Large-Scale Controlled Testing of Geotextile Puncture Resistance for Rock Impact

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ABSTRACT: The puncture resistance of a range of geotextiles was measured using a method designed to represent large-scale field conditions without sacrificing repeatability or experimental control. The test method simulates rock impacts on a subgrade overlain by a geotextile, a very common condition encountered during the installation and construction of bund walls and revetments. The test apparatus allows controlled and repeatable testing of rock impacts up to 1 tonne in mass, dropped from heights of up to 2.5m. Variables such as geotextile anchorage, subgrade consistency, and rock shape were controlled. The extent of geotextile damage was inspected, measured, and analysed. Two types of polyester non-woven geotextiles were tested: staple fibre (SF) and continuous filament (CF). It was found that the staple fibre geotextile performed remarkably better than the continuous filament geotextile in the same test conditions. The paper discusses the development and key features of the testing apparatus as well as the damage results measured from a range of geotextiles. The test regime described in this paper, which consists of over 100 rock impacts incorporating varied drop heights and geotextiles, has shown that it can be used to inform a general revetment installation design guideline.

Keywords: Staple Fibre, Continuous Filament, Puncture, Installation Damage, Revetment

1 INTRODUCTION

The predicted rise in sea levels due to global warming puts greater strain on our coastal protection systems and gives new meaning to 100 year and even 50 year design life. As geotextiles become an increasingly important component of coastal structures, engineers must endeavour to improve upon current methods of geotextile selection and design. Perhaps the most significant challenge in this endeavour is to select a geotextile that will survive installation and site construction without incurring puncture damage. With time, even a small puncture can become the nucleus for a large failure.

Geotextile resistance to puncture has been examined in a number of different ways. Although their limitations are recognized, index tests such as the CBR Burst Strength Test are commonly specified as an indicator of puncture resistance. Lawson (1992) provided early design guidance by correlating the drop cone test results, trapezoidal tear strength, and mass properties with in-situ performance. Lawson's results, which were based on the exhumation and inspection of samples, have remained a popular reference for designers. Index properties are well known to have limited utility to designers as they fail to isolate the many complex phenomena which occur in when a rigid object impacts a geotextile. In fact, testing by Wong et al (2000) found that ultimate strength (both tensile and CBR) is a poor indicator of relative damage due to impacts. Hence, it is not uncommon for designers to perform on-site tests to compare geotextiles against each other as was described in the work of Ameratunga et al. (2006). Although field tests can closely represent installation conditions, it has been shown that geotextile puncture is a stochastic event and a limited number of repeat trials may not fully capture the risk of puncturing the geotextile during the construction of a large site. Testing has shown that even in highly controlled conditions, punctures can occur quite unpredictably. On any given site, variation of overlaying stone size and shape as well as subgrade consistency will undoubtedly make it more difficult to predict a safe puncture threshold.

Wong et al (2002) had success in isolating tensile elongation and cutting failure mechanisms and then correlating those to values to the kinetic energy of the impacting object. By using an "Energy Level" they were able to combine the effects of mass and velocity of the impacting object and correlate this to the deformation energy (via plastic elongation) of the geotextile. This is a useful step in understanding geotextile impact resistance. This study seeks to advance this understanding with the aim to develop a geotextile revetment design guideline.

Wong et al. (2000) describe the following key parameters influencing the behaviour of geotextiles subjected to drop tests

- Geotextile characteristics including the polymer type, woven or non-woven, mass per unit area, thickness and mechanical properties of geotextile
- Primary armour stone size, weight, angularity, and type.
- Height of release of the impact zone
- Distribution of sizes, weight, and angularity of secondary armour placed on the geotextile
- Geotextile anchorage
- Type and density /consistency of base soil (loose/dense sand or silt, soft/hard clay)
- Slope of base soil
- Ground water condition
- Geotextile specimen size, and the anchoring effectiveness.
- Number of drops on the geotextile specimen.

The test apparatus was designed to isolate and control each of these parameters so that the factors governing the extent of damage may be identified. For the testing described in this paper, the geotextile characteristics and the height of release were the control variables.

2 EXPERIMENTAL STUDY

2.1 *Test Equipment*

Figure 1 shows the equipment used in this testing. It can be seen that a gantry crane is used to suspend a trolley, and electric hoist, a quick release mechanism and the suspended load. The rock armour stone used in the tests was a concrete cube with sides measuring 750mm and weighing approximately 1000kg. The cube was dropped on a corner point giving it consistent and repeatable angularity. The concrete cube was dropped onto the subsoil which was overlain with a geotextile. No secondary armour was used. The dimensions of the contained subgrade onto which the cube was dropped were 1580mm x 1350mm x 600mm (LxWxH). The subgrade is contained by hardwood sleepers which were reinforced with steel plates and anchored to the underlying concrete base slab.

Figure 1. Concrete test cube suspended over the subgrade container with no geotextile in place.

2.2 *Materials and Specimen Preparation*

The sand subgrade was prepared by manual compaction between each rock drop. This was performed by a hand tamping system. The hand tamping was achieved by pattern of 45 repeated drops of a 4.2kg plate measuring .0.4m x 0.3m from a height of 0.5m across the surface of the sand container. This method of subgrade preparation was tested for repeatability. Control rock drops were performed without the overlaying geotextile and the depth of rock penetration was measured to ensure a consistent penetration depth. A density profile of the subgrade was also measured by extracting known cylindrical volumes from the impacted area of the subgrade and measuring the dry mass. This confirmed that repeated tests did not significantly alter the density of the prepared subgrade beyond the average bulk density of 1656.7kg/m^3 for this soil.

The geotextile was securely clamped to the entire perimeter of the subgrade container to ensure that no slippage occurred between the geotextile and the subgrade container. The geotextile samples were further prepared by drawing a grid with 50mm square cells in the impact area. This would be used to measure the resulting elongation of the geotextile post impact. Eight mass samples and four CBR samples were collected around the unaffected edges of the specimen. These would be used to measure mechanical properties of the specimen locally to ensure accurate comparisons with the damaged areas of the geotextile could be made. The CBR burst test consists of a 50mm diameter steel plunger which is pushed at a constant rate through a 150mm diameter specimen until a peak load is reached. Strains and loads and loads can be measured thus.

During testing, the rock drop height was measured using a rigid staff of known length to measure drop heights of 0.5, 1.0, 1.5, and 2.0m with an accuracy of +/- .01m. The drop height was measured from the lowest point of the rock to the surface of the geotextile. The height of the rock was controlled by an electric hoist whilst a trolley on the crane rail was used to bring the rock over the target zone. Once in place, a quick release mechanism allowed the operator to safely drop the rock at a consistent orientation by pulling on a release cord. The test was repeated 5 times for each geotextile grade and drop height.

2.3 *Failure Criteria*

The failure criterion chosen by previous researchers varies widely in scope and level of conservatism. Lawson, who investigated 45 revetment structures up to 7 years old, found that even when approximately 10% of the geotextile was punctured, the revetment structures were not compromised because the stones remained in the puncture holes and prevented soil loss (Lawson, 1982). E. Berendsen (1996) used a similar approach in his analysis. This criterion assumes that the rock armour remains static for the lifetime of the structure and effectively seals any damage the installation may have cause to the geotextile. Researchers such as Naughton (2002), Levacher (1994), and Greenwood (2000) consider installation damage, strength retained, and creep. These considerations can have significant implications for the expected design life of the structure. It should be expected that partial damage, creep, and the continued shifting of strains over time (due consolidation, tidal flows, etc.) will have an effect on the life expectancy of the structure but these effects rely on index value measurements, will be largely theorized, and are difficult to measure. A design approach developed by Koerner (1998) for separation and filtration applications incorporates strength reduction factors to account for installation damage (RF_{ID}) as well as creep (RF_{CR}). The failure criteria and methods of this paper focus on visible evidence of damage in a controlled but realistic environment and efforts focus on giving designers guidelines for a puncture free installation. Installation damage, creep damage, resulting reduction factors, and theorized lifetime predictions are acknowledged but not discussed in this paper.

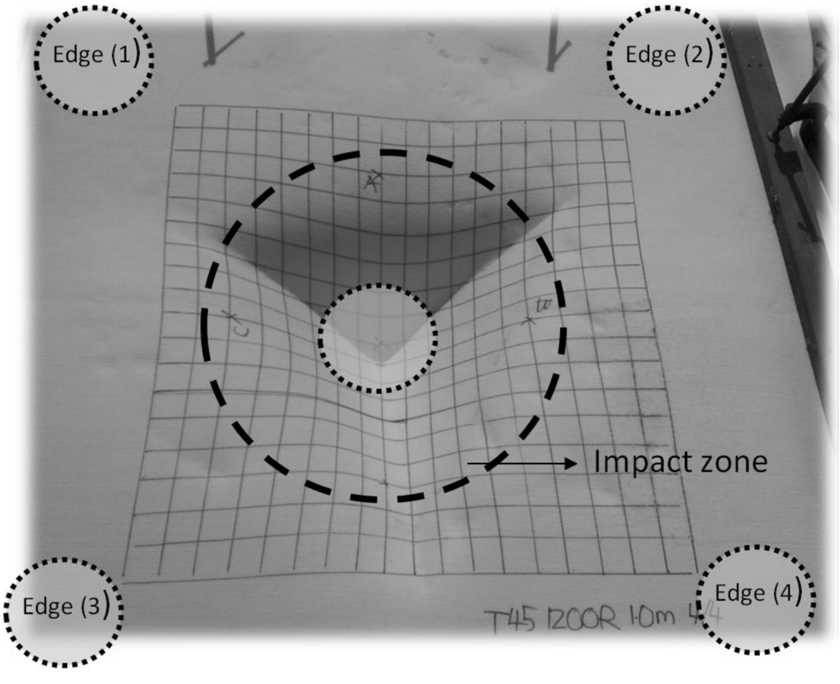

Figure 2. Impact zone and CBR specimen locations.

Throughout the testing undertaken, any visible puncture after removal of the rock was considered to be a failure. While the geotextile may still function as a filter with the armour rock sealing the hole, a long term service life should allow for shifting in the position of armour rock and subgrade which would likely expose this hole or expand the damaged area. For impacted geotextile samples which did not have a visible puncture, a CBR test was performed and compared with the average of 4 undamaged CBR results from the corner edges of the corresponding specimen as seen in Figure 2. If the centre CBR puncture value was less than 50% of the average of the undamaged samples, then the specimen was considered a failure. The 50% strength retained threshold was chosen simply for consistency as it has been used other published design guidelines by Greenwood et al. (2012). The elongation of the geotextile as a result of the impact was also measured via a grid which was drawn on each specimen. The elongation may be a useful measurement for further puncture resistance analysis however it was not incorporated into the failure criteria of this paper.

3 TEST RESULTS

The properties of the geotextiles tested are presented in Table 1 and puncture results are shown in Table 2. A clear outcome of the trials is that the staple fibre product is much better suited for this rock size and subgrade application. The heaviest continuous filament product did not outperform any of the staple fibre products. This large discrepancy in performance is not evident in any index specifications seen in Table 1 and is indicative of the hazards of relying on index values.

Table 1. Mechanical properties of tested geotextiles. (Typical values)

	Test		Standard	Units	SF1	SF2	SF3	SF4
Mechanical Properties	Wide Strip Tensile Strength	MD	AS3706.2	kN/m	10.7	17.7	26.0	36.8
		XMD			21.4	39.0	54.6	82.7
	Trapezoidal Tear Strength	MD	AS3706.3	N	320	477	656	842
		XMD			542	917	1264	1774
	CBR Burst Strength		AS3706.4	N	2719	4522	6526	8824
	Grab Tensile Strength	MD	AS2001.2.3	N	686	1161	1753	2469
		XMD			1097	1948	2948	4539
	Test		Standard	Units	CF1	CF2	CF3	
Mechanical Properties	Wide Strip Tensile Strength	MD	AS3706.2	kN/m	21.5	29.5	57.9	
		XMD			21.0	28.0	55.9	
	Trapezoidal Tear Strength	MD	AS3706.3	N	540	753	1485	
		XMD			510	700	1425	
	CBR Burst Strength		AS3706.4	N	3600	4800	9696	
	Grab Tensile Strength	MD	AS2001.2.3	N	1430	2100	4290	
		XMD			1350	1910	4300	

Each specimen that did not puncture was also tested for residual strength via a CBR burst test taken from the center of the impacted area. As mentioned, this value was compared to the average of 4 unaffected specimens around the perimeter of the geotextile. The results of these tests can be seen in Table 2. It is interesting to note that only one of the specimens showed a residual CBR strength of less than 50%. All but one indicated failures are therefore due to the visible puncture criteria. Residual strength does not appear to be a clear indicator of whether the damaged specimen was at the threshold of a puncture for a given drop height. Additionally, it is interesting to note that for a given drop height and geotextile grade, the occurrence of a puncture has an element of randomness. In the five repeat tests, it often happened that some specimens would fail, and some would not.

Table 2. Results of puncture resistance testing. Failures are indicated by an X. Specimens that did not fail are shaded grey and contain the % CBR strength loss when compared to undamaged edge specimens. Cells with no values were not tested because the result could be assumed based on adjacent drop heights.

	Drop Height (m)			
	0.5	1.0	1.5	2.0
SF 1 (380g/m^2 Typical)	-12.3	-4.5	5.3	
	9.3	-28.3	X	
	-5.0	X	X	
	X**	X	X	
	NA*	-24.6	X	
SF 2 (611g/m^2 Typical)	-12.8	-10.1	X	X
	-1.4	-23.0	X	X
	-4.7	-17.2	X	X
	-3.0	-9.2	X	X
	-6.3	X	X	X
SF 3 (846g/m2 Typical)		-8.0	X	X
		-10.1	X	X
		-26.4	-19.7	X
		-7.1	X	X
		7.1	-35.8	X
SF 4 (1224g/m^2 Typical)		6.7	-10.0	X
		-15.7	X	-33.3
		0.0	-8.4	-6.6
		3.6	X	X
		5.4	-5.4	0.1
CF 1 (280g/m2 Typical)	X	X		
	X	X		
	X	X		
	-31.5	X		
	X	X		
CF 2 (379g/m^2 Typical)	X	X		
	X	X		
	-48.3	X		
	X	X		
	X	X		
CF 3 (740g/m^2 Typical)	-24.5	X	X	
	-11.3	X	X	
	X	X	X	
	-20.2	X	X	
	X	X	X	

*this test value was omitted in error;

**this was the only drop to fail by the residual strength criteria with a loss of 56.1%

A mode of failure not previously described by other researchers was observed. Damage to the geotextile can be induced by the impacting object as well as the subgrade. Once the test rock makes contact with the geotextile it loses speed and quickly comes to a stop. During this interval a number of potentially damaging things occur. Firstly, the geotextile strains and elongates to accommodate the object as it decelerates. This strain occurs along the contours of the object. The object in this case was a concrete cube with flat surfaces as well as rough edges not unlike a recently quarried rock. As expected, the rough edges often caused cutting failures. Interestingly, noticeable damage frequently occurred on the subgrade-geotextile interface along the flat surfaces of the cube. This damage, seen in Figure 3, appears to be the result of friction as the geotextile moves in a downward direction relative to the subgrade. It can also be seen that fibre layers of the geotextile were sheared away as it slid against the subgrade. "Abrasive shearing" was taken to be a descriptive terminology for this type of damage. The abrasive shearing was seen to reduce the thickness of the geotextile and was occasionally evident in the punctured specimens. It can be inferred that this damage is directly related to the depth that the test rock travels as it decelerates. Therefore, a greater amount of "abrasive shearing" damage can be expected from higher drop heights and weaker soil subgrades. This additional damage mode adds complexity to attempts to build a model for puncture failures.

Figure 3. Specimen showing the effects of abrasive shearing on the subgrade side of the geotextile. This specimen had no puncture and appeared relatively undamaged on the opposite side.

4 CONCLUSION

An apparatus which can measure puncture resistance of geotextiles in field applications has been developed and tested. The test device allows the creation of representative field conditions and control of experimental variables. This is an important step in modelling geotextile puncture resistance. Initial tests show that for applications involving large, angular, one tonne rock armour dropped onto geotextiles overlaying a soft subgrade, the product form and the manufacturing method plays a key role in the puncture resistance of nonwoven geotextiles. It was observed that under the same conditions, greater puncture resistance could be achieved by the staple fibre geotextiles when compared to similar or superior strength continuous filament geotextiles. The substantial commitment to replicate testing showed that the puncture threshold for a given geotextiles grade can be difficult to identify. Even in a controlled, repeatable environment, geotextiles puncture stochastically at a given drop height and this behaviour should be acknowledged to reliably avoid punctures during installation.

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