Overtopping erosion of rockfill dams – Research in Norway

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1. INTRODUCTION

The most important element to avoid damages from overtopping on an embankment dam is the spillway. A sufficient spillway will be capable of bypassing large floods and debris arriving at the dam site. However, there could still be a possibility that situations outside the design criteria can cause consequences where the dam will be exposed to erosion from overtopping. Such situations are for example:

- Floods with magnitudes much larger than that considered design floods
- Blocked spillway
- Landslide generated waves in the reservoir
- Unexpected settlements in the dam or foundation

Downstream slope erosion protection is commonly constructed of coarse rockfill, dumped riprap or ripraps constructed with stones placed in an interlocking pattern. Further, erosion from excessive throughflow in the dam body can also have similar effects to the downstream side as from overtopping, but is normally a dam toe issue.

During the last 15 years, several research programs (in Norway) have been carried out to study the erosion and the erosion protection on the downstream side. The most important research projects are:

- Stability and Breaching, 2002 – 2005, incorporated in the EU-project IMPACT.
- Full scale testing of riprap, 2011 – 2013
- PlaF, Riprap on rockfill dams, 2013 – 2017
- PlaF2, 2017 – ongoing, Stability of key stones in dam toe and steep sloping abutments

This article provides a brief overview of the past research work conducted in the area of downstream slope erosion protection and their key findings.

2. STABILITY AND BREACHING, 2001 – 2005

In the period 2001 – 2003, a test program with 23 laboratory tests (dam height 0,6 – 1,2 m) and 12 full-scale tests on seven different dams were carried out, Jenssen and Søreide (2006) and Løvoll (2006). None of the dams were tested with riprap and none of the full scale dams failed from throughflow which means that all of them failed of a consequence of erosion resulting from overtopping. Relevant data and relationships between grain sizes, compaction and unit discharge were found together with several other findings like flow pattern, failure modes, breaching parameters, etc. The main findings relevant for downstream erosion from overtopping were, see also Figure 1, E (◊) represents the test results compared with former equations C & D:

1. The tests showed significant higher capacity (critical grain size/unit discharge) than former criteria based on just model tests.
2. For homogeneous dams and zoned dams under overtopping conditions, erosion was found to be the underlying failure mechanism and not mass slope instability.

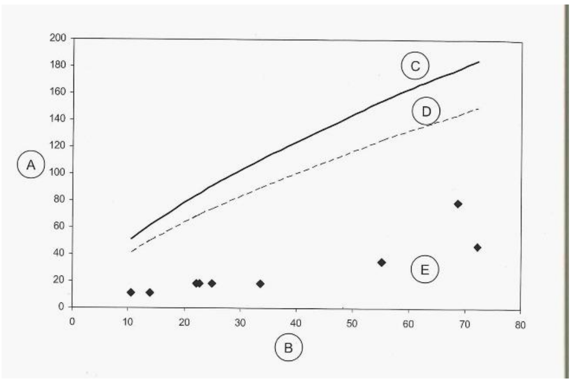

Figure 1, Relationship between unit discharge [l/s·m] on x-axis and stone diameter [mm] on y-axis, Jenssen and Søreide (2006)

Figure 2, Downstream erosion on rockfill dams, Photo: EnFo

3. Throughflow of water did not bring rockfill dam slopes milder than 1:1,5 to failure, whereas overtopping did.

All the tests were run without any kind of riprap structure on the downstream slope, thus the seven full-scale test dams (H = 6 m) failed as a result of exposure to severe erosion processes. Further, the documented magnitudes of failure initiation overtopping flows were low, EBL (2007). The erosion propagated in a pattern influenced by the grain size distribution, briefly described in EBL (2007).

3. FULL SCALE TESTING, 2011 - 2013

A research program intended at investigating riprap protection on the downstream slopes of rockfill dams was initiated by Energy Norway at NTNU in 2011. The objective of the project was to detect the parameters influencing the strength of the riprap on steep slopes (1:3,0 - 1:1,5) with throughflow and overtopping. The main parameters investigated were stone size, inclination of stones, shape of stones by axis ratios (a-b-c), interlocking pattern and compaction. By numerous physical model tests both at NTNU and UPM in Spain the principles were detected and also the failure mechanisms as stability failure and erosion failure (1:2,5), see Figure 3.

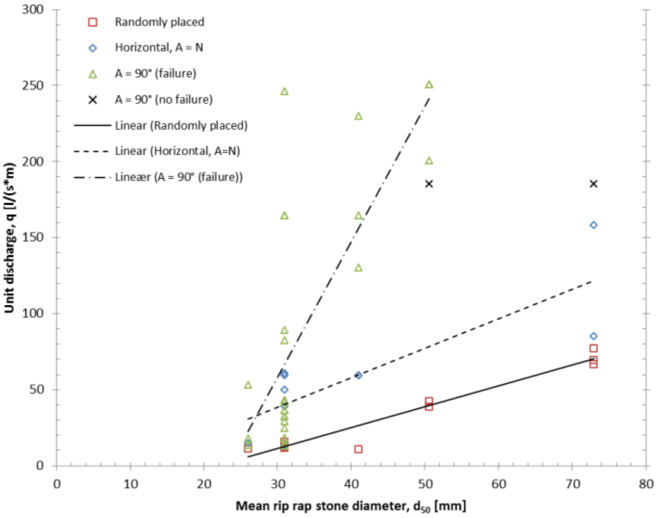

Figure 3, Capacity of riprap stones, from Lia et.al. (2013)

Following this, a series of four large scale test dams (H = 4 m) were constructed with full scale riprap on the downstream side with d_{min} = 600 mm according to the requirement for rockfill dams in Norway. The test program and results are described in Lia et.al. (2013). The riprap stones were placed in four different inclinations from 30° – 90°, see Table 1. Placing full scale stones in 0° inclination to the slope for research purpose only is very inconvenient because the stones will end up with little interlocking and may slide out of the riprap.

TABLE 1: TEST PROGRAM AND RESULTS, FROM LIA ET.AL (2013)

#	Target angle A (°)	Achieved angle A (°)	Rip rap size d_{50} (mm)	Failure unit discharge q ($m^3/(s*m)$)
1	Random	-	650	2,1
2	33,7	36,7	650	5,1
3	33,7°<A<90°	62,7	650	6,3 – 8,3*
4	90°	70,7	650	8,3*

* DAMS DID NOT BREACH COMPLETELY, RAN OUT OF DISCHARGE CAPACITY

The dams were first tested with throughflow, but the total discharge through the highly permeable dam body was in the range of 5 – 10% of the total discharge when the riprap failed and had minor influence on the capacity of the riprap. In the tests that followed, the ripraps were overtopped with a total discharge up to of 130 m^3/s. The discharge was controlled from a bottom outlet gate, and thus it was possible to monitor accurate discharges over the dams crest and downstream slope. Photos from the test are presented in Figure 4.

Step 1, Throughflow starts

Step 2, Throughflow without overtopping

Step 4, Overtopping 0,5 m *Step 5, Overtopping 1,5 m*

Figure 4, Tests performed in Step 1 – 4, from Lia et.al. (2013)

Summarized results show that a properly built riprap can withstand the erosion from unit discharges as high as q = 10 $m^3/s{\cdot}m$. The riprap failed in different ways from in accordance with method of construction, categorized in three main failure modes;

- erosion of stones in the crest
- the riprap slided down the slope or keystones in the toe or abutment lost their grip
- the riprap structure failed

All these findings were crucial when the new large research project PlaF was initiated by Energy Norway and implemented at NTNU.

4. PLAF – DOWNSTREAM PROTECTION ON ROCKFILL DAMS, 2013 – 2017

Motivation

Dam safety guidelines in some nations such as Norway prescribe the construction of a layer of riprap stones placed in an interlocking pattern referred to as 'placed riprap' on the downstream slope of rockfill dams (Hiller et al., 2017). Many of the existing rockfill dams in Norway have to be upgraded in the near future. This is due to various reasons such as reclassification of these dams into a higher consequence class or due to more stringent dam safety requirements as per the revised dam safety regulations of 2009 (details about the dam safety regulation can be found in Midttømme et al., (2012)). Upgrading of rockfill dams often includes expensive reconstruction of the downstream riprap. It is against this background that a research project 'P*lastring av fyllingsdammer (PlaF)*' (riprap protection of rockfill dams) was initiated by Energy Norway and NTNU in 2013 to study the stability of placed riprap on the downstream slopes of rockfill dams Hiller et al. (2017).

Information on the design of dumped ripraps is readily available in international literature. However, literature on the design of placed ripraps on steep slopes on rockfill dams are scarce. The primary objective of the project was to add to the accumulated knowledge on the behavior of placed ripraps, especially on steep slopes under overtopping situations to comprehend the underlying failure mechanisms through identification of key hydraulic parameters influencing stability of placed ripraps. Also, the study was aimed at quantifying the difference in capabilities of dumped and placed ripraps exposed to overtopping, Hiller et al. (2017).

LABORATORY AND LARGE SCALE EXPERIMENTAL SETUP

Small-scale models of placed, dumped riprap were constructed in a flume in the hydraulic laboratory at NTNU, and the constructed ripraps were exposed to overtopping flows to comprehend the impacts of key hydraulic parameters on riprap stability. Further, to evaluate laboratory and scaling effects and for further validation of the physical modeling test results, overtopping tests on placed and dumped ripraps at prototype scale were conducted.

Physical modeling investigations were carried out in a 25 m long, 2 m high and 1 m wide horizontal flume in the laboratory. A conceptual 1:10 scale model of the downstream section of a rockfill dam with embankment slope of 1:1,5 was constructed, see Figure 5. The discharge in the flume controlled by valves and discharge meters. The upstream water level was monitored with ultrasonic sensors. Further, an automated 3D traverse system coupled with a laser displacement meter at the top of the flume spanned the model section and allowed for the determination of coordinates of individual points along the model dam. Placed ripraps were constructed by placing the riprap stones by hand in an interlocking pattern on the filter layer from down- to upstream and dumped ripraps was constructed by placing the stones with random orientation and without interlocking pattern.

Some riprap stones were marked at specific locations to monitor their position, see 'MSXX' in Figure 5, where 'xx' indicates the distance in flow direction from the edge between the horizontal crest and the chute. The ripraps were loaded with step-wise increased discharges and the discharge was stopped between each step to inspect the riprap and to measure the positions of the marked stones. Consequently, valuable data about stone displacements (Δx, Δy and Δz) within placed riprap could be obtained.

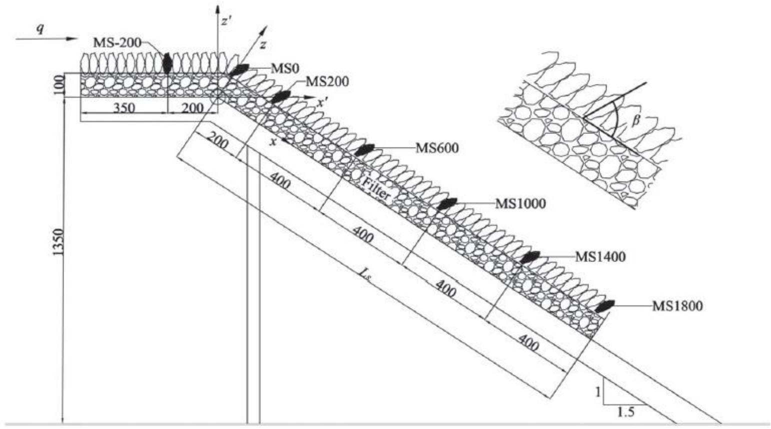

Figure 5: Model setup in the hydraulic laboratory at NTNU. All lengths in [mm].

The field tests with large-scale riprap stones were executed at the same site as described in Chapter 3, in Sirdal, Norway. Test dams of approximately 3 m height and 12 m crest length (9.5 m bottom length) with a downstream slope of 1:1,5 were built with placed and dumped ripraps in the outlet channel of a tunnel spillway and overtopping tests were conducted. The test dams were constructed with excavators by placing a row of large stones across the channel on the clean bedrock as dam toe. Further, a permeable support fill consisting of angular stones was constructed upstream of the initial stone row. Finally, the test dams were covered with either placed or dumped riprap. During overtopping, the water surface elevation at the tunnel outlet was monitored by two ultrasonic sensors and numerous pressure sensors were installed within the test dams for stage and load measurements, Hiller (2017).

Figure 6, Test with full-scale riprap stones in 2015 (in the Stavanger ICOLD Congress Technical tour)

PROJECT FINDINGS AND RECOMMENDATIONS

A total of 10 overtopping tests were conducted at the hydraulic laboratory in NTNU, Trondheim. Eight of these tests were on placed ripraps and two of them were on dumped ripraps. Further, five large scale field tests were conducted out of which four tests were conducted on placed ripraps and a single test on dumped riprap. The results from the model tests demonstrated that the stability in terms of the stone related Froude number

$$Fs,c = \frac{q_c}{\sqrt{gd^3}}$$

was on average five times higher for placed ripraps with diameter (d) in comparison with dumped ripraps. Similar observation were made from results obtained from large scale field tests that the critical stone related Froude number for placed ripraps were much higher compared to that obtained for dumped riprap thereby validating the physical modeling test results. The observations revealed furthermore that the chute length covered with riprap L_S, see Figure 5 and the packing factor P_c

$$P_c = \frac{1}{Nd_S^2}$$

where N is the amount of stones per m^2, influence the stone displacements and in turn stability of placed ripraps. Lower values for chute length and packing factors resulted in stability gain for the placed ripraps. A comparative study between the model and prototype tests showed good agreement for the dumped riprap tests in terms of critical stone-related Froude number, packing factor and flow pattern. Placed riprap showed good comparability in the visual observed flow pattern and the relative overtopping depth, but the stability in terms of the stone-related Froude number was higher in the model tests. The deviation in stability comparison between model and prototype was attributed to lower packing factors in the model resulting in higher stability against overtopping flows.

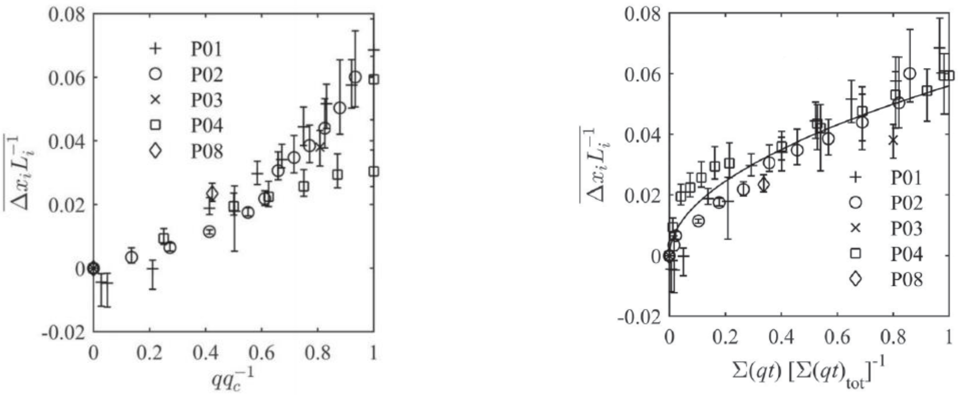

Figure 7: (Left) Averaged dimensionless displacements over MS0 to MS1400 compared to the relative discharge and (Right) compared to the volume of water passed over the riprap, Hiller et.al. (2017)

P01-P08 represent test numbers 1 to 8 conducted on placed ripraps.

The main finding of the project was that accumulating stone displacements have to be considered as potential failure mechanism for placed riprap on steep slopes exposed to overtopping. During the tests with placed riprap, a developing gap was observed on the downstream edge of the dam crest. The overtopping flow compacted the placed riprap on the downstream part of the chute during the tests, resulting in loosening further upstream. Stones adjacent to the gap gradually lost their interlocking leading to overall riprap failure. The stone displacements were proportional to the distance between the stone location and the downstream fixed end. This was a deduction made from Figure 7 which clearly pointed out the fact that the relative stone displacements ($\Delta x_i L_i^{-1}$) were similar for all of the marked stones. It was also an important observation that the maximum absolute displacements were observed at MS0 (transition point from horizontal crest to inclined riprap) where L_i was maximum ($L_i \approx 1.8$ m).

A statistical analysis to comprehend the combined effect of loading period and discharge on stone displacements resulted in a plot presented in Figure 7. The data was fitted by a power law with a coefficient of determination $R^2 = 0.85$ presented in the equation below and further investigations revealed the possibility that the riprap became unstable when the maximum stone displacements exceeded the size of the longest axes of the riprap stones.

$$\Delta x_i {L_i}^{-1} = 0.056 \left(\frac{\sum(qt)}{\sum(qt)_{tot}} \right)^{0.51}$$

5. FURTHER RESEARCH ON STONES IN DAM TOES AND STEEP ABUTMENTS

A research project with the working title 'Rockfill dam safety under extreme loading conditions' favoring continuity from the recently concluded research on stability of placed ripraps PlaF was initiated by the research center HydroCen, Norway. The primary objective of this new project is to develop design criteria and construction specifications defining the optimum design and construction of dam toe and steep abutments of rockfill dams. Findings presented in Chapter 3 prove that stones along steep abutments are less stable when compared to other stones in the riprap, see Figure 8.

Figure 8, Red ellipse shows where two stones were dislodged from the riprap during overtopping.

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 factors influencing toe stability such as the geotechnical properties of rockfill, hydraulics of turbulent flow through rockfill and abutment configuration will be investigated to arrive at optimum design of rockfill dam toes in which theory and practical applications are intertwined, emphasizing enhanced construction techniques.

6. CONCLUDING REMARKS

Over the past 16 years, dedicated research in erosion on steep downstream slopes on rockfill dams has been carried out in Norway. Main parameters influencing the riprap stability are detected and relationship between unit discharge and stone diameter were derived. The difference in stability featured of no riprap, dumped riprap and riprap placed in an interlocking pattern are quantified. The research findings have been achieved through extensive laboratory tests (H < 1,2 m), full-scale tests (H = 6 m) and tests with full-scale riprap (d < 600 mm).

Finally, failure mechanisms in the riprap as time and discharge dependent longitudinal displacements in the slope are investigated and quantified. Further research in dam toe stability and stability of key stones in steep abutments is currently ongoing.

Acknowledgements

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