A Centrifuge Experimental Investigation of Strain Development in Geotextile Containers and Tubes

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ABSTRACT
Geotextile tubes and containers have been used to construct coastal structures and coastal protection structures. Recently, geotextile tubes and containers are used as a means of containing dredged or contaminated material for disposing and dewatering purposes. In a recent coastal project in Singapore, geotextile tubes and containers have been proposed as a form of containment for dredged materials such as soft sediment and soft clay. At the same time, this system will form a temporary breakwater to prevent the transportation of sediment plumes and seawater pollution to the vicinity area during the construction stage. It was envisaged that this system will be installed at deep water depth of 25 meters. One of the major design considerations is the integrity of the geotextile containers during the dumping and landing process. To address the considerations on the integrity of the geotextile containers, a centrifuge model study has been conducted using the geotechnical centrifuge in National University of Singapore. This paper presents the model tests results and compared with some existing design methodology.

1. INTRODUCTION

The idea of using geotextile as a containment system took place in the ’60s and ’70s in the Netherlands. Started with the classical sandbags used in the field of flood protection at rivers and at the coast, geotextile has been used in various forms and sizes to meet the specific requirements of the individual task. These containment systems have been successfully applied in hydraulic and coastal applications in recent years. These examples include the use of geotextile to store and isolated contaminated materials obtained from harbour dredging and as bunds for reclamation works (Fowler and Sprague, 1993, Pilarcyzk, 1995, 1996).

Existing literatures on geotextile containers shows that maximum forces are exerted on the geotextile during dumping and during the impact on the subsoil. These literatures further showed that ruptures may occur in geotextiles during their placement. The challenge for the study involving the falling of a geotextile container in water is that the behaviour of falling ground is normally not studies in soil mechanics (Pilarczyk, 2000). It is more common to study how to prevent movements of soil, and is rather uncommon to study the behaviour of falling soil.

In a recent coastal project in Singapore, stacking of geotextile containers have been proposed as a solution for the containment of dredged material and at the same time, as part of the revetment structure in the project. The geotextile containers, up to a size of 6m diameter and 30m length, will be dumped from split-bottom hopper barge. The installation depth of the geotextile containers will be up to 25m water depth, but the placing accuracy of geotextile containers are known to be limited at water depths larger than 15m (Bezuijen, 2004). Therefore, there is a concern on the integrity of the geotextile containers during dumping and impact on the subsoil.

One of the key parameters in the study of the installation of geotextile container is the development of strain (and tensile force) of geotextile during this process. In order to have a better understanding on the strain development of the geotextile container during dumping and impact on subsoil, the geotextile container has been modelled and tested in a geotechnical centrifuge.

2. EXPERIMENTAL SETUP

The NUS geotechnical centrifuge has been used for the model tests on geotextile container. This section will discuss the configuration of the model test, the instrumentation used and the methodology of the centrifuge model test.

2.1 Centrifuge Model Setup

The centrifuge model tests were conducted in 100g and the model setup is shown in Figure 2.1 below. The strong box used for this experiment features an internal dimension of 420mm x 420mm x 480mm (L x W x H). The front sidewall of the container is made of Perspex plate, which allows observation to be done visually. The opening mechanism of a split-bottom hopper barge has been modelled in the centrifuge by using two Perspex plates measuring 220mm by 40mm. These two plates are placed side by side, with both ends supported by 2 short end plates. The end plates are connected to the hydraulic piston. By lowering the end plates, the Perspex plates will be opened, simulating the opening of the split bottom barge.

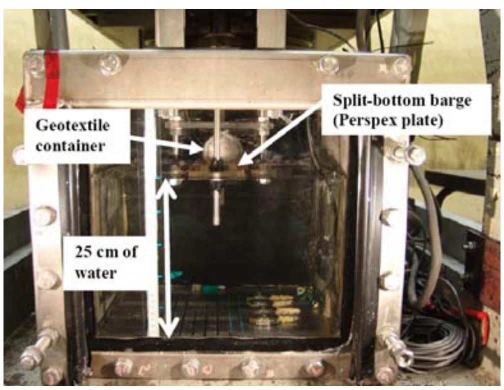


Figure 1: Experimental set-up in the NUS Geotechnical Centrifuge.

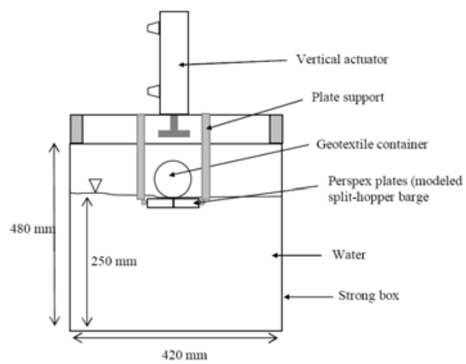


Figure 2: Schematic diagram of experimental set-up.

The model geotextile container used in this study has a diameter of 60mm (6m in prototype scale) and length of 150mm (15m in prototype scale). The scaling relationship of the centrifuge model and full scale prototype is shown in Table 1. A summary of the dimension relationship between the model and the prototype geotextile container is shown in Table 2. The geotextile container is modelled by some weaker geotextiles manually stitched into a shape of a cylindrical container. The model geotextile container is made from non-woven geotextile, TS 20. This material is made of 100% polypropylene. The stress-strain characteristics of the model geotextile are given in Table 3.

Table 1: Scaling relationships applied in this centrifuge study.

Parameter	Scale (model/prototype)
Linear dimension	1/n
Volume dimension	$1/n^3$
Strain	1
Mass	1/n
Time (dynamic)	1/n
Velocity (dynamic)	1

Table 2: Summary of relationship between model and prototype of geotextile container

Parameter	Model	Prototype
Diameter (m)	0.06	6.0
Length (m)	0.15	15.0
Volume (m^3)	0.0004	424

Table 3: Stress-Strain Characteristics of geotextile used in model(TS-20).

Characteristics	Model	Prototype (100g)
Tensile strength @ 2.2% strain (radial), $T_{1,rad}$	3.37 kN/m	337 kN/m
Tensile strength @ 2.2% strain (axial), $T_{1,ax}$	1.85 kN/m	185 kN/m
Ultimate tensile strength (radial), $T_{ult,rad}$	9.5 kN/m	950 kN/m
Ultimate tensile strength (axial), $T_{ult,ax}$	9.5 kN/m	950 kN/m
Strain at ultimate tensile strength (radial), $\varepsilon_{ult,rad}$	35 %	35 %
Strain at ultimate tensile strength (axial), $\varepsilon_{ult,ax}$	70 %	70 %

2.2 Instrumentation of Geotextile Containers

The model geotextile containers were installed with resistant-type strain gages and pore pressure transducer. At least one Druck PDCR81 miniature pore pressure transducers (PPT) was used to measure the variation in pore water pressure during the falling of geotextile containers in the centrifuge tests. The position of the PPTs that were installed in the geotextile container is at the front section of the model geotextile container. Resistant-type strain gauges were attached on the geotextile container to measure the geotextile strain and the corresponding tensile force in the geotextile container. The method of attachment of strain gauges to the geotextile is adapted from Chew et al. (2000).

2.3 Experimental Procedure

Firstly, the strong box was filled with water to a height of 25 cm (25 m in prototype scale). Secondly, the model geotextile container was prepared in 1g, and then placed on the modelled barge. Excess length of cable has to be provided to the various sensors connected to the geotextile container to allow for the falling process. The centrifuge model is being spun up to 100g. Once the centrifuge is stabilized at 100g, the vertical actuator is being activated to open the modelled barge. The geotextile container went through the barge opening, simulating the dumping process of a geotextile container. The falling velocity is being captured by the pore pressure transducers and the strain development is being captured by the strain gages.

3. EXPERIMENTAL RESULTS

A series of 3 centrifuge tests has been conducted and their results are shown and discussed in this paper. The key information of the tests is summarized in Table 4.

Table 4: Test Configuration of Centrifuge Test.

Test ID	Diameter (m)	Fill Material	Filled Ratio
1A	6.0	Dry Sand	70%
1B	6.0	Wet Sand	70%
1C	6.0	Wet Sand	85%

3.1 Comparison of test 1A and test 1B (Effect of dry and wet sand)

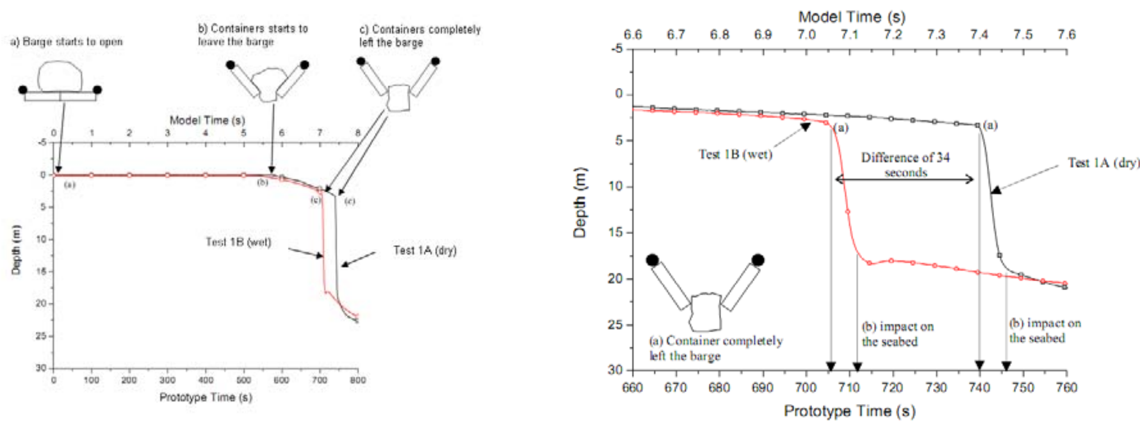
The performance of geotextile container during falling process and upon impact on the seabed can be affected by the fill material. The effect of dry fill material versus wet fill material can be seen by comparing the results of Test 1A and Test 1B. Figure 3a shows the overall process of the geotextile containers in Test 1A and Test 1B recorded by the PPT installed at the bottom front portion of each geotextile container. The installation process includes the gradual opening of the barge, the falling of geotextile container and the landing on the seabed. For a clearer picture of the comparison, Figure 3b zoomed in the 100 seconds details during the fall of the geotextile containers. It is shown that Test 1A took 740 seconds to exit the barge (opening width of 3.80m) and Test 1B took just 706 seconds to exit the barge (opening with of 3.57 m). This indicates that Test 1B which has a heavier weight is able to squeeze through the opening faster than Test 1A. Otherwise, the results of Test 1A and Test 1B are almost identical, which proofs the repeatability of the test.

As for the radial strain development in the geotextile, Figure 4a shows that the strain response for both tests were very similar. It is also shown that the strain in the wet container (Test 1B) has been consistently higher than the strain in the dry container (Test 1A). Due to the barge opening, the radial strain would increase gradually as the opening becomes bigger. The dry container in Test 1A registered a slightly higher peak strain of 19,200 microstrain compared to 18,800 microstrain in the wet container in Test 1B.

Figure 4b shows the detailed 100 seconds of the strain development of the geotextile containers during the fall and upon impact on the seabed. It is clear that when the geotextile container leaves the barge, the radial strain will reduce dramatically. Upon impact on the seabed, a small peak can be seen and after the impact, the residual strain can be obtained. The residual strain for Test 1A is about 7,000 microstrain and Test 1B is about 5,500 microstrain.

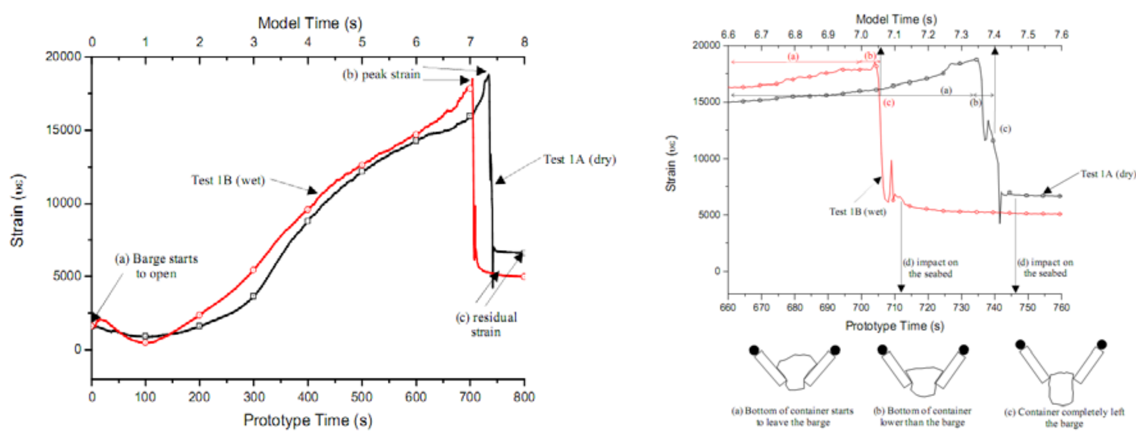
Figure 5a shows the comparison of axial strain development in the geotextile for Test 1A and Test 1B. The axial strain for both tests remained low even after the barge opening. At about 690 seconds, the axial strain of 1B rapidly increased to the peak, and followed by sudden drop in strain. This signifies the building up of strain just before the leaving of the opening. Similar trend was observed for Test 1A at 35 seconds later.

The axial strain in Test 1B showed a peak strain of about 7,500 microstrain when it left that barge around 703 seconds and the peak axial strain in Test 1A was much higher at 16,500 microstrain at time 738 seconds. Even though the unit weight of the dry fill material in Test 1A is lesser than the wet fill material in Test 1B, the axial strain in Test 1A was 220% higher than Test 1B. This suggests that the fall of the geotextile container in Test 1A was much more non-uniform along the length as compared to Test 1B and the most probable cause of this phenomenon is the uneven fill material along the length of the geotextile container. These two results also verified the consistency of the testing procedure and the sensing capability of the sensors.



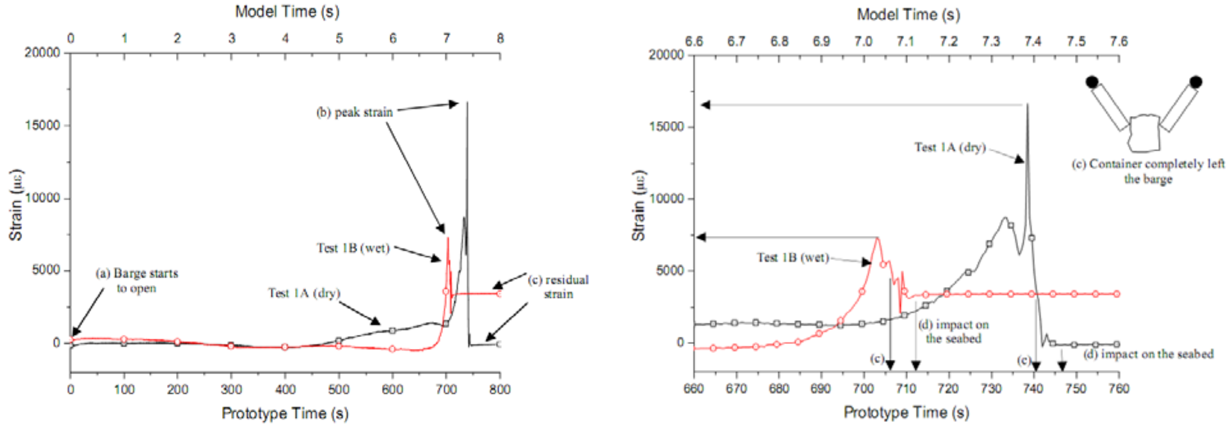
a) Time from 0 to 800 seconds
b) Time from 660 to 760 seconds

Figure 3: Comparison of the fall of geotextile container in Test 1A and Test 1B



a) Time from 0 to 800 seconds
b) Time from 660 to 760 seconds

Figure 4: Comparison of strain development in the radial direction at the bottom of geotextile containers in Test 1A and Test 1B



a) Time from 0 to 800 seconds b) Time from 660 to 760 seconds

Figure 5: Comparison of strain development in the axial direction at the bottom of geotextile containers in Test 1A and Test 1B

3.2 Comparison of test 1B and test 1C (Effect of fill percentage)

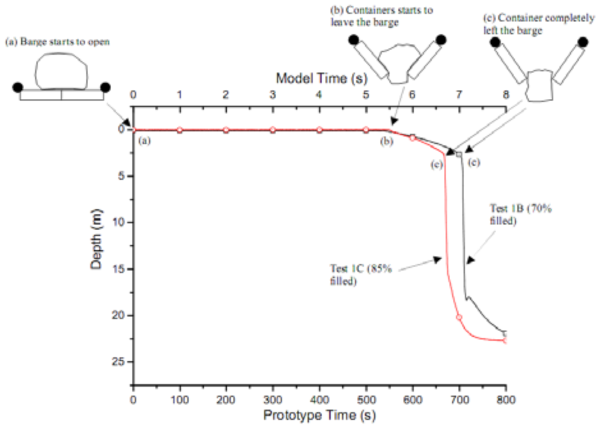
The performance of a geotextile container during falling and upon impact on the seabed can also be affected by the fill percentage used in the container. The effect of fill percentage in the geotextile container can be seen by comparing the results of test 1B and test 1C. Test 1B has a fill percentage of 70% compared to 85% in Test 1C.

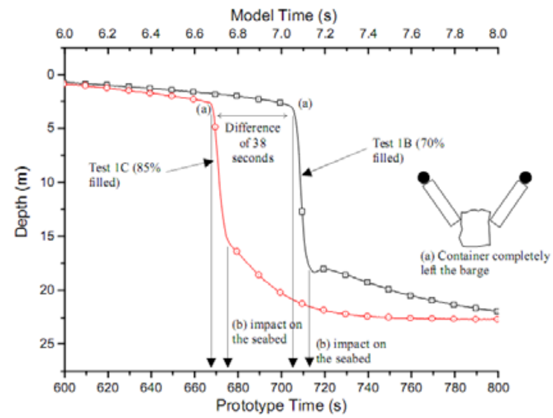
Figure 6a shows the overall installation process of the geotextile containers in Test 1B and 1C and we can see that the higher percentage filled container (Test 1C) completely left the barge earlier than the lesser filled container (Test 1B). This exact time difference can be seen in Figure 6b. Test 1C completely left the barge at around 668 seconds and Test 1B took 38 seconds more and left the barge at 706 seconds. This shows that the 85% filled geotextile container of Test 1C managed to overcome the friction between the geotextile and the bottom of the barge faster, due to its additional weight compared to the 70% filled geotextile container in Test 1B. In addition, a higher percentage filled geotextile container will have a closer-to-circular cross section, hence resulted in less slack for elongation of geotextile at this stage.

As for the strain development in the geotextile, Figure 7a shows that the radial strain increases gradually for both tests for the first 300 seconds after the barge opening. After 300 seconds, the strain development in Test 1B (70% filled) continued to increase at faster rate than the increase in Test 1C (85% filled). Looking at Figure 7b, the strain in Test 1B (70% filled) increased until about 705 seconds, where the geotextile container managed to overcome the friction of the barge and fall out from the barge. At this stage, the radial strain in Test 1B reduced drastically and followed by a peak upon impact on the seabed. But the strain in Test 1C (85% filled) seems to develop in a different manner. After 300 seconds, the strain in Test 1C (85% filled) developed at a slower rate until around 500 seconds, where it reached a peak of 10,500 microstrain. After that, the strain development reduced slightly until it finally left the barge at around 668 seconds. Comparing the magnitude of strain during the barge opening phase, the radial strain in Test 1C (85% filled) was 40% lesser than the radial strain in Test 1B (70% filled). However, during the impact on the bottom of the seabed, the bottom radial strain for Test 1C (85% filled) hit the value beyond 22,250 microstrain, the maximum that the dynamic strain recorder is able to record.

Based on the above observation, it seems that for the 70% filled geotextile container, the strain development during the barge opening phase is more critical than the impact of the geotextile container on the seabed. However, for the 85% filled geotextile container, the strain development was more critical during the impact than during the barge opening. This observation explains the reason that why totally opposite conclusion was made by different researcher, e.g. Den Adel et. al. (1996) concluded that the geotextile strain is critical during the impact, while Fowler et. al. (1994) concluded that the strain is critical during the barge opening. Their experiences have different fill percentage of the geotextile container. In general, higher percentage of fill will result in an almost circular cross-section, with higher weight per meter-run. This will cause the geotextile container to overcome the barge-bottom friction faster and leave the barge earlier, with more uniform and lower value of radial strain developed. However, when the higher percentage fill geotextile container hits the floor (especially with some stiffness), it will result in higher strain upon impact.

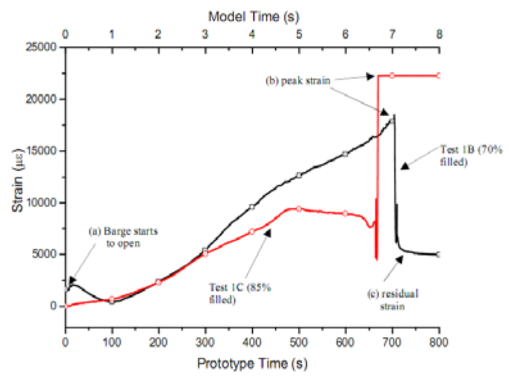
Figure 8a shows the comparison of axial strain development in the geotextile for Test 1B (70% filled) and Test 1C (85% filled). It seems that the axial strain development was rather insignificant during the first 600 seconds after the barge starts to open up. By looking into the detailed 200 seconds of the axial strain development (Figure 8b), it seems that for Test 1C (85% filled), the axial strain increased to about 3,600 microstrain when it left the barge and for Test 1B (75% filled), the axial strain increase to about 7,500 microstrain. It seems that the container in Test 1C (85% filled) managed to leave the barge faster, and thus the lower strain developed in the geotextile in the axial direction. Besides that, it could be also due to the fact that the sand filled in Test 1C (85% filled) was more uniform along the length of geotextile container than in Test 1B (70% filled).

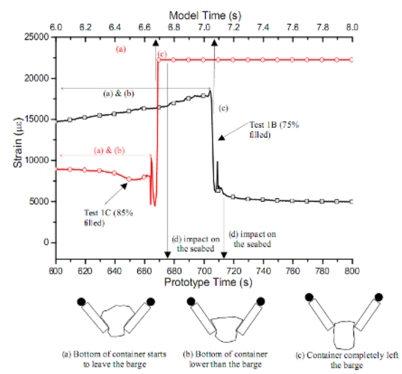




a) Time from 0 to 800 seconds b) Time from 600 to 800 seconds

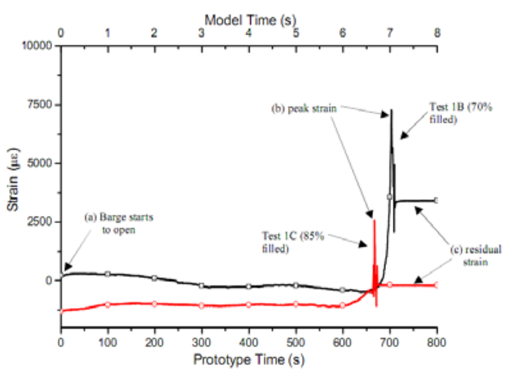
Figure 6: Comparison of the fall of geotextile container in Test 1B and Test 1C

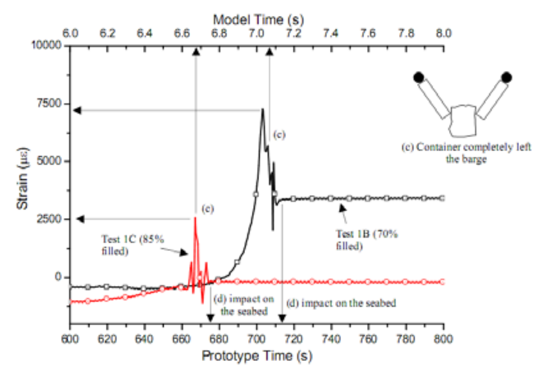




a) Time from 0 to 800 seconds b) Time from 600 to 800 seconds

Figure 7: Comparison of strain development in the radial direction at the bottom of geotextile containers in Test 1B and Test 1C





a) Time from 0 to 800 seconds b) Time from 600 to 800 seconds

Figure 8: Comparison of strain development in the axial direction at the bottom of geotextile containers in Test 1B and Test 1C

4. DISCUSSIONS ON EXPERIMENTAL RESULTS

The centrifuge test results obtained have been analysed and the strain development in the geotextile has been converted to tensile force in the geotextile. Table 5 summarizes the maximum strains (both radial and axial directions) that were recorded. The calibration of the strains measured by the strain gages to the corresponding tensile forces was conducted using the standard wide-width tensile test methods (EN ISO 10319). The critical tensile stresses at various phases are shown in Table 6.

Table 5: Summary of Maximum Strain Recorded at Various Phases

Test ID	Conditions	Radial Strain (%)			Axial Strain (%)		
		Opening	Impact	Residual	Opening	Impact	Residual
Test 1A	70% filled, Dry	1.92	0.19	0.70	1.65	0.10	0.00
Test 1B	70% filled, Wet	1.88	0.38	0.55	0.75	0.30	0.35
Test 1C	85% filled, Wet	1.05	2.23	2.23	0.36	0.17	0.05

Table 6. Tensile Forces Measured in Geotextile Container at Various Phases

Test ID	Conditions	Tensile force in radial direction					
		Model (kN)			Prototype (kN)		
		Opening	Impact	Residual	Opening	Impact	Residual
Test 1A	70% filled, Dry	3.085	0.500	1.650	308.5	50.0	165.0
Test 1B	70% filled, Wet	3.035	1.000	1.335	303.5	100.0	133.5
Test 1C	85% filled, Wet	2.185	>3.370	>3.370	218.5	>337.0	>337.0

Test ID	Conditions	Tensile force in axial direction					
		Model (kN)			Prototype (kN)		
		Opening	Impact	Residual	Opening	Impact	Residual
Test 1A	70% filled, Dry	1.515	0.100	0.000	151.5	10.0	0.0
Test 1B	70% filled, Wet	0.710	0.330	0.375	71.0	33.0	37.5
Test 1C	85% filled, Wet	0.275	0.235	0.000	27.5	23.5	0.0

These experimental values are compared against some theoretical estimations. A conservation estimation of the loading on geotextile during barge opening phase is given by Bezuijen et al. (2004). The equation is given below:-

$$T = 0.45\frac{W'}{L} \qquad [1]$$

Where W' is the net buoyant weight of the geotextile container, and L is the length of the geotextile container.

Using the above equation and the parameters of the centrifuge experiments, the estimated loading for various fill density have been plotted in Figure 9. The tensile forces in the radial direction in the opening phase obtained from centrifuge experiments are also plotted in the same figure. It is shown that the measured tensile force in the geotextile container during the barge opening phase is much higher than the estimation of Equation [1]. This seems to suggest that Equation [1] is not a conservative estimation of the tensile force in the geotextile container at this phase. However, it should be noted that the centrifuge model of geotextile container has a high elastic modulus, E value of 2714 kN/m in prototype scale. During the barge opening phase, the geotextile deforms continuously as the barge opening becomes bigger and more filled material goes through the opening. The deformation of geotextile material depends on the strain development of the geotextile. A stiff geotextile material (high E) would have developed much smaller strain compared to a less stiff geotextile (low E). Therefore, it is believed that the elastic modulus of the geotextile will influence the strain development of the geotextile at this phase. The strain developed just before the geotextile container leave the barge opening is also dependent on the physical dimension of the opening. Hence, stiffer material will develop higher tensile force at this stage.

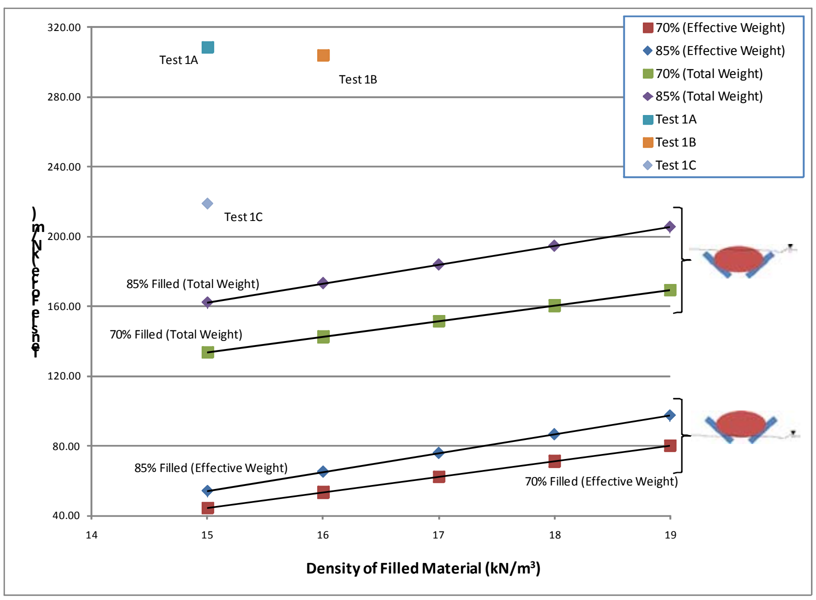


Figure 9: Tensile Force in Geotextile during Barge Opening Phase.

5. CONCLUSION

A series of 3 centrifuge tests has been conducted to model the falling process of a geotextile container. The strain development in the geotextile containers has been monitored and the findings of these experiments led to the following conclusion:-

i. Centrifuge modelling is capable of capturing the strain development in a geotextile container during the falling and during the impact on the subsoil. The repeatability of the tests has been proven in Test 1A and Test 1B.

ii. The strain in the radial direction is generally higher than the strain in the axial direction.
iii. A higher percentage filled geotextile container might be able to leave the barge earlier during the barge opening stage (as shown in Test 1B and Test 1C).
iv. A higher percentage filled geotextile container might have a more circular cross-section than a lower percentage filled geotextile container. Hence, the friction between the geotextile material and the barge bottom surface can be overcome earlier in a higher percentage filled container.
v. The stiffness modulus of the geotextile container (E) will influence the strain development in the geotextile container during the barge opening phase. However, current estimation does not take into consideration the effect of E on the tensile force developed in a geotextile container at this phase.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the laboratory officers in the NUS Geotechnical Centrifuge Laboratory for their assistance in carrying out the centrifuge model test.

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