INNOVATIVE FIBRE OPTIC SENSORS FOR MONITORING STRAIN IN GEOTEXTILE CONTAINERS

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Abstract: Geotextile containers have become increasingly popular in land reclamation related applications. In a recent major land reclamation project in Singapore, geotextile containers were designed as a solution for the containment of dredged material and at the same time, form part of the revetment structure. These containers will be dumped into a maximum water depth of 25 m. This posts a great challenge as most experiences on the use of geotextile containers are limited to water depths of less than 20 m. The geotextile container is being modelled and tested in the geotechnical centrifuge in National University of Singapore with the aim to investigate the strain development of the geotextile containers during the falling and landing process. For the purpose of monitoring strain in geotextile containers, a novel method of using innovative fibre optic sensor has been tested on the model geotextile container. Conventional resistant type strain-gages have also been installed onto the same container to compare with the response of the fibre optic sensor. The innovative fibre optic sensor relies on the modulation of light intensity, and relates that to the strain development in the geotextile. This sensor has the advantage of immunity to electromagnetic interference, capability for distributed monitoring, long-term monitoring without susceptibility to drift and better water resistance. The results demonstrated that intensity-based optical fibre sensor has a great potential for the monitoring of strain in the geotextile container in the actual site operations.

Keywords: centrifuge, geotextile containers, innovative-geosynthetics, optical fibre, reclamation.

INTRODUCTION

Classical sandbags have been 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. Since then, rapid development has been made in the ’80s and many successful applications have been recorded in countries including the Netherlands, Australia and the United States. One of the main advantages of this system is the possibility of using locally available materials as in-filled material.

According to Pilarczyk (2000), the application of geosynthetics and geosystems in hydraulic and coastal engineering has a very incidental character, and it is usually not treated as a serious alternative to the conventional solutions. However, there has been great interest in recent years in using geosynthetics in various structures and systems in hydraulic and coastal engineering. In a reclamation project involving a lot of dredging of soft sediment and soft clay, dredged material often requires a specially designated containment area for disposal. Geotextile containers can be a good solution for the containment of dredged material. In Southern Island, Singapore, geotextile container was used to form a continuous perimeter bund for dumping ground of dredging spoils (Wei, 2001). Besides forming a perimeter bund, the filled containers can also be stacked to form part of the revetment structure in land reclamation projects. In addition, this geotextile container itself can be filled with dredged material itself, rather than with sand.

In a recent land reclamation project in Singapore, 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. These containers will be dumped into a maximum water depth of 25 m. This posts a great challenge as most experiences on the use of geotextile containers are limited to water depths of less than 20 m. Therefore, there is a concern on the strain development in the geotextile containers at installation depths of up to 25m.

During the design stage, the geotextile container is being modelled and tested in the geotechnical laboratory centrifuge in National University of Singapore with the aim to investigate the strain development of the geotextile containers during the falling and landing process. Both conventional resistant type strain-gages and new fibre optic sensors have been installed onto the model geotextile container in geotechnical centrifuge.

The type of fibre optic sensor used is known as plastic optical fibre (POF). Recent research has shown their potential as a low-cost sensor for damage detection and structural health monitoring applications (Kuang, 2004). Optical fibre sensors have a number of significant advantages over the existing electrical based sensors. These advantages include their immunity to electromagnetic interference, capability for distributed monitoring, long-term monitoring without susceptibility to drift, multiplexing capability and better water resistance.

The more common type of fibre optic sensor that is being used in the industry uses Fibre Bragg Gratings (FBG). However, FBG interrogation systems are costly and require trained personnel to handle both the acquisition system as well as the FBG sensors. In our application where the precise strain measurement of up to 1 microstrain is not required, a less sophisticated system may be more attractive. Therefore, intensity-based optical fibre sensors offer a more cost-effective alternative. The feasibility of these sensors to accurately monitor the dynamic response of a beam has been proven by Kuang (2005).

This paper presents the results of centrifuge model tests done using both the intensity-based optical fibre sensors and conventional resistant type strain-gages. The potential of using the intensity-based POF in measuring strain in geotextile will be demonstrated and discussed.

CENTRIFUGE MODEL TEST

Centrifuge model setup

The National University of Singapore's geotechnical centrifuge has been used for the model tests on geotextile container. This geotechnical centrifuge has a payload capacity of 40 g-tonnes and a maximum working g-level of 200g (Lee *et al.* 1991). Figure 1 shows an overview of the experimental set-up in the geotechnical centrifuge. 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. A split-bottom hopper barge has been modelled in the centrifuge using Perspex plates. The model split bottom barge will be installed in the middle top portion of the strong box.

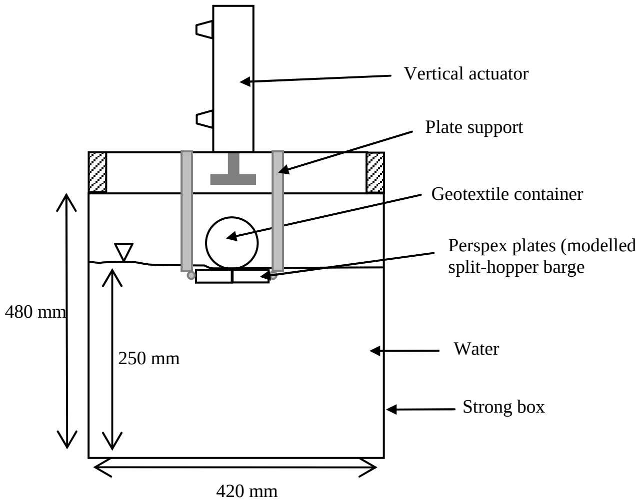

Figure 1. Schematic drawing of experimental set-up

The model geotextile container used in this study has a diameter of 60mm and length of 150mm. This corresponds to a diameter of 6m and length of 15m in prototype as the experiment was conducted at an acceleration field of 100g. 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 with UV stabilise. It has a bi-directional ultimate tensile strength of 9.5 kN/m in the machine direction at 35% strain at break and in the cross machine direction at 70% strain at break.

Instrumentation of geotextile containers

The model geotextile container has been installed with resistance type strain gage, plastic optical fibre (POF) strain gage and pore pressure transducer.

The strain gauge used is resistance type strain gages of model YFLA-20 manufactured by Tokyo Sokki Kenkyuko Co. Ltd. The method of attachment of strain gauges to the geotextile is adapted from Chew *et al.* (2000). Figure 2 shows the schematic diagram of the strain gauging method.

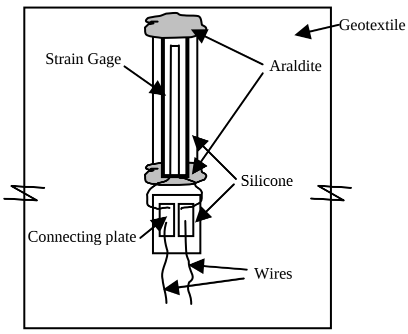

Figure 2. Schematic diagram of strain gauging method used

Druck PDCR81 miniature pore pressure transducers (PPT) from GE Sensing were used to measure the variation in pore water pressure during the falling of geotextile containers in the centrifuge tests.

The type of POF used in the centrifuge test was a 1 mm diameter multimode fibre. The core is made of super pure polymethylmethacrylate (PMMA) and the cladding material from fluorinated PMMA. The specification of the POF is given in Table 1. The intensity-based POF can have 2 types of configuration; one is known as “bend sensor” and the other is called “extrinsic sensor”. “Bend sensor” is a single continuous fibre while the “extrinsic sensor” is made of two cleaved fibres held in place by a housing.

The “bend sensor” relies on the monitoring the modulation of light intensity as the sensor is subjected to flexural and axial loading conditions. A segment of the protection layer of the sensor was removed over a predetermined length. The two ends of this exposed segment were glued to the geotextile, thus representing the equivalent gage length. The subsequent bending of this segment due to elongation will then cause the difference in light intensity, which can be captured and back-calculated the strain.

Table 1. Specification of POF used (Kuang et al. 2004)

	Core	**Cladding**
Material	PMMA resin	Flourinated polymer
Diameter (typical)	980 μm	1000 μm
Young’s modulus	3.09 GPa	0.68 GPa
Poisson’s ratio	0.3	0.3
Refractive index	1.492	1.405
Yield strength	82 Mpa	
Transmission loss (@650 nm)	200 dB km^{-1}	
Maximum operating temperature	70°C	
Approximate weight	1 g m^{-1}	

“Extrinsic POF’s” sensing capability relies on the modulation of optical signal intensity with changes in the longitudinal separation of two cleaved plastic optical fibres. A good quality cleave can be obtained at the end faces of the POF using a sharp razor blade or using commercially available plastic fibre cutter. The POF sensor is housed in a polytetrafluoroethylene (PTFE) sleeves and a PTFE outer tube as shown in Figure 3. PTFE material was used because of its excellent fracture toughness, almost universal chemical resistance, high temperature resistance and self-lubricating properties. The sensor fabrication procedure requires neither precision boring nor heating for the purpose of sensor construction. The PTFE can be cut to desired length readily and the housing constructed easily. The gauge length used is this experiment was 20 mm.

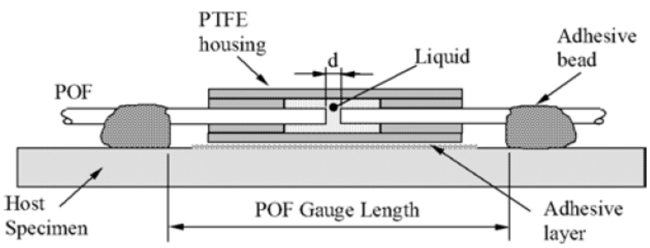

Figure 3. Schematic diagram of POF sensor (Kuang et al. 2004)

Experimental Procedure

In this series of centrifuge test, the level of gravitational acceleration used was 100g. The scaling relationship of a small-scale centrifuge model and full scale prototype was based on the commonly used scaling relations from Leung et al., (1991).

Firstly, the strong box was filled with water to a height of 25 cm (25 m in prototype scale). The barge can be adjusted accordingly to the height of water so that it is just right above the water surface. The model geotextile container would be placed on the barge and extra caution has to be given on the amount of excess lose cables connected to various instruments on the geotextile container required for the falling of the geotextile container.

The centrifuge was spun up to 100g. The whole spinning up process would take about 7 minutes to reach a stabilized g-level of 100. The opening of barge is then initiated via the hydraulic controls in the remote control room. By lowering the hydraulic piston, the barge will open and allow the geotextile container to fall through the opening. Thus, simulating the drop of the geotextile container.

Analogue signals from PPT are transmitted via the slip rings and digitised before being captured by the data acquisition system with Dasylab 5.0. Meanwhile, signals from strain gages are captured by dynamic strain meter which is connected to an on-board PC seated on top of the centrifuge machine.

RESULTS FROM CENTRIFUGE TEST

Two centrifuge test results shall be presented in this paper. In test 1, the model geotextile container was installed with one bend POF sensor and one extrinsic POF sensor. The objective of this test was to assess the response of both sensors in terms of monitoring strain in geotextile.

In test 2, the almost identical model geotextile container was installed with one extrinsic POF sensor and one resistance type strain gage. The objective of this test was to make comparison on the response of POF sensors and the conventional type of strain gage in terms of monitoring strain in geotextile. Due to the limited size of the model geotextile container, it is too constricted to place all 3 sensors in one model container.

Test 1 (Comparison of bend POF sensor and extrinsic POF sensor)

In this test, the two types of POF sensors (i.e. bend POF sensor and extrinsic POF sensor) were installed at the bottom of the geotextile container in the radial direction. The geotextile container used has a 6.0 m diameter and was filled up with dry sand to 80% of the geotextile container's volume. The purpose of this test was to determine the response of both types of POF sensors in centrifuge.

The POF sensors were installed in the radial direction and not in the axial direction because based on our previous observations, the strain in the radial direction is much higher and critical. In addition, one number of PPT was installed in the bottom of the geotextile container for the purpose of determining the exact position of the geotextile container during the fall. The results obtained from the PPT are shown in Figure 4 and the results obtained from the POF sensors are shown in Figure 5. In Figure 4, the position of the geotextile container can be clearly indicated based on the pore pressure recorded from the PPT.

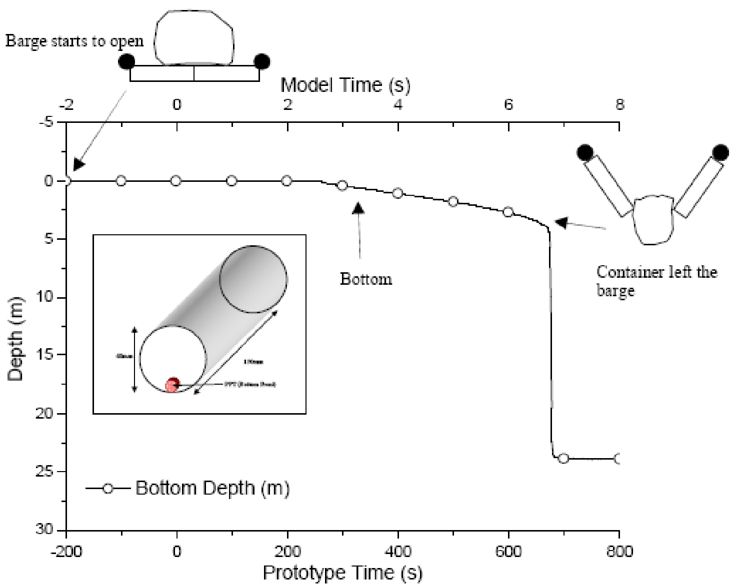

Figure 4. Fall of geotextile container in Test 1 (based on PPT)

The readings given by the POF sensors were in terms of intensity loss, whereby the higher intensity loss means the larger strain experienced by the geotextile container. The results on Figure 5 showed that both sensors detected intensity loss (strain increment) almost immediately after the barge starts to open (model time = 0 second). The bend POF sensor has better response compared to the extrinsic POF sensor up to about 40% intensity loss in the first 2 seconds of the barge opening. After that, the bend sensor's response became slower than the extrinsic sensor. In fact, the extrinsic POF sensor demonstrated a rather linear response from 20% to 95% intensity loss. On the other hand, the bend POF sensor showed a bi-linear response, where the sensor's response was faster in the first 40% of intensity loss and followed by a slower response after 40% intensity loss.

After 6 seconds of barge opening, the extrinsic POF sensor detected a clear reduction in strain, while the bend POF sensor showed less obvious change. At that point of time, the bottom part of geotextile container where the sensors were installed was about to leave the barge. As the shape of geotextile container continuously changed while it forces through the barge opening, the extrinsic POF sensor managed to capture the response of slight reduction in strain. However, due to the nature that bend POF sensor is made of a single continuous fibre, its response in detecting strain reduction is not as good as the extrinsic POF sensor.

Based on the observations of this test, it seems that both the extrinsic POF sensor and bend POF sensor are capable of measuring the strain in the geotextile in the radial direction. Comparing the performance of these two sensors, the extrinsic sensor showed better response when the geotextile container is about to leave the barge. Meanwhile, calibration is currently being conducted using wide-width tensile test for geotextile to convert the intensity loss values to strain values.

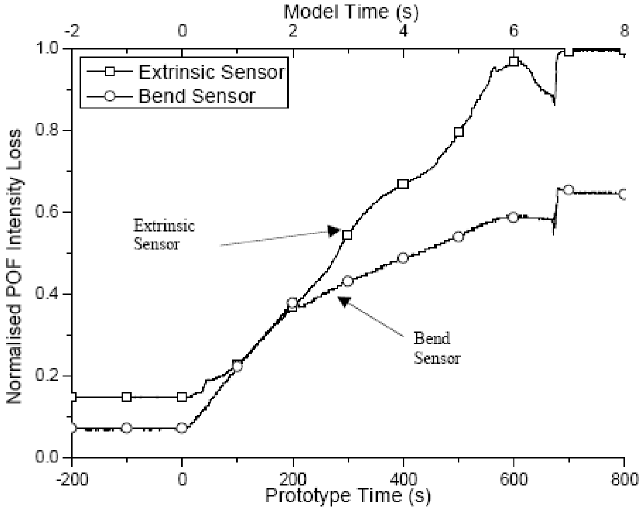

Figure 5. Intensity loss of POF in Test 1

Test 2 (Comparison of extrinsic POF sensor and resistance type strain gage)

In test 2, a 6.0 m diameter geotextile container was filled up with dry sand to up to 85% of the geotextile container's volume. One extrinsic POF sensor was installed in the bottom radial direction and another conventional resistant type strain gage was installed in the radial direction for the purpose of comparison the response of these two sensors in the monitoring of strain in geotextile. One PPT was also installed in the bottom of the geotextile container to determine the position of the geotextile container during the fall as seen in Figure 6.

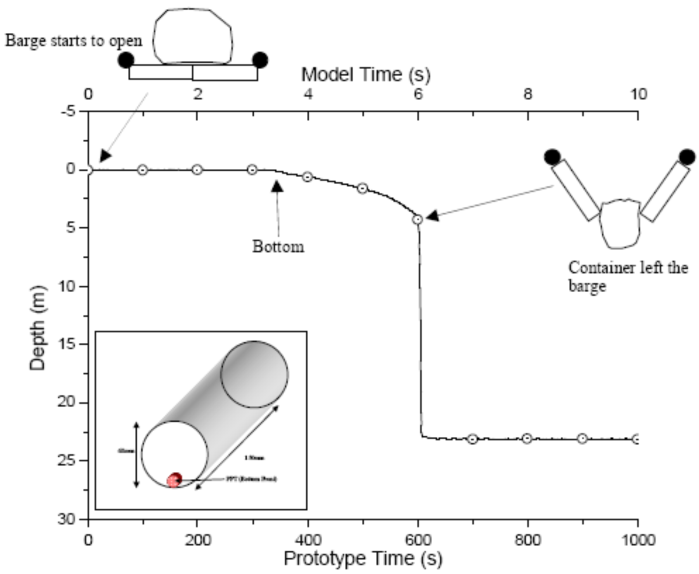

Figure 6. Fall of geotextile container in Test 2 (based on PPT)

Figure 7 shows the strain at the bottom of the geotextile in the radial direction and the normalised POF intensity loss of the extrinsic sensor. As the barge opening width increases, both the strain gage and extrinsic sensor (POF) exhibited the same trend in terms of the response of increment in strain at the beginning. Extrinsic POF sensor indicated that the geotextile container started to leave the opening at 5 seconds (model time). While the resistance type strain gage did not show any significant change until 5.8 seconds (model time).

The detailed responses of these two sensors at the time when the geotextile container is about to leave the barge (i.e. model time = 5.0 to 6.5 seconds) are plotted in Figure 8. From 5 seconds to 6 seconds (model time) of this test, the extrinsic sensor showed slight reduction in intensity loss which is marked as zone (a) and slight increment in intensity loss in zone (b). However, the resistant type strain gage did not show much change in strain at the same time frame. This shows that the extrinsic sensor was able to capture the response of the slight reduction in strain when the container started to go through the opening; while the resistant type strain gage did not capture that response.

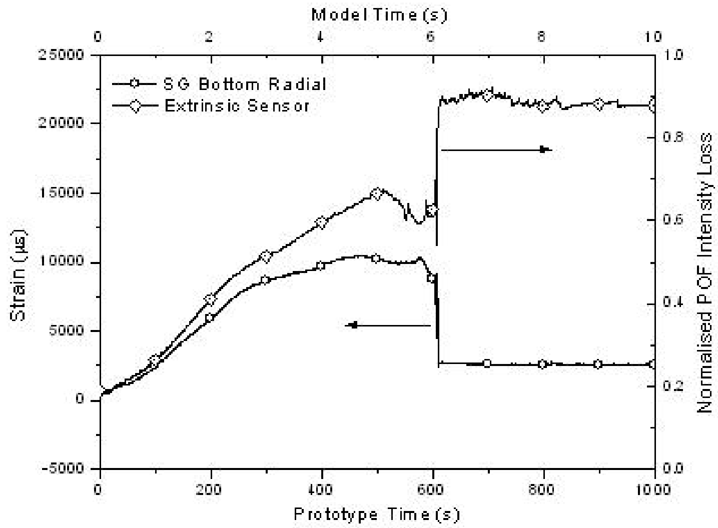

Figure 7. Strain at bottom of geotextile and Intensity loss of POF sensor in Test

Looking at the zone (c) in Figure 8, both sensors showed further reduction in strain when the container completely left the barge and fall through the water depth in the time range of 6 to 6.1 seconds. After that, the impact of the geotextile container was recorded by the resistant type strain gage by a clear peak in terms of strain at around 6.1 seconds. During the impact, the extrinsic sensor (POF) showed a fast increase in intensity loss from about 55% to over 90%. Therefore, the impact is also shown in the extrinsic sensor by the sudden increase of intensity loss. The probable reason that the extrinsic sensor did not show any reduction after this stage is that the extrinsic sensor cable was held in place by the weight of geotextile container and could not retract back.

Overall, the response of the extrinsic POF has very good agreement with the response of the resistant type strain gage.

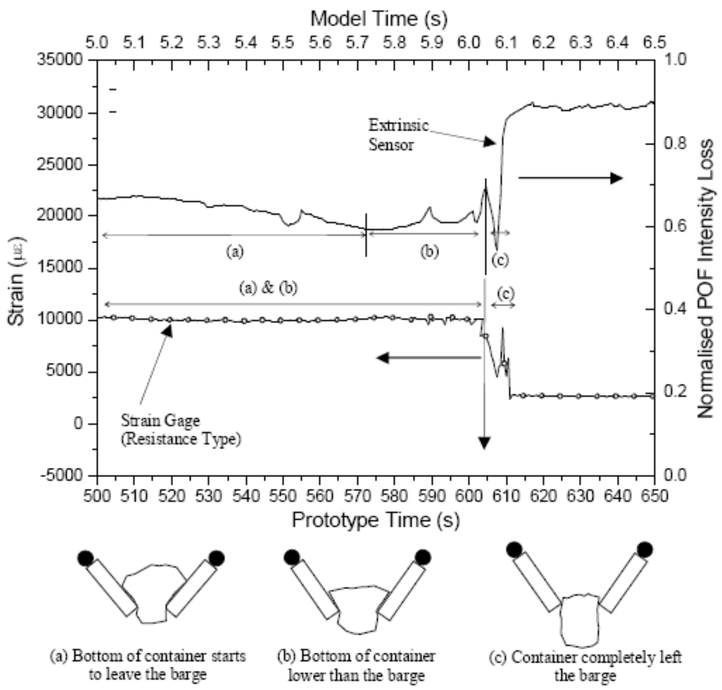

Figure 8. Strain at bottom of geotextile and Intensity loss of POF sensor in Test 2 (Zoomed In)

CONCLUSION

The strain development in the geotextile containers at the top and bottom surface has been monitored using strain gages and a new POF sensor. The results of test 1 indicates that both types of POF sensors, namely “extrinsic sensor” and “bend sensor” give similar response in the radial direction of the geotextile container. Although the extrinsic sensor gave better response than the bend sensor, extrinsic sensor might fail in high strain where the fibre come out from the housing. To solve this problem, a longer housing can be used for the extrinsic sensor. The results of test 2 proved that the response of the extrinsic sensor (POF) is consistent with that of a strain gage. Therefore, with proper calibration POF sensors can be used to determine the strain in geotextile.

Acknowledgements: The assistance of technicians at National University of Singapore's geotechnical centrifuge is gratefully acknowledged. The first author, C.Y. Tan would also like to acknowledge the support provided by the National University of Singapore's Research Scholarship.

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