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Stone drop tests on different compositions of geotextiles and protective layers

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ABSTRACT: Geotextiles are often used as a filter layer in coastal engineering. To stabilize the geotextile and the soil layers underneath, they are covered with one or several layers of stones. The installation procedure, involving dropping of stones from a certain height on the geotextile, proves to be quite risky. Regularly, the geotextile does not survive the installation of the stones and is punctured. This paper describes experimental research on the impact of stones directly on a geotextile on sand, and the influence of a layer of smaller stones that is on top of the geotextile for ballast and protection. Surprisingly, a ballast layer of stones demonstrated limited protective efficacy, leading to damage due to sharp edges and localized point loadings. Reed proved effective in preventing damage, likely due to reduced friction and impact damping. Additionally, impact on a flat plane of the falling stone, resulted in less penetration but higher perpendicular impact loads compared to a point or rib impact. Calculations show lower impact velocities underwater, prompting recommendations for further underwater impact investigations.

1 INTRODUCTION

Coastal engineering structures are designed preventing erosion of fine granular materials and withstanding the force the waves. Nowadays, erosion is often prevented with a geotextile with sufficient small openings to avoid washing out of the fine granular material underneath. Damage due to wave attack is prevented by large stones that resist movement during wave attacks.

During construction, the vulnerability of geotextiles to damage due to the impact of stones dumped onto them, raising concerns about the existing design rules; they may result in constructions that contain a punctured geotextile.

To address this issue, laboratory and field tests were performed to determine the energy levels at which geotextiles are punctured by stone impacts (De Strijcker & De Craene, 2017; Cheah, 2017; CROW 2024). Bezuijen (2023) developed a calculation model that describes the impact of a single stone on a geotextile on sand, and showed the importance of the friction between the geotextile and the sand, and between the geotextile and the stone. Tests at Ghent University (De Strijcker & De Craene, 2017) showed that within multi-layer constructions, the lowest layer is most vulnerable to puncturing. Field tests (CROW, 2024) showed that, what is sometimes called a protective layer of smaller stones, doesn't reliably protect the geotextile; on the contrary, it often leads to damage at lower impact energies.

To gain a better understanding of the mechanisms causing this damage, a series of laboratory test were conducted at Deltares, the Netherlands. These tests were performed in a laboratory to have controlled conditions and the use of high-speed cameras allowed for detailed observation of the impact process.

2 TEST SET-UP

Figure 1 shows the test set-up.

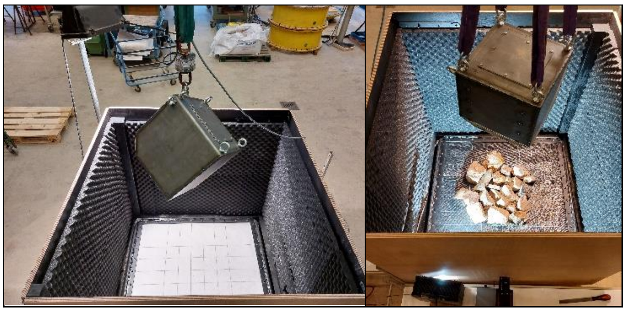

Figure 1. Setup examples with stone drops directly on a non-woven (left) and on a stone ballast layer (right). The stones were randomly placed.

A hollow metal block filled with sand of 78.5 kg was lifted to the desired height and then released using an electro-magnet. The block dropped on the geotextile, or on a 'protective' layer on top of it. The geotextile was attached to a stiff steel frame positioned on a supporting square frame with a circular opening above a circular container filled with sand. Directly underneath the geotextile was dry sand or another sublayer. There was no space between the geotextile or the sublayer and the sand surface. The sand was Baskarp sand with a d_{50} of 150 μm. The density of the sand was kept constant by loosening the sand after an impact test, so that the same amount of sand again filled the container. After each test, the block and protective layer were removed, and the geotextile was inspected on possible damage and if there was damage, the size of the damaged area was measured. The lowest drop height at which damage was noticed is the critical drop height (H_{cr}).

The geotextiles used were polypropylene wovens (PP in Table 1) and non-wovens (NW in Table 1). All non-wovens were stapled fibers. The number behind the letters indicates the approximate tensile strength for the wovens and the approximate weight per square metre for the non-wovens.

The block was specially made for these tests. Earlier tests (De Strijcker & De Craene, 2017) had shown that the edges of concrete blocks became blunt during the tests. It was therefore decided to make a steel block. By lifting the block in different positions, it could fall on one point, on a rib or on a plane, see Figure 3 to Figure 5.

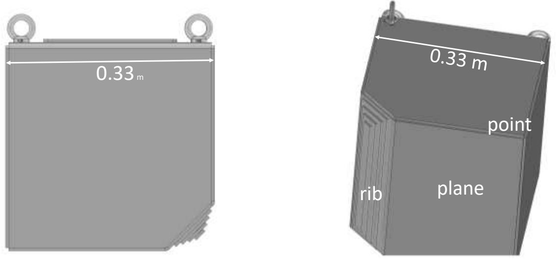

Figure 2. Cross-section block and 3D drawing to show the shape.

Tests were recorded with 1500 fps using the previously mentioned high-speed cameras. Altogether, 217 impact tests were performed. Tests were performed with 1, 2 or 3 geotextiles, with or without a granular ballast layer, and with or without reed between the geotextiles and the granular layer.

3 RESULTS

Figure 3 until Figure 5 show examples of tests with and without a protective ballast layer and with reed as protection. These figures also show the different block positons mentioned in Table 1, except the position `point rough`. This is a point of the block that was on purpose made rough to resemble the point of a stone.

Table 1. Test results. Test are performed with different drop heights. Red means damage, green no damage. One or two geotextile layers were used, with (y) or without (n) a ballast layer. Point s is a drop on the smooth point, point r on the rough point, see Figure 2. In the series 17-21 there was a stone in the sandy subsoil.

						Drop height (m)					
no	ballast layer	geotextile upper layer	primary geotextile	geotextile bottom layer	stone impact location	1	2	3	4	5	6.1
1	n		PP40		point s	🟥					
2	n		PP40		point r	🟥					
3	n		PP40		rib	🟩	🟩				
4	n		NW 300		point s	🟩	🟥	🟥			
5	n		NW 300		point r	🟩	🟩	🟥			
6	n	pp40	NW 300		point s	🟥					
7	n	pp40	NW 300		point r	🟥	🟥				
8	y	pp40	NW 300		flat	🟥	🟥				
9	y	pp40	NW 300		rib	🟥					
10	n	pp40	NW 300		rib	🟩	🟥				
11	n	pp40	NW 300	PP40	point r	🟩	🟩	🟥			
12	y	pp40	NW 300	PP40	flat	🟩	🟩	🟩	🟥		
13	y	pp40	NW 300	PP40	rib	🟩	🟩	🟥			
14	y	pp40	NW 600		rib	🟩	🟩	🟥			
15	y	pp40 + reed	NW 600		rib	🟩	🟩	🟥			
16	y	pp40	NW 600	reed	rib	🟩	🟩	🟩	🟩	🟥	
17	y	pp40	NW 600	PP40+reed	rib	🟩					
18	y	pp40	NW 300	PP40+reed	rib	🟩					
19	y	pp40 + reed	NW 300		rib	🟩	🟥				
20	y	pp40 2xreed	NW 300		rib	🟩	🟥				
21	y	pp40 + reed	NW 600		rib		🟥				
22	y	pp40	NW 300	reed	rib			🟥			
23	n		NW 600		rib	🟩	🟩	🟩	🟩	🟩	🟩
24	n	pp40	NW 600		rib	🟩	🟩	🟩	🟩	🟩	🟥
25	n	pp40	NW 600	PP40	rib	🟩	🟩	🟩	🟩	🟩	🟩
26	y	pp40	NW 600	PP40	rib	🟩	🟩	🟩	🟩	🟩	🟥
27	y		nw 273		flat	🟩	🟩	🟥			
28	y	pp40	nw 273		flat	🟩	🟥	🟥	🟥		
29	y	pp40	nw 273		rib	🟩	🟥				
30	y	pp40	nw 317		rib	🟩	🟩	🟥			
31	n		nw 317		point r	🟩	🟩	🟥			
32	n		nw 460		point r	🟩	🟩	🟥	🟥		
33	n		nw 630		point r	🟩	🟩	🟥			
34	y	pp40	nw 630		rib	🟩	🟩	🟥	🟥		
35	y	pp40	nw 630	reed	rib	🟩	🟩	🟩	🟩	🟩	🟩
36	y	pp40	nw 630	PP40	rib					🟥	
37	y		nw 630		rib	🟩	🟩	🟩	🟥		
38	y		nw 1001		rib	🟩	🟩	🟩	🟩	🟩	🟩
39	y	pp40	nw 1001		rib	🟩	🟩	🟩	🟩	🟩	🟩
40	n		nw 1001		point r			🟥	🟥	🟥	🟥
41	n	pp40	nw 460		point r			🟥			
42	y	pp40	nw 460		rib	🟩	🟩	🟥	🟥		
43	y	pp40	nw 460	PP40	rib	🟩	🟩	🟥	🟥		
44	y	NW170	PP40		rib	🟩	🟥				
45	y		NW 300		flat	🟩	🟥	🟥			
46	y	pp40	NW 600		flat	🟥	🟥	🟥	🟥	🟥	🟥
47	y		NW 600		flat	🟥	🟥				
48	y	pp40	NW 800	PP40	flat	🟩	🟩	🟩	🟩	🟩	🟥
49	y	pp40	NW 800	PP40+reed	flat	🟩	🟩	🟩	🟩	🟩	🟩
50	n	pp40	NW 800	PP40	point s	🟩	🟩	🟩	🟥	🟥	🟥
51	n	jute	NW 800	jute	point s	🟩	🟩	🟩	🟩	🟩	
52	n	pp60	NW 800		point r	🟩	🟥	🟥			
53	n	pp60	NW 300	PP60	point r	🟩	🟩	🟩	🟥		
54	n	pp60	NW 600	PP60	point r	🟩	🟩	🟩	🟩	🟥	
55	y		NW 400		rib	🟩	🟥				
56	y		NW 400		flat	🟩	🟩	🟥	🟥		
57	n		NW 400		point r	🟩	🟥	🟥			
58	n	pp60	NW 800		rib	🟩	🟩	🟩	🟩	🟩	🟥
59	n	NW 170	pp60/60		rib	🟩	🟩	🟩	🟩		
60	n	pp60	NW 300		rib	🟩	🟩	🟥	🟥		
61	n	pp60	NW 300	PP60	rib	🟩	🟩	🟩	🟩	🟩	🟩
62	n	pp60+reed	NW 1000		point r	🟩	🟩				

Figure 3. Impact test on non-woven on the smooth point (point s).

Figure 4. Impact test on ballast and reed. Block on rib.

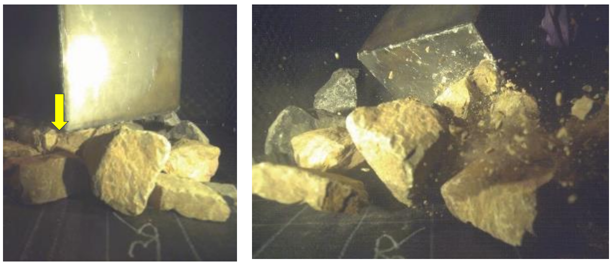

Figure 5. Test 136. Series 46 Flat side of block dropped on stones ballast layer and geotextile from 5 m. Start impact (left picture) and after impact (right). The arrow at the left picture indicates breakage of stones due to impact.

A summary of the test results is presented in Table 1. Each line in the table represents a series of one to a maximum of 21 tests, determining the critical drop height for the primary layer. The top and bottom layer could be damaged at a lower or higher drop height.

Some results are as expected: heavier geotextiles show less damage on average. Though not explicitly shown in the table, detailled results indicate that the lower geotextile is often damaged before the middle and top one, in agreement with results by Bezuijen & Izadi. (2021) and Bezuijen (2023). The critical drop height increased when the block fell on a rib compared to a drop on the point.

Some results differ from the expectations of the researchers: in tests where a PP40 top layer was placed over a nonwoven primary layer, a lower drop height was found without damage than in the tests without the PP40 top layer.

The ballast layer was supposed to lead to less damage. However, this was not observed. Especially where the stone dropped with a flat part downwards on a geotextile with a ballast layer, but without a bottom layer, damage occured at low drop heights, as seen in test series 8, 28, 46 and 47. With a PP as bottom layer under the primary layer, the critical drop height increases remarkably, see test series 48 and 49. In these last two tests, the primary layer was also a bit heavier, but it is unlikely that this would have led to the strength increase measured without the bottom layer. Series 49 had also reed as sublayer this further increased the resistance agains puncturing.

The results show that in numerous tests, damage occured at a drop height of less than 1 to 2 m. Interestingly, a protective layer of reed seems to increase the critical drop height. This is not the case for an additional ballast layer.

The idea was that a ballast layer would improve the restistance against impact: the falling block would not directly hit the geotextile but first the ballast layer. Consequently, not all kinetic energy of the falling block would be transferred to the geotextile. However, earlier tests (CROW, 2024) had already showed that this idea may not be true, and the tests described in this paper confirmed these findings. Comparing tests with and without a ballast layer, test series 9 and 10 and test series 25 and 26 in Table 1, show that the critical drop height was lower for tests with a ballast layer.

The position of the block during impact was determined from the high-speed video for three tests. The videos setup was primarily designed for qualitative analysis and therefore automatic evaluation for all tests was not possible. The impact velocity can be calculated from the drop height and the acceleration of gravity. By determining the conversion factor between pixels and centimeters from the movement of the block in two adjacent video images, it is possible to determine its position in time, see Figure 6.

The method appeared not very accurate, but the block movement after the start of the impact is clearly less when a flat part of the block impacts on a ballast layer (T136 and T141) than for impacts of a point of the block. The movement after first contact is less than 0.025 m for the flat impact on a ballast layer and more than 0.05 m for the impact of the rough point directly on geotextile, despite the drop height being only 2 m instead of 3 and 5 m for the tests were a flat part of the block fell on the ballast layer.

Reed as protective layer between the primary geotextile and the soil reduces the damage during impact more effectively than reed between the ballast layer and the upper geotextile layer. This is evident when comparing test series 14,15 and 16; 34 and 35; and 48 and 49 in Table 1.

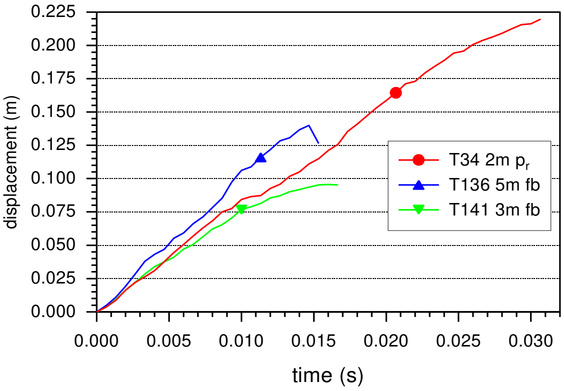

Figure 6. Vertical position of block just before and during impact. The markers indicate the point of first contact between block and stones or geotextile. Figure 5 gives some photos of Test 136. The tests 34 is from series 11, 136 and 141 are from Series 46.

4 DISCUSSION

4.1 Blocks directly on geotextile

Bezuijen et al. (2021) proposed a model to estimate the forces on a geotextile. An improved version of this model is given in Bezuijen (2023), see Figure 7. This model is valid for blocks penetrating with a certain angle.

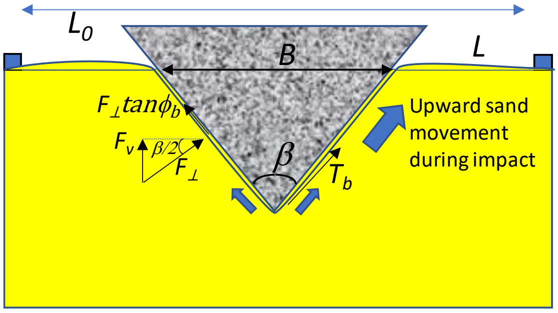

Figure 7. Movement of sand and forces against penetrating block (Bezuijen, 2023).

Based on earlier tests, Bezuijen (2023) calculated a maximum deceleration during impact of 340 times the acceleration of gravity. This means that the forces on the geotextile become rather high. A bottom layer of a woven geotextile will reduce the friction between the sand and the primary layer due to the low friction coefficient between the geotextiles. With less friction, force T_b in Figure 7 decreases allowing for an increase in drop height. A layer of reed between geotextile and sand will also reduce the friction and therefore also has a beneficial effect.

4.2 Fall velocity above and below water

As previously mentioned, it appears that the critical falling height is often limited. This has raised concerns that dumping stones on the geotextile during construction can damage the geotextile regularly. Therefore, an investigation has been initiated of the geotextile underneath stones in two revetment sections in the harbour of Rotterdam (Heide, 2024). Results of this investigation are not yet available. However, it should be realized that the impact tests described in this and other papers are performed above water. When a stone is dropped from the water line into a few meters of water, the impact velocity will be lower than in air. Figure 8 shows the fall velocity above and in water, for a stone with a weight of 78.5 kg, as used in these tests, and assuming a density of 2650 kg/m^3.

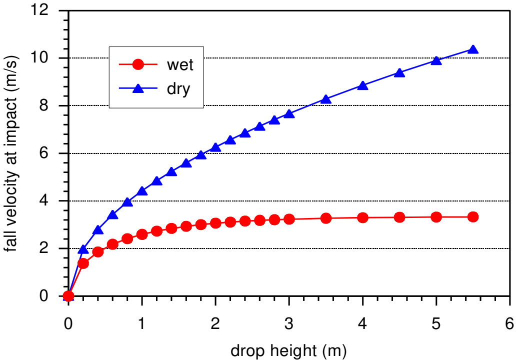

Figure 8. Calculated fall velocity of stone of 78.5 kg with a density of 2650 kg/m^3, in water or in dry conditions.

The fall velocity in water is calculated assuming that the stone is released either under water or at the water line. The plot shows that for this situation, thus with a stone of 78.5 kg, the equilibrium velocity - the velocity that does not increase anymore with increasing depth - corresponds with the velocity reached at around 0.6 m drop height for this block type. Only in 8 out of the 62 tested combinations of Table 1, damage occurred with a drop height of less than 1 m. This means that, from the stones dropped from the water line or below, assuming consistent behaviour of the geotextile and the sand, most combinations will not be damaged underwater when the stone weight is 78.5 kg or less.

4.3 Ballast layer

The protective effectiveness of the ballast layer seems to be limited. Two reasons were found while studying the tests results:

Stone breakage: At a drop height of several meters, the impact of stones on a ballast layer often results in stone breakage. The freshly broken parts often have sharp edges that can easily cut through the geotextiles.

Deceleration Forces: Many tests on a ballast layer were performed with the flat part of the block downwards. This orientation results in huge deceleration forces.

This last aspect may need some explanation. For a subsoil without cohesion and subjected to surface loading, such as the impact of a stone, the bearing equation for a strip footing can be simplified to:

$$q = 0.5\gamma B N_{\gamma} F \qquad (1)$$

Where: q (kPa) is the bearing capacity, γ (kN/m^3) is the density of the soil, B (m) is the width of the footing and $N\gamma$ (-) is bearing capacity factor only depending on the friction angle of the soil. F (-) is a shape factor for the case that the shape is different from a strip footing. Here, a rather high value of 2.4 is used for F, to account for the influence the geotextile. This value was calibrated from earlier tests (Bezuijen, 2023). The equation shows that the bearing capacity is a function of the footing width. The impact of the same mass with a wider footing will result in much less penetration but a significantly higher peak pressure. Using the equations given in Bezuijen & Izadi (2022) leads to Figure 9.

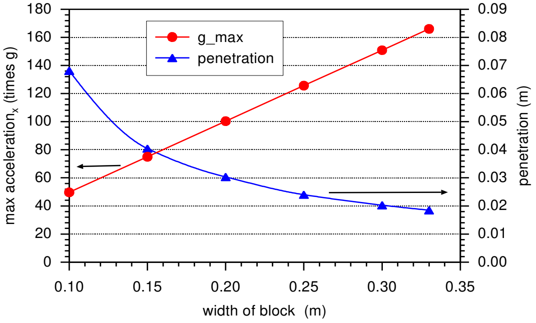

Figure 9. Results of calculations. Penetration and deceleration as a function of the width of the block. Drop height 3 m. friction angle 45 degrees.

For an impact on a rib, the width will be around 0,1 m and the maximum deceleration nearly 50g. In case of a drop on a flat surface of the artificial stone, the width is 0.33 cm and the maximum deceleration is more than 166 g. This means that in the latter case, the pressure loading on the geotextile is 3 times higher. The loading is than more than 160 times the acceleration of gravity, which means that the loading on the geotextile is 78.5*160=12,560 kg. In cases with a ballast layer, there will be more localized loading where the edges of the stones are in contact with the geotextile. However, this should not be interpreted as the loading with block with a smaller width. The localized loading in various points will increase the average effective stress in the sand underneath the geotextile, leading to a stiffer behaviour of the sand and thus a higher impact loading compared to a single point.

The presence of sharp, freshly broken stones in the the ballast layer, combined with the high deceleration values, may be potential reasons for the damage underneath the ballast layer at the geotextile after the impact of a block.

There is no standard test to measure what loading a geotextile can withstand perpendicular to the plane on a stiff subsoil. However, the finding that a geotextiel on densified sand is damaged by a lower drop height than the same geotextile on looser sand indcates that also the loading perpendicular to the plane can lead to damage when high enough.

4.4 Calculation model and statistics

In previous research (Bezuijen & Izadi, 2022, Bezuijen, 2023), where stones with a predefined shape were dropped on one or more geotextiles, pointed toward a calculation model that calculates when damage can be expected. For geotextiles in combination with a ballast layer, the variation in the current test results seems too big to aim for such a calculation model. Sometime the block hits one single stone of the ballast layer, sometimes, the stones in the ballast layer break under the impact, leaving sharp edges.

Since 217 tests were performed, an alternative approach to find general rules, is employing statistical analysis. As an example, the influence of the weight of a non-woven as primary geotextile is investigated. The weight of the non-woven is taken from Table 1 and the lowest value of the drop height that leads to damage (H_{crit}) was also taken from that table. Putting all the results together, regardless the construction, leads to a significant variation in the results, see Figure 10.

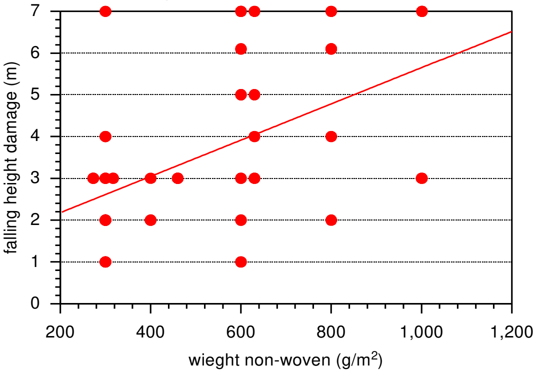

Figure 10. Minimum drop height that led to damage (H_{cr}) as a function of the weight of the primary non-woven geotextile.

In general, the critical drop height increases in these tests with the weight of the geotextile, but there is a large scatter. Furthermore, damage at a drop height of less than 1 m even occurred for non-wovens up to 600 gr/m^2 underneath a ballast layer, probably due to the breaking of the stones in the ballas layer resulting in sharp edges. This means that it is hardly possible to select a non-woven underneath a ballast layer that will be safe for most (dry) circumstances.

Comparing all measurement data is like comparing apples and oranges. Therefore, specific selections were made from the data: namely only the tests with:

- one non-woven as primary layer (P) and the block fell on a rib (r),
- a PP40 as upper layer (U), a non-woven primary layer and the block fell on a rib (r):
- a ballast layer (B), a PP40 upper layer (U) and a non-woven primary layer (P) and the block fell on a rib (r)
- a ballast layer (B), a PP40 upper layer (U) and a primary layer (P) and the block fell on a flat surface (f).

This resulted in only a limited number points for each series and a rather unexpected depedency for the last series, although based on three points only. Again the scatter is high. Apart from the last series, the falling height at which damage occurs increases with increasing weight of the non-woven primary layer. It is likely that a stone falling on the flat surface results in large deceleration forces, leading to breakage of ballast stones and damage to the geotextile, even at lower falling heights, compared to a stone falling on a rib.

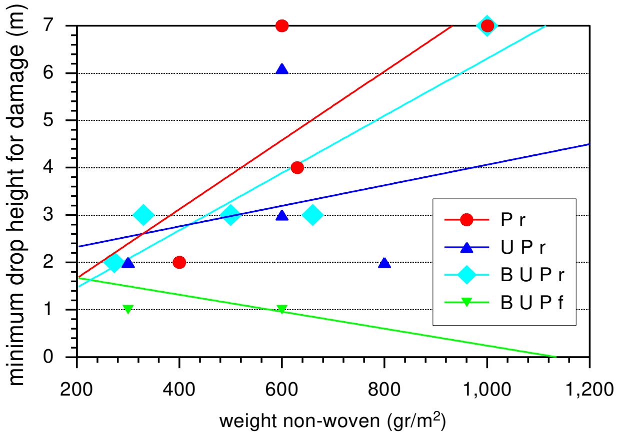

Figure 11. Minimum drop height that led to damage (H_{cr}) for some selected series, see text.

The limited number of tests with a reed layer showed that the reed between the geotextiles and the sand increases H_{cr}, see Figure 12. A reed layer underneath the geotextiles seems more effective than a reed layer above the geotextiles. The reed may reduce the friction between the sand and the geotextiles resulting in less loading on the geotextiles, as explained in Section 4.1.

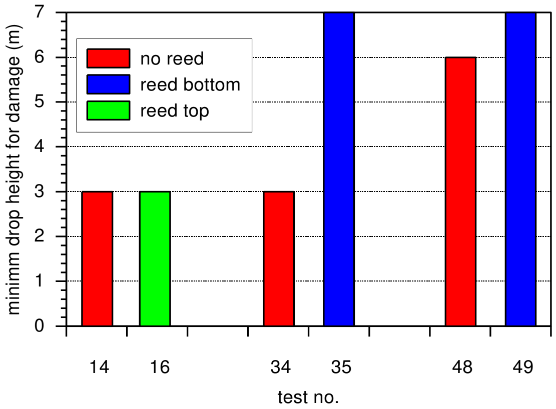

Figure 12. Influence of a reed layer, see Table 1 for details of the tests shown.

Based on the results of this research, the following measures can be taken to minimize damage due to falling stones on a geotextile or a ballast layer:

- The drop height should be limited such that the stones of the ballast layer do not break. This can be tested on beforehand. The study indicated that the maximum drop height will be significantly lower above the water line than below the it.
- A reed layer between the stones and the subsoil proves effective in preventing damage of the geotextile. More tests will be necessary to quantify this effect.
- In general, the drop height should be limited, especially when blocks are placed above the water line.
- Stones in the subsoil reduce the allowable drop height significantly.

5 CONCLUSIONS

Over 200 impact tests were performed in the laboratory on various filter compositions on dry sand. The conclusions from the test results are:

- Although tests are performed under well controlled conditions there is still a significant scatter in the results. This means that it is difficult to define a minimum drop height for which the geotextile will certainly survive the impact of the block.
- Calculation showed that for a block as tested, with a weight of 78.5 kg, the impact velocity under water is much less than above water, likely resulting in less damage. Tests under water are recommended to investigate this influence further.

- A ballast layer of stones cannot serve as a protective layer against impact. Breakage of stones, leading to sharp edges and localized point loadings contribute to damage.
- Reed underneath a geotextile proves effective in preventing damage. Likely due to reduced friction between geotextile and soil, along with the damping during impact.
- In most cases, H_{cr} increases with the weight of the non-woven primary layer. However, there is a significant scatter in the results.
- Impact on a flat plane of the block results in less penetration but a higher peak impact load perpendicular to the geotextile, compared to impact on a point of a rib of the falling stone. The influence of such a high impact load should be investigated further.

ACKNOWLEDGEMENTS

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