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Effect of compressed riprap thickness on the stability of river banks

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ABSTRACT: One of the common measures for river bank protection is the installation of riprap. There are several methods to design riprap appropriately, which are however generally limited to dumped medium size blocks. Nevertheless, an additional resistance against erosion can be achieved by individually placing blocks in one or several layers instead of dumping them arbitrarily. An experimental investigation has thus been performed to study the stability of large blocks which are compressed as a river bank protection. Tests were carried out including one layer of stones as well as two layers, to evaluate the influence of the riprap layering (e.g. riprap thickness) on the bank stability. The effect of the thickness on the stability of ripraps is investigated in a 10 m long and 1.2 m wide tilting flume, with a rough fixed bed. Riprap median particle size was $D_{50} = 37$ mm. Testing was conducted for channel longitudinal slopes 0.015 and 0.030 and riprap bank inclinations of 27, 31 and 35 degrees. The riprap was installed on the top of a wide grain size distribution filter. Supercritical flow conditions were considered, given the steep channel slope. The complete removal of the riprap in a section under a constant discharge was defined as the failure criterion. The riprap failure threshold discharge was determined based on the series of tests with duration of maximum 180 minutes. In each test, riprap transport rate was measured every minute while the stones were tracked by a video camera and collected in a sediment trap at the channel end. The time of total failure was defined by standard video-image processing techniques. A time based analysis of failure was performed and first results revealed that, for similar conditions, the second layer stabilizes the riprap significantly and delays the time for total failure. Nonetheless, transport rate was found to be increased in this latter situation.

1 INTRODUCTION

Among several methods to protect river banks, riprap is one of the most commonly used. A riprap protection is permanent, flexible and simply to be constructed, if correctly placed (Schleiss, 2000). There are various methods developed to design riprap. According to Stevens et al. (1976) and Maynord et al. (1987) significant design parameters in these methods are block size, thickness, slope of channels and characteristics of the filter behind. There are different mechanisms which riprap failure happens. According to Julien (2002) and Lagasse et al. (2006), these modes of failure are direct block erosion, translational slide, slump, and side-slope failure. Direct block erosion is the common mechanism of erosion and it occurs when one block rolls out due to the flow action. Translational slide occurs by the downslope riprap material movement. This failure happens due to toe scouring or direct block erosion. Modified slump failure of riprap is similar to translational slide, however different layers of blocks slide on each other. Possible causes of modified slump are steep slope of bank and absence of toe support. Side-slope failure of the riprap begins mostly due to overtopping and it corresponds to a rotation-gravitational movement of the stones. In overtopping, the water soaks the riprap and the material behind it. Once the level of the water decreases, the water in the saturated part induces a steep pressure gradient and slide-slope of the riverbank riprap takes place (Jafarnejad et al. 2012 and 2013).

There are different methods to design riprap resisting against direct block erosion. Some of them are discussed in Garcia (2007). Stevens et al. (1976) offered a safety factor based technique by considering the stability of individual blocks in riprap. They supposed that each block is stable if the several forces causing a possible displacement of a block represent less than the reaction caused by the submerged weight. Wittler and Abt (1988) adapted Stevens' study by adding frictional and contact forces from contiguous blocks. Abt et al. (2008) studied the round-shaped riprap stabilization in overtopping flow as well. Froehlich (2011), Ulrich (1987) and Stevens et al. (1984) also considered the weight of the submerged rock as the only resisting force. Froehlich and Benson (1996) worked on wide angles of repose to refer the slope of embankment effect on riprap stability. They proposed a "particle angle of initial yield" which was as well introduced earlier by Straub (1953), Grace et al. (1973), and Reese (1984). Probabilistic procedures for design of riverbank riprap were developed by Li et al. (1976), PIANC (1987), and later by Froehlich and Benson (1996). Froehlich (2011) studied the stability of loose rock riprap regarding the protection of stream banks from erosive forces and proposed an evaluation based on the ratio of static moments resisting overturning. The ratio of moments in this research defined a safety factor which specified the potential of failure in riprap.

Existing design methods are generally limited to dumped blocks and first movement of particles is used as failure criterion (De Almeida and Martín-Vide, 2009). However, if large and dense blocks are needed for stability reasons, they must be positioned individually due to their heaviness. According to Schleiss (2000), the critical shear stress of these large mountain blocks are $\theta cr = 0.1$ instead of Shields critical shear stress taken usually as 0.047. Therefore, in large compressed blocks as rock ripraps, erosion of one block is not the cause of total failure due to the added support of compressed blocks. Failure happens when a group of blocks slips and makes the river bank unstable. This kind of failure, included the observation of laterally breakdown of the blocks in the river bank slope (as a slide or slump) is identified as failure criterion in this investigation.

This research presents the influence of the thickness in large blocks individually placed as riprap. However, one of the issues which not yet fully known in the design of riprap protection is the influence of time (flow duration) on their stability (Jafarnejad et al. 2013). Thus, the effect of thickness in riprap installation on changing the time of failure is investigated herein. This is succeeded through flume experiments by considering the behavior of compressed large blocks. The present article is based on the result of twelve series of tests performed to evaluate the failure process. The analysis focuses mainly on characteristic time of failure and critical hydraulic parameters.

2 EXPERIMENTAL SETUP AND PROCEDURE

The main goal of this study is to define the effect of thickness in the resistance of river bank riprap protection, built by individually placed large blocks, due to hydrodynamic forces.

Twelve systematic experiments were performed to analyze the impact of thickness on the stability of compressed riprap. The tests were conducted in one layer and two layers of the same size blocks. These laboratory tests were applied in a straight 10 m long, 1 m wide and 0.5 m deep tilting flume with a trapezoidal section in the Laboratory of Hydraulic Constructions at École Poltechnique Fédérale de Lausanne. Water in the channel was supplied by the internal closed pumping circuit of the laboratory. A schematic sketch of the longitudinal and cross section of the setup can be seen in Figure 1.

The experiments were performed for a longitudinal slope of the flume as 1.5% and 3%. The transversal inclinations of the riprap were varied as 2.5V-5H (27°), 3V-5H (31°), and 3.5V-5H (35°). Studied riprap material included uniform crushed stones with block sizes of $D_B = 0.37$ m. Blocks were compressed and placed over a wide grain size distri-

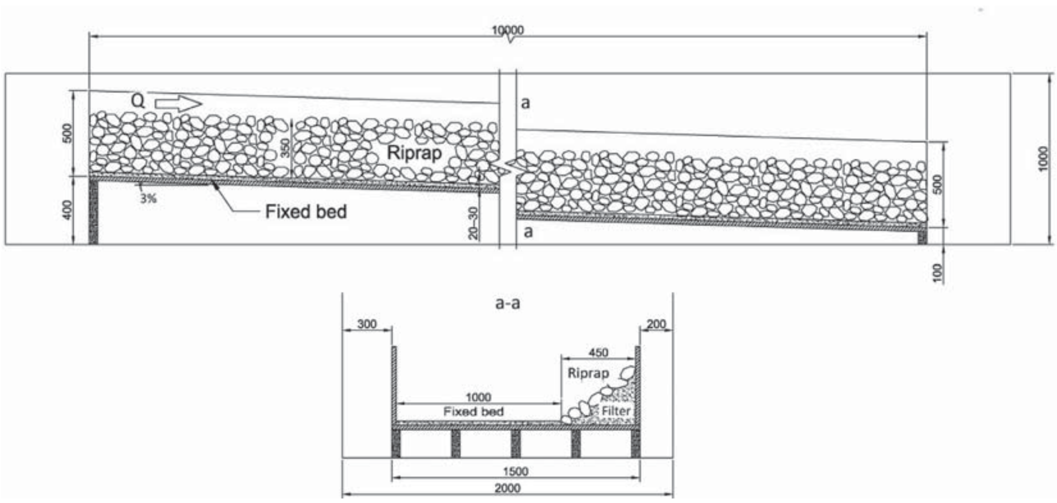

Figure 1. Sketch of longitudinal and cross-section view of the experimental flume (units in mm).

bution filter. In order to simulate natural hydraulic conditions, the roughness of the natural river bed was reproduced with the same material of the filter (Table 1), fixed on the bed of the channel.

According to Table 2, 12 tests run with the parameters including thickness (number of layers), slope of channel, slope of riprap (bank inclination), unit discharges (q), water depth (h) and time to total failure (tf) considering uniform flow conditions.

The discharge was kept constant during three hours of each experiment in one and two layer tests. Thus the delay of failure due to the changing on the thickness of the riprap is comparable. Lower discharges may cause direct block erosion during the experiments but not full failure of the bank slope whereas higher discharges may cause very fast failure. Tests were carried out under supercritical flow conditions (Table 2). Water depth, block erosion rate and time of failure were measured during the tests. Channel was fed by two pumps, measured by electromagnetic flow meters with of ±2 l/s of precision. Water depth was measured in four different positions with 2 m distance in the test reach by means of ultrasonic sensors with a precision of ±0.5 mm. They were all transversally located at the center of the channel cross section. To avoid undesirable upstream effects at the model inlet, the first 5 m of the riprap was fixed at the upstream by sticking the blocks together with cement allowing the flow to develop. Riprap erosion rate was measured every minute by counting

Table 1. Grain size distribution of the filter.

D_m (mm)	D_{10} (mm)	D_{35} (mm)	D_{50} (mm)	D_{75} (mm)	D_{90} (mm)	D_{max} (mm)
8.5	3.2	4.4	5.3	9.1	14.8	32

Table 2. Tests program.

Group	Series	Number of layers	Slope of channel (%)	Slope of riprap (°)	q (m^2/s)	h (m)	t_f (min)
I	1	1	3	39	0.301	0.165	62
I	2	2	3	39	0.298	0.163	161
II	3	1	3	34	0.316	0.147	27
II	4	2	3	34	0.314	0.151	78
II	5	1	3	34	0.359	0.170	3
II	6	2	3	34	0.345	0.167	14
III	7	1	3	29	0.301	0.158	33
III	8	2	3	29	0.304	0.150	92
III	9	1	3	29	0.344	0.170	17
III	10	2	3	29	0.344	0.170	21
IV	11	1	1.5	39	0.360	0.190	9
IV	12	2	1.5	39	0.466	0.227	73

Figure 2. The experimental set up before (left) and after (right) one test (the test I-2, Table 2).

the eroded blocks which were videotaped from the top of the channel.

Furthermore, the eroded rocks were collected and weighed in a sediment trap at the downstream end of the channel. Experiments were divided in four groups. Group I, II and III, corresponding to the slope of channel as 3%. Tests were performed with one layer riprap as well as with two layers. Group IV included tests with the slope of 1.5% in order to investigate independently the effect of channel slope in the stability from varying riprap thickness. Each run of tests had a constant specific discharge. Tests were run during maximum three hours unless the total failure of the blocks occurred in a section.

Figure 2 shows an example of the view before and after one test of two layers (the test I-2 in this case, Table 2). Figure 2 (left) presents the set up before the test, where only the external layer (white stones) can be witnessed. Eroded parts of riprap in both layers and the collapsed area can be seen as red blocks in Figure 2 (right).

3 RESULTS AND DISCUSSION

In group I to III of the experiments (Table 2), with longitudinal slope of the channel of 3%, one layer of blocks as well as two layers was tested and water depth, rate of erosion and time of failure were measured in constant discharges which were verified to cause the total failure. The group IV includes tests with 1.5% longitudinal slope.

Figure 3 shows two examples of the riprap before (left) and after (right) experiments IV-12. In this test, with the slope of channel as 1.5% and a unit discharge of $q = 0.466$ m^2/s, direct block erosion occurred at the beginning of the test. However, total failure was observed in the minute 73. It can be observed that in the failed sections the filter and the second layer were fully visible, while other areas were still stable. In this experiment with channel slope of 1.5% the external layer is covered with red blocks.

Figures 4 to 6 present the time evolution of the cumulated number of eroded blocks. Time is normalized by the maximum duration of the tests $T_{max} = 180$:

$$t^* = \frac{t}{T_{\max}} \tag{1}$$

Failure corresponding to the sudden change of the slope in the graphs is related to the transport of the blocks causing in the total failure of a bank slope.

Figures 4 to 6 show the time evolution of the transport rate of the material from the riprap protections which is measured at the downstream section of the channel by video analysis. The time evolution allows the identification of the total failure of a section of the bank protection corresponding to a sudden increase in the transport rate, where a vertical asymptote is observed.

Figure 4a shows that having two layers of riprap induces a significant delay on the failure time of the protection. By increasing about 12% of the discharge which the bank protection is exposed to, the effect of the second layer becomes insignificant. The results indicate thus that the use of two layers protection for high discharges became ineffective on the delay of structural failure. The effect of the increase in the unit discharge on decrease of the time to failure is evident when comparing the results in Figures 4a and 4b.

However, for the case of one layer protection, the effect on the reduction of the time to failure is less (about 15% when compared to 38% in the two layers case), showing once again that there is a limit for the advantage of the use of two layers in riprap bank protections in postponing the failure.

For a different bank inclination with the same channel slope (Fig. 5), the results in terms of time evolution of structural failure of the riprap, for the one layer and two layers, situations are similar to the results shown in Figure 4 and above

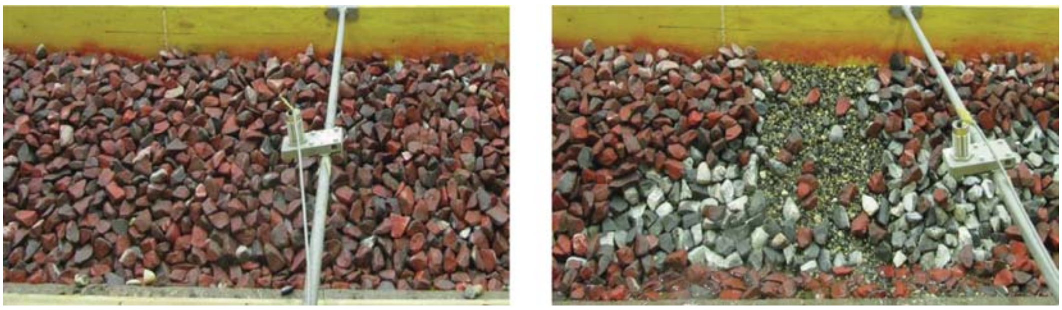

Figure 3. Riprap before (left) and after (right) failure for test IV-12 (see Table 2 for test description).

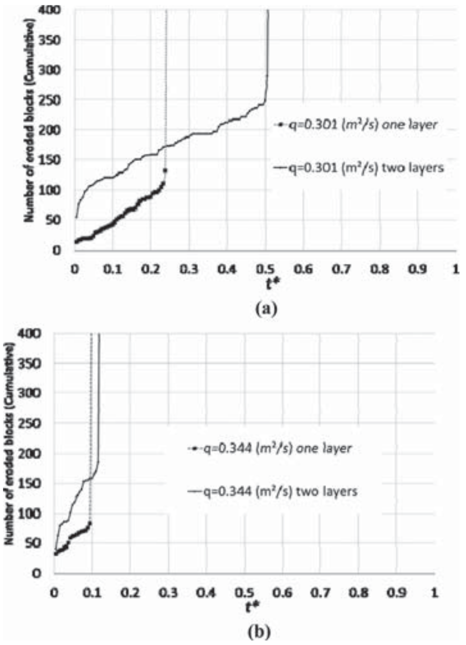

Figure 4. Time evolution of cumulative block erosion rate for one layer and two layers with the same discharge for channel slope of 3% and riprap slope of 27°.

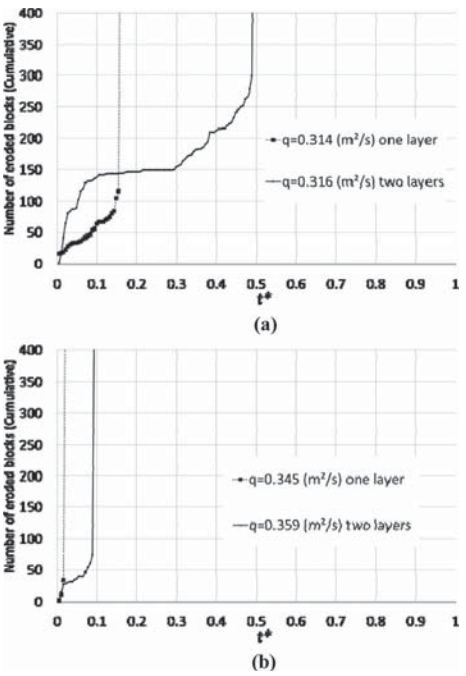

Figure 5. Time evolution of cumulative block erosion rate for one layer and two layers with the same discharge for channel slope of 3% and riprap slope of 31°.

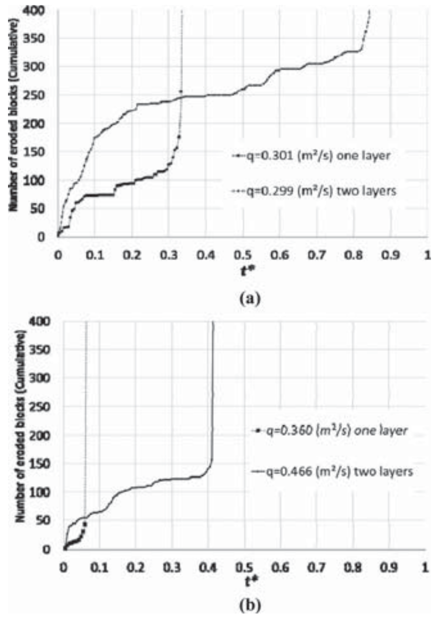

Figure 6. Time evolution of cumulative block erosion rate for one layer and two layers with the same discharge for channel slopes of 3% (a) and 1.5% (b), with riprap slope of 35°.

commented. Once again, results in Figure 5, for a different bank inclination show that the use of two layers of riprap as bank protection delays the failure time. The effectiveness of the delay of the failure time by the use of two layers again is also reduced with the increase of the discharge acting on the bank protection, for this different bank inclination.

In both cases represented in Figure 6 a significant reduction on the time of occurrence of total failure is visible, which has been reduced by more than 50%. In Figure 6b, different discharges are compared; for one layer the tested discharge that imposed the fastest failure, whereas for the two layers the unit discharge q = 0.466 m^2/s (channel slope of 1.5% and bank inclination of 35°) was the lowest discharge that produced total failure in this case. This shows that the use of two layers not only delayed considerably the time to failure, but also increased greatly the resistance of the protection to the erosive action of the flow. Results also show that the longitudinal slope of the channel has a significant stabilizing effect on the riverbank riprap.

4 CONCLUSIONS

Empirical results on the stability of compressed riprap protections for preventing riverbank erosion are shown in terms of channel longitudinal slope, bank inclination and thickness of the protection layer.

A remarkable relationship between the thickness and the time for occurrence of total failure of riverbank riprap protections was observed. The second layer postponed the time of failure. However, this increased the block erosion rate significantly. By considering the two layer test, first results revealed that under the same conditions, the second layer stabilizes the protection system considerably, in addition to delaying the failure time. Results show also that longitudinal slope of the channel seems to be the most dominant parameter regarding the effect of thickness in resistance of riprap.

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