle metoder for sikring av tåstein som gir tilstrekkelig stabilitet av plastring på fyllingsdammer.

Introduction

Dams are essential for hydropower development as they enable storage of water in reservoirs, in turn assisting stable power production. There are over 360 large dams in Norway at present (over 15 m high) and over 180 of these are rockfill dams. Several of the existing Norwegian rockfill dams are poised to be upgraded in the near future to meet requirements of revised dam safety regulations. Upgrading of rockfill dams often includes expensive reconstruction of the downstream riprap. Riprap is one of the most common measures for erosion protection of downstream slopes of rockfill dams (e.g. Abt et al., 2013, Ravindra et al., 2018a, Hiller et al., 2018a and Ravindra et al., 2019). Ripraps can be broadly classified into two categories based on the method of construction. Dumped ripraps comprise of randomly placed stones while placed ripraps are characterized by stones arranged in a specific interlocking pattern (Hiller et al., 2018a and Ravindra et al., 2019).

Evaluation of stability aspects of placed ripraps constructed on rockfill dams is important from economical and safety standpoints. Although extensive literature is available within the discipline of dumped riprap design, available international literature on the stability and design aspects of placed ripraps in connection with rockfill dams is limited (Ravindra et al., 2018a). Past studies such as Knauss (1979), Larsen et al. (1986), Sommer (1997), Dornack (2001), Peirson et al. (2008), Hiller et al. (2018a) and Ravindra et al. (2019) have been aimed at investigating the underlying failure mechanisms of placed ripraps exposed to overtopping flows. These experimental investigations were conducted on model placed ripraps constrained at the toe using metallic support structures.

It should be noted that toe section of the riprap in this article refers to the last row of riprap stones placed on the downstream dam foundation (Figure 1). On the other hand, the term rockfill dam toe refers to either an internal or an external structure constructed in tandem with the downstream rockfill shoulder comprising of coarser material as compared with the rockfill shoulder material. This facilitates expulsion of seepage or accidental leakage flows from within the dam structures thereby preventing build up of excess pore pressures. Hence, rockfill dam toe is constructed to assure enhanced stability of the downstream shoulder under extremely high through-flow conditions (Morán et al., 2019). This article is intended at investigating construction aspects of only the toe sections of placed ripraps on rockfill dams.

Several past investigations looking into the stability of ripraps under overtopping situations have suggested that the probability of initiation of failure at the toe section of ripraps can be significant (Figure 1). Hiller et al. (2018b) and Lia et al. (2013) present findings concerning placed riprap stability from large-scale overtopping tests stating that none of the tested ripraps failed as a consequence of breach of the riprap structure in itself. All failures were observed to have initiated at the toe or along the sidewalls of the ripraps. Further along similar lines, Solvik

(1991) based on model studies has argued that special attention should be directed towards stabilizing toe section of ripraps.

These observations can be considered to be a consequence of the toe stones and stones placed along the abutments being exposed to higher magnitude hydrodynamic forces during overtopping events in comparison with riprap stones placed on the dam slopes. Flow concentration at the toe section of ripraps under throughflow conditions result in highly erosive hydrodynamic drag and lift forces on the toe stones (Figure 1). Further under overflow conditions, the destabilizing forces on the riprap toe are amplified as the toe has to deal with dynamic forces transferred by the overlying riprap layer in addition to the destabilizing drag and lift forces (Figure 1) (Ravindra et al., 2018b). Hence, the riprap toe stones need to be provided with adequate support to inhibit removal of the stones under the influence of destabilizing hydrodynamic forces.

In order to safeguard dams against accidental overtopping events, dam safety regulations in Norway prescribe construction of single-layered placed ripraps on the downstream slopes of rockfill dams. The individual riprap stones are to be placed in an interlocking pattern with their longest axis inclined towards the dam (OED, 2009; NVE, 2012). Placed ripraps on rockfill dams exposed to overtopping can fail as a consequence of sliding or structural collapse of the riprap structure depending on the toe support conditions. In case of a constrained toe support, the riprap structure may fail because of structural collapse as a fixed support is provided to avoid sliding of the riprap structure (Ravindra et al., 2019). However, in case of an unrestrained toe, the riprap section could undergo sliding along the steep slope as a result of limited frictional resistance offered at the foundation (Ravindra et al., 2019). Hence, configuration of the toe section of placed riprap can be considered a key factor influencing the overall failure mechanism of placed ripraps exposed to overtopping flows.

The Norwegian Water Resources and Energy Directorate (NVE, 2012) recommend design specifications for placed ripraps in general. However, protocols addressing specifics on the design aspects of toe support for the riprap structures are currently unavailable. The available references within the NVE recommendations pertinent to riprap toe stability state that it may be necessary to secure the lowermost part of the downstream slope and the abutments of rockfill dams with larger stones, or other reinforcing measures based on the dam cross-section and overtopping flow magnitude. It is also stated that rock foundation should provide good support against sliding of the toe stones. If the foundation should provide good support against sliding of the toe stones, one has to blast a trench or cast a foot, especially for foundations with inclinations larger than 10°. Although these statements point out key design considerations

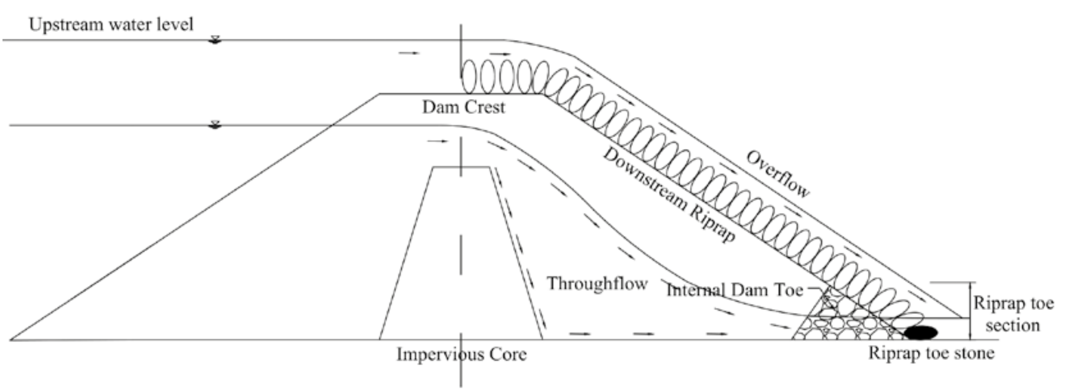

Figure 1. Description of throughflow and overflow scenarios in rockfill dams

with regards to riprap design, technical details of design and construction of riprap toe support structures is currently not provided. But, earlier discussions with regards to riprap toe brings forth the possibility that probability of initiation of unraveling riprap failure could be high at the toe section. Since previous studies conducted to investigate placed riprap stability under overtopping conditions have been conducted with placed riprap structures constrained at the toe section using rigid support structures, it is of relevance to comprehend existing toe support conditions on rockfill dams. This would help facilitate development of experimental studies for realistic evaluation of stability of placed ripraps exposed to overtopping flows.

The present field survey was intended at investigating toe structures and construction aspects of placed ripraps and riprap toe conditions of several Norwegian rockfill dams. As part of the survey, key parameters describing quality of placement of riprap and toe stones such as size, shape and inclination were recorded and these have been further analysed and discussed in the present article. Further, conformity of placed riprap toe construction with official dam safety guidelines are evaluated as part of the present study. Observations from the field survey concerning existing toe conditions for placed ripraps are also presented. This article is primarily aimed at facilitating evaluation of practical applicability of findings from past experimental investigations.

Study methodology

A field survey of placed ripraps on 33 different Norwegian rockfill dams was conducted by Hiller (2016). The present study adds to the findings of Hiller (2016) through investigation conducted to study details concerning toe construction of placed ripraps on nine Norwegian rockfill dams. Details regarding the dam location, consequence classification, height and length are presented in Table 1. The rockfill dams chosen for the field surveys consisted of varying sizes of dams from 5 m up to 142 m in height (H) and from 70 m to 1400 m in length (L). The criteria for dam selection was presence of well-defined toe structures within the dam structure. The selections included Oddatjørndammen (H = 142 m and L = 466 m) which is the highest rockfill dam in Norway and Storvassdammen (H = 90 m and L = 1400 m) which is the largest Norwegian rockfill dam by volume. Further, the selection also comprised of dams belonging to different Norwegian dam safety consequence classes (2 to 4). The classification considers potential for damage to life and property in case of dam breach (NVE, 2012). Class 4 designates dams with very high potential for damage in case of dam failure. Class 3 indicates dams with high damage potential and class 2 signifies dams with medium damage potential (Midttømme et al., 2012). The variability in dam sizes was considered as an important parameter in order to obtain a representative picture of placed riprap toe construction in Norwegian rockfill dams.

The methodology adopted by Hiller (2016) with regards to their field survey of placed riprap construction on Norwegian rockfill dams has further been incorporated in this study to investigate construction aspects of both the riprap and the toe structures. The nominal stone size (d_n) has been employed to quantify sizing of the riprap stones as this can be considered as the representative size of individual riprap stones (equation 1). Computation of d_n requires measurements of the longest, intermediate and the shortest axes dimensions of the riprap stones (a, b and c stone axes dimensions) (Hiller et al., 2018a). The median stone size (d_{50}) for the stones is further computed as the average of individual nominal stone sizes. Furthermore, the placement angle of the riprap stones with respect to the downstream dam slope is characterized through the parameter (α) (Figure 2), which is the sum of the downstream embankment slope (θ) and the inclination of the longest stone axis with respect to the horizontal (β) (equation 2).

$$d_n = (abc)^{1/3} \tag{1}$$

$$\alpha = \beta + \theta \tag{2}$$

Table 1. Details of the dams surveyed as part of the study

Dam Index	Dam name	Location	Consequence class	Dam Height (*H*) (m)	Dam Length (*L*) (m)
1	Vessingsjø Secondary dam	Tydal, Trøndelag	2	5	70
2	Skjerjevatnet Secondary dam 1	Masfjord, Hordaland	2	18.7	101.2
3	Skjerjevatnet main dam	Masfjord, Hordaland	3	29.5	251
4	Nesjø main dam	Tydal, Trøndelag	4	45	1030
5	Fjellhaugvatn dam	Kvinnherad, Hordaland	2	52	72.8
6	Akersvass dam	Rana, Nordland	4	53	485
7	Førreskar dam	Suldal, Rogaland	3	81	640
8	Storvass dam	Suldal, Rogaland	4	90	1400
9	Oddatjørn dam	Suldal, Rogaland	3	142	466

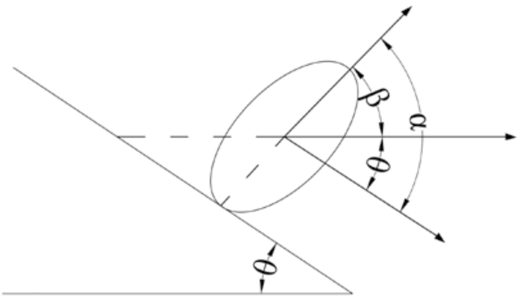

Figure 2. Portrayal of stone inclination with respect to the dam slope (α) as sum of inclination with respect to the horizontal (β) and embankment slope (θ)

The field measurements were subdivided into two different measurement phases. The first phase included measurements conducted to study the properties of the riprap section and the second phase was primarily intended at investigating properties of the toe stones and the toe support conditions. During the first phase of measurements, sizing of the riprap stones (*a*, *b* and *c*) and the inclination of the stones with respect to the horizontal (β) were measured for individual stones lying within a random 5 m x 5 m strip of the riprap. The stone dimensions were measured employing standard rulers and the inclinations were measured using a digital inclinometer. During the second phase of the survey, the dimensioning and the placement inclination of toe stones placed along the length of the dam toe were measured at regular distance intervals dependent on the dam length. Also, details regarding existing support conditions for the toe stones were recorded during this phase of the survey.

Data analysis

The data sets accumulated as part of the field survey of placed ripraps have been subjected to a statistical evaluation in this section of the article. Measurements of stone sizes (*a*, *b* and *c*) have been used to analyse the size distribution and angularity of the riprap and the toe stones. Further, measurements of inclination of the stones with respect to the horizontal (β) have been employed to compute the angle of placement of the stones with respect to the downstream slope (α). These results have further been subjected to a comparative evaluation with Norwegian dam safety requirements and recommendations to comprehend compatibility between construction practices and official guidelines.

The Norwegian Ministry of Petroleum and Energy (OED, 2009) is the official body providing

Table 2. Summary of official regulations and recommendations with respect to placed ripraps

Parameter	OED (2009) regulations	Additional NVE recommendations
Minimum stone size (d_{min})	The downstream slope should have slope protection which ensures that the dam can withstand large overtopping due to accidental loads or damage to the dam. Stones within the riprap must have satisfactory size and quality and be arranged in a stable manner.	$$d_{min} = 1.0\ S^{0.43}\ q_f^{\ 0.78}$$ (3)*
Uniformity of stone size (d_{max} /d_{min})		d_{max} / d_{min} < 1.7*
Angularity		The stones be situated within the bladed to rod shape regimes within the Zingg diagram (Zingg, 1935) to ensure optimum interlocking with minimal void formation**.
Stone placement	The individual riprap stones are to be placed in an interlocking pattern with their longest axis inclined towards the dam.	As stated in the OED (2009) regulations*

*Obtained from NVE (2012) and ** from the presentation Hyllestad (2007).
where d_{min} and d_{max} denote the minimum and maximum riprap stone sizes; *S* stands for the downstream embankment slope (*S* is the ratio of the vertical to the horizontal slope dimensions) and q_f represents recommended minimum design discharge value for the respective dam consequence classifications.

regulations regarding design and construction of rockfill dams in Norway and the NVE puts forward additional technical recommendations in this regard (NVE, 2012). Table 2 succinctly summarizes the official regulations and recommendations concerning design and construction of placed ripraps.

Stone sizing

The size distribution of the stones were computed as fractions of individual stone weights to the cumulative weight of the measured stones (Figure 3). Individual stone weights (*W*) were computed employing Equation 4 with the nominal stone size (d_n) obtained employing equation 1.

$$W = d_n C_f \gamma_S \qquad (4)$$

with C_f representing the form factor for the stones, generally assumed as 0.6 (NVE, 2012) and γ_S denoting stone density (assumed herein as 26 kN/m^3).

To conduct a comparative evaluation between field measurements of riprap stone sizes and official dam safety recommendations with regards to minimum required sizing of riprap stones, the minimum stone sizing recommendations obtained from equation 3 have been compared with the computed gradation curves within Figure 3. As per the recommendations of NVE dam safety guidelines of 2012, placed ripraps need to be constructed with stones of volume of minimum 0.15 m^3 (d_{min} = 0.64 m) for dams classified within consequence class 4. To determine the minimum median riprap stone sizing for dams in classes 3 and 2, NVE prescribes equation 3 assuming minimum unit discharges 'q_f' of 0.5 m^3/s for class 3 and 0.3 m^3/s for class 2 respectively (NVE, 2012).

Figures 3a, 3c and 3e depict size distributions for riprap stones from the surveyed placed ripraps constructed on different dams classified within dam safety classes 2, 3 and 4 respectively and Figures 3b, 3d and 3f present size distributions for toe stones from the respective dams. Furthermore, minimum stone sizing recommendations for the respective dam safety classes (equation 3) are presented within the respective plots. It can be observed from the depictions that all dams meet the recommended minimum sizing criteria for all dam safety classes. It should also be noted that the sizing of the riprap stones was in general closely resembling the sizing of the toe stones with $d_{50,T}$ / $d_{50,RR}$ ranging from 1 to

1.25 with $d_{50,\,T}$ / $d_{50,\,RR}$ representing the ratio of median toe stone size to that of the riprap stones. However, for Fjellhaugvatn dam (Figures 3a and 3b) and for Storvass dam (Figures 3e and 3f), the toe stones were found to be of comparatively larger sizing than the riprap stones with $d_{50,\,T}$ / $d_{50,\,RR}$ of 1.53 and 1.45 respectively.

Further, the NVE guidelines for design and construction of placed ripraps also recommend that the ripraps should be comprised of uniform sized stones conforming to the criteria d_{max} /d_{min} < 1.7 (NVE, 2012). Figures 4a and 4b portray the ratio of the maximum to the minimum stone diameters for the riprap and the toe stones respectively from all the surveyed dams. The NVE guideline in this regard has also been overlaid within these plots. The depictions demonstrate that none of the dams meet the criteria considering size distribution of the riprap stones (Figure 4a). Two of the dams, Vessingsjø secondary dam and Fjellhaugvatn dam met the recommendation with regards to size distribution of the toe stones (Figure 4b).

Shape

The Zingg shape classification scheme (Zingg, 1935) is widely employed within numerous research disciplines to classify particles into different form categories such as spheroids, discs, rods and blades based on the *b*/*a* and *c*/*b* ratios. This technique has been employed in this study to determine the angularity of the measured

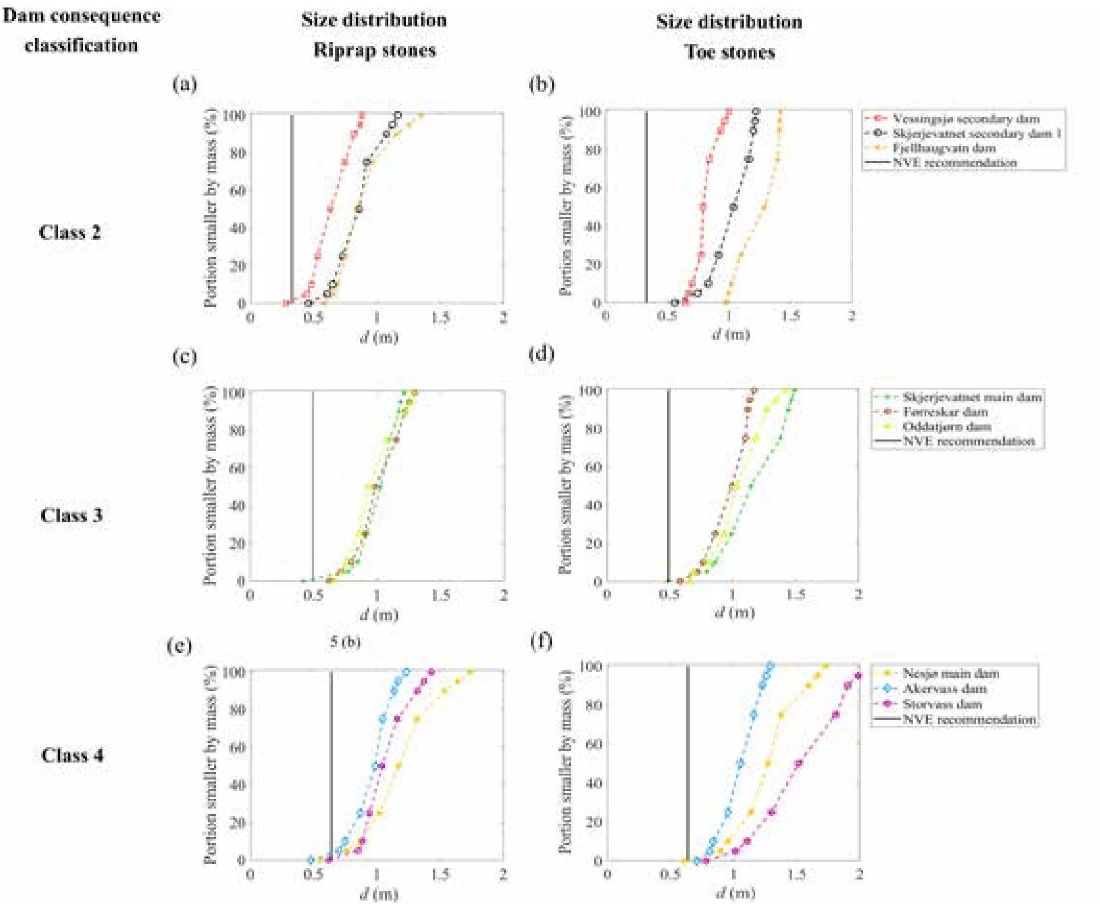

Figure 3. Panels a, c and e present size distributions for riprap stones from dams classified within consequence classes 2, 3 and 4 respectively. Panels b, d and f present size distribution for toe stones from dams classified within consequence classes 2, 3 and 4 respectively.

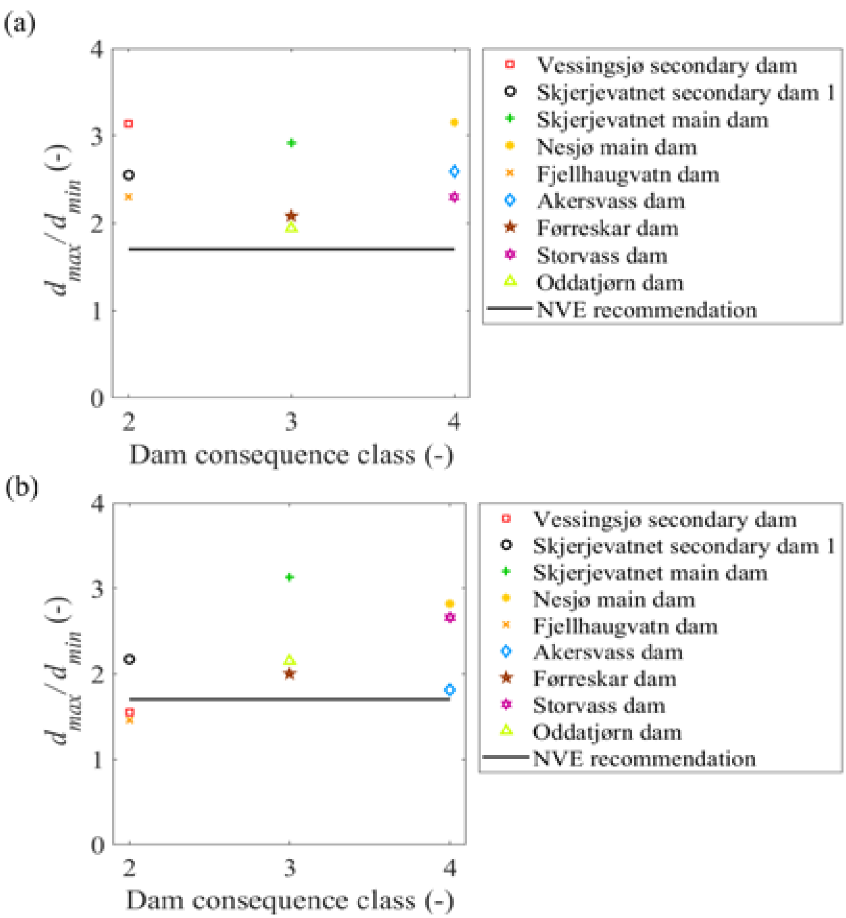

Figure 4. Panel a present plots depicting the ratio of the maximum to minimum stone diameters for the riprap stones for all the surveyed dams. Panel b presents the ratio of the maximum to minimum stone diameter for the toe stones for all the surveyed dams.

stone in line with the technique demonstrated by Hiller (2016). The NVE recommends that the stones should be situated within the bladed to rod shape regimes within the Zingg diagram (Figure 5) in order to ensure optimum interlocking with minimal void formation.

Figures 5a and 5b portray Zingg diagrams for all the measured riprap and toe stones respectively from the surveyed dams. Majority of the measured riprap stones (67 %) lie outside of the NVE specified region within the Zingg diagram with dense clusters formed at the disc to the spheroidal regions (Figure 5a). This was a trend observed also for the toe stones with 69% of the measured toe stones lying outside of the NVE recommended region with cluster formation closely resembling that of the riprap stones (Figure 5b).

Stone placement and inclination

Measurements of inclination of the stones with respect to the horizontal (β) obtained from field survey of the riprap and the toe stones have been employed to compute the angle of placement of the stones with respect to the downstream slope (α) as part of this study.

Figures 6a and 6b present the computed inclinations (α) for the riprap and the toe stones respectively for all the surveyed dams. The dam index in the respective plots represent the designations assigned for the individual dams as shown in Table 1. As can be inferred, the computed α

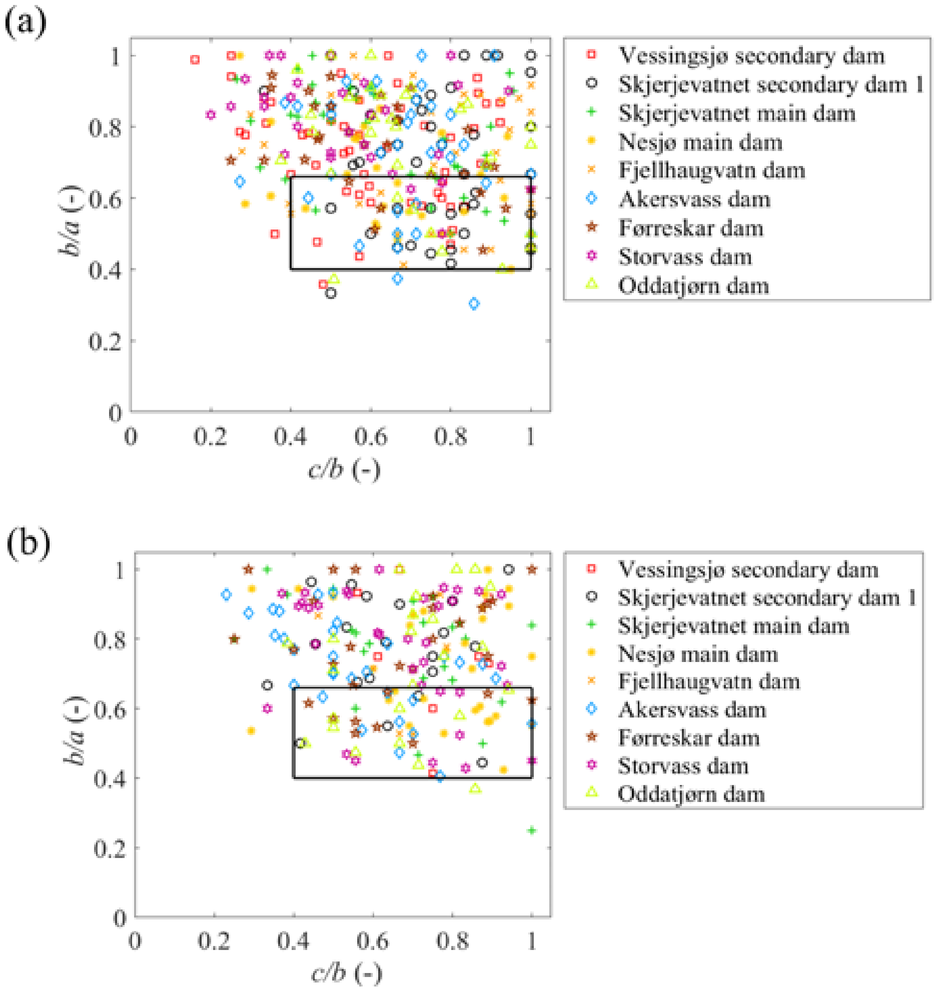

Figure 5. Panel a presents a Zingg diagram for all the measured riprap stones, and panel b presents a Zingg diagram for all the measured toe stones.

angles varied over broad ranges of 30° to 120° for the riprap stones and from 0° to 60° for the toe stones. The average placement inclinations for the riprap and the toe stones from all the surveyed dams were found to be α_{RR} = 56° and α_T = 16° with α_{RR} and α_T representing mean inclination for the riprap and the toe stones for all the surveyed dams respectively.

As stated in Table 2, the official dam safety guidelines put forward by OED (2009) or NVE (2012) state that the individual riprap stones are to be placed in an interlocking pattern with their longest axis inclined towards the dam. However, no angle of placement for the stones is specified. The conducted field surveys revealed that the riprap stone placement in general were in accordance with this requirement.

Toe classification

Details concerning toe construction of the placed ripraps charted as part of the present study were recorded during the survey of toe stones placed along the length of the dam toes. Based on these observations, toe conditions for the surveyed dams have been classified into five different categories (Table 3). The following discussions intend to describe the current state of riprap toes and outline various construction

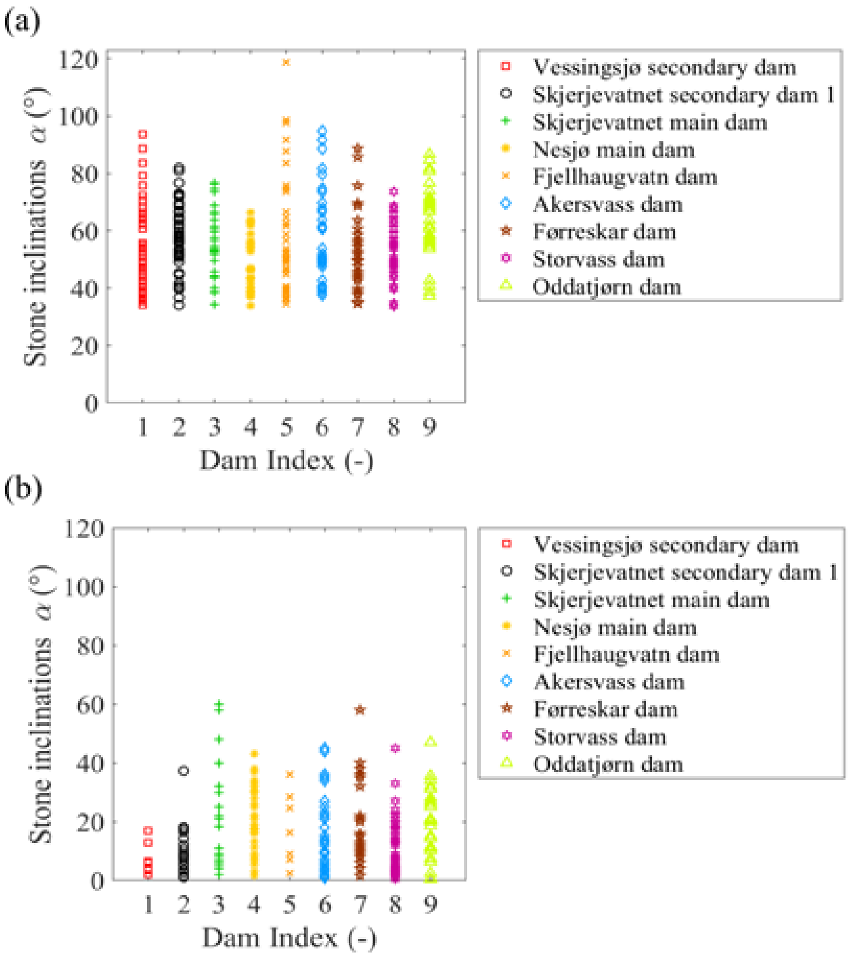

Figure 6. Panel a presents computed inclinations (α) for the riprap stones from all the surveyed dams. Panel b presents computed inclinations (α) for the toe stones from all the surveyed dams.

and stabilizing methods observed during the field inspections.

The first category of riprap toe construction includes ripraps built with no toe support. This entails that the toe stones were either lying on bare rock surfaces or buried underneath moderate amounts of soil cover. Placed ripraps buried with earth/grass cover are considered to have no toe support considering the fact that under overtopping conditions, highly turbulent throughflow and overflow forces would lead to rapid erosion of the soil/grass cover. All the surveyed ripraps can be classified under this category as majority of the toe sections were resting on bare rock surfaces or buried with moderate amount of soil cover. Illustrations of these toe support conditions are presented for dams Fjellhaugvatn, Oddatjørn and Skjerjevatnet main dam in Figure 7a, 7b and 7c respectively. Toe stones at Fjellhaugvatn dam and Skerjavatnet main dam were found to be resting on rock surfaces whereas toe stones at Oddatjørn dam were buried under moderate soil cover.

The second category of observed riprap toe conditions at the surveyed dams consists of submerged riprap toe sections. This was the case at certain reaches of riprap toe sections of Skjerjevatnet main dam and Skerjevatnet secondary dam 1. An illustration of the scenario at Skjerjevatnet main dam is depicted in Figure 7d.

Table 3. Classification of different riprap toe conditions

Category	Description of toe condition	Dam name
1	No toe support	All surveyed dams (Table 1)
2	Submerged toe	Skjerjevatnet main dam Skjerjevatnet secondary dam 1
3	Larger stones at the toe	Fjellhaugvatn dam Storvass dam
4	Tie back rods	Storvass dam
5	Concrete wall	Akersvass dam

Figure 7. Depiction of existing conditions of placed riprap toe sections. Category 1 at dams (a) Fjellhaugvatn dam (b) Oddatjørn dam and (c) Skjerjevatnet main dam. Category 2 at (d) Skjerjevatnet main dam. Category 4 at (e) Storvass dam. Category 5 at (f) Akersvass dam.

Accumulation of water at the downstream toe section of the dams could be due to a variety of causes such as seepage from the dam, snowmelt and rainfall.

Further, the third classification of riprap toe conditions observed was the placement of larger sized stones at the toe section of the riprap. Fjellhaugvatn dam and Storvass dam fall under this category as larger size stones ($d_{50,T}$ / $d_{50,RR}$ = 1.53 and 1.45 respectively) were found to be placed at the toe sections of these dams. For the rest of the surveyed dams, stone sizing at the toe and the riprap were found to be comparable.

The fourth category of riprap toe construction observed was the use of steel bars for stabilization of the toe stones. A small section of the riprap toe at Storvass dam was observed to be supported employing reinforcing steel bars (Figure 7e) measuring 25 mm in diameter with average outcrop length of 0.3 m. Although majority of the riprap toe sections of Storvass dam were observed to be unsupported, the reinforcing bars were used to stabilize toe sections of the riprap close to the right abutment where the foundation was observed to be at a steep inclination.

At Akersvass dam, a small stretch of the riprap toe section was seen to be supported with a concrete wall (Figure 7f) and this is classified as the fifth riprap toe state observed as part of this field study. The concrete wall was constructed in tandem with a leakage measuring station and hence, it was evident that riprap toe stabilization was not the primary intention of constructing the structure but rather to facilitate leakage measurements from the dam.

Discussions

The size distributions for the riprap and the toe stones presented as Figure 3 demonstrate that the stones employed for construction are of larger sizing in comparison with NVE recommendations. Further, Figure 4 depicting the ratio of the maximum to the minimum stone dimensions show that sizing of riprap and the toe stones were non-uniform in nature (d_{max} / d_{min} > 1.7) as opposed to the NVE recommended d_{max} / d_{min} < 1.7. Furthermore, majority of the measured riprap and toe stones were found to be disc to spheroidal in shape (Figure 5). These observations are further corroborated by the findings of Hiller (2016). The stone size distribution plots from Hiller (2016) also show that sizing of riprap stones is larger than the NVE recommendations. The d_{max} / d_{min} ratios for the measured riprap stones were documented to be larger than 1.7 in all of the surveyed dams. Further, the Zingg diagrams from the present study correspond well with those documented within Hiller (2016).

As stated in Table 2, the official dam safety regulations (OED, 2009) only stipulate that the downstream slope should have slope protection which ensures that the dam can withstand large overtopping due to accidental loads or damage to the dam and that the stones within the riprap must have satisfactory size and quality and be arranged in a stable manner. It is evident from the outcomes of the present study that the OED (2009) requirements for placed riprap construction have been met at all of the surveyed dams. This is considering that the riprap stones employed for constuction were of sufficient sizing (Figure 3) and the stones were observed to be placed with good interlocking with the longest stone axes towards the dam slopes. Furthermore, analysis results also show that additional recommendations presented within the NVE guidelines with regards to uniformity and angularity of stones are not strictly adhered to. Placed riprap construction is a labor and resource intensive activity and thus can influence overall economical viability of the project. Hence, existing placed riprap constrution practices take into account the most important parameters influencing riprap stability and additional recommendations with regards to uniformity and angularity of stones are not prioritized. This is considering that obtaining large volumes of stones from the quarrey strictly adhering to such criteria can add significant costs to construction.

Analysis of obtained field measurements on riprap and toe stone placement inclinations revealed that the average placement inclinations for the riprap and the toe stones from all the surveyed dams were found to be $\alpha_{RR} = 56°$ and $\alpha_T = 16°$ respectively. Placement inclinations for toe stones are considerable lower in comparison with riprap stones because ripraps are constructed by placing individual stones commencing at the toe section progressing in the upstream direction. The stones placed at the toe section of the ripraps are generally laid on the ground or at the inclination of the downstream foundation, thereby resulting in low inclinations. Further, stones are placed at incremental inclinations progressing upwards, resulting in higher stone inclinations with respect to the dam slope. Furthermore, findings from large scale field tests conducted by Lia et al. (2013) show that placing riprap stones at an inclination of $\alpha \approx 60°$ resulted in considerable stability gain as compared to stones placed at flatter inclinations. Hence, existing placement techniques for placed riprap stones can be considered as adequate from a stability point of view.

Riprap toe stones at Fjellhaugvatn dam and Storvass dam were found to be of relatively larger size as compared with the riprap stones ($d_{50,T} / d_{50,RR} \approx 1.5$). Certain sections of the riprap toes at Skjerjevatnet main dam and Skerjevatnet secondary dam 1 were found to be in a submerged state. A small section of the riprap toe at Storvass dam was observed to be supported employing tie back rods. Further, at Akersvass dam, a small stretch of the riprap toe section was seen to be supported with a concrete wall.

Albeit the sizing of the toe stones are comparatively larger than the riprap stones at Fjellhaugvatn dam and Storvass dam ($d_{50,T} / d_{50,RR} \approx 1.5$), they can still be considered of comparable scale. Further, Fjellhaugvatn dam is constructed in a narrow channel thereby giving rise to possibility of flow concentration at the dam toe under throughflow and overtopping conditions. To achieve favorable degree of toe stability, adoption of more robust toe support structures would be necessary. Further, certain reaches of riprap toe sections of Skjerjevatnet main dam and Skerjevatnet secondary dam 1 were found to be in submergence states. However, raised downstream water level elevates the point of exit of the phreatic surface (under which the rockfill dam is saturated with water) of the seepage water under throughflow or overtopping conditions, in turn resulting in exposure of larger area of the downstream riprap to flow forces. Raising tail water level can also lead to issues with leakage measurements from the dams. Further, 25 mm steel bars were employed to stabilize the key stones at a certain stretch of riprap toe at Storvass dam with steep foundation inclination. Considering that Storvass dam is a 90 m high rockfill dam with riprap comprised of stones of the order of $d_{50} = 1$ m, use of such reinforcement bars can be considered to offer insignificant stability increment against overtopping flow forces. Furthermore, a concrete retaining wall has been constructed along a small reach of the riprap toe section at Akervass dam. Although this may offer certain degree of resistance against hydrodynamic forces in case of accidental overtopping events, the capacity of the wall to withstand the high magnitude hydrodynamic forces needs to be ascertained.

Observations made with regards to toe support conditions for placed ripraps on the surveyed dams suggest that none of the ripraps are currently equipped with well-defined toe support structures. Since the current understanding of failure mechanisms of placed ripraps stems from experimental investigations conducted on model ripraps with fixed toe supports, it seems necessary to investigate the importance of toe support in discerning the failure mechanism and in turn, overall stability of placed ripraps. To address this concern, experimental overtopping tests on model placed ripraps with unconstrained toe sections have been recently conducted at the hydraulic laboratory of NTNU, Trondheim. Investigation outcomes suggest sliding as the failure mechanism in placed ripraps without a fixed toe support in contrast with the buckling failure mechanism described by Ravindra et al. (2019) for the same placed riprap model coupled with a fixed toe support structure. Further, the average ratio of failure discharges for placed ripraps with and without toe supports was found to be 4.2 suggesting significant reduction in stability. Furthermore, critical discharges for placed ripraps without toe support were found to be similar to those for dumped ripraps whereas Hiller et al. (2018a) documented ratios of failure discharges between 5 and 10 between placed ripraps with toe supports and dumped ripraps. Toe support was found to have minimal effect on stability of dumped ripraps. Further details in this regard will be presented within a seperate article.

These observations suggest that toe support conditions can have significant impact on overall stability of placed ripraps. Since existing placed ripraps on Norwegian rockfill dams are constructed without any form of toe support, it is essential to stabilize toe sections of these structures to enhance overall stability. Further experimental investigations in this regard to arrive at ideal methods for providing toe support for existing placed ripraps is recommended.

Conclusions

This study is intended at shedding light on a key issue related to placed riprap stability which can place findings from experimental studies into a practical framework and also facilitate further research in this study discipline. This article presents findings from a field survey conducted to investigate construction aspects of placed ripraps on rockfill dams. Key parameters describing quality of placement of riprap and toe stones such as size, shape and inclination with respect to the dam slope have been analysed as part of this study. Details concerning existing state of toe conditions for the surveyed riprap structures have been outlined. Further, conformity of construction practices with Norwegian dam safety guidelines is also addressed.

Study findings suggest that construction practices adopted for placed ripraps meet the requirements of Norwegian dam safety regulations. However, investigation outcomes also show that construction practices adopted at present do not prioritize on addressing additional recommendations put forward by the dam safety authorities with regards to placed riprap stability. Furthermore, observations from the present study document the fact that placed ripraps built on Norwegian rockfill dams are currently not equipped with well-defined toe support structures stabilizing the toe stones. However, outcomes from recent experimental tests conducted at the hydraulic laboratory of NTNU, Trondheim suggest configuration of the toe section of placed riprap as a key factor influencing the overall failure mechanism in placed ripraps exposed to overtopping flows. Hence, it is essential to stabilize toe sections of existing placed riprap structures to enhance overall stability. Further experimental investigations in this regard to arrive at design criteria for the toe support of existing placed ripraps is recommended.

Acknowledgements

The authors acknowledge the financial support provided by HydroCen, Norway. The support and co-operation offered by all the dam owners BKK, SKL and Statkraft during the field surveys is greatly appreciated.

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