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To cite this article: J W Koh *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1260** 012016

The behaviour of containment bund using stacked geotextile tubes filled with lightly cemented soft soil

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Abstract. This land reclamation project used stacked geotextile tubes to construct a 1 km long containment bund. In the past, sand is the preferred infilling material of geotextile tubes due to its ease of construction. However, due to sand scarcity in Singapore, soft soil becomes a potential alternative infilling material. One of the challenges of using soft soil as infilling material is that there will be an excessive settlement and concerns about the overall stability of the stacked tubes. Hence, the soft soil is lightly cemented before infilling into the geotextile tubes. This paper presents the design consideration and the construction sequence of the construction of a stacked geotextile tubes containment bund. Extensive instrumentation was installed at a section of the containment bund to study the behaviour of this geotextile tube. The instrumentation includes strain gauges, pore pressure transducer and total pressure cell. After two years of construction was completed, Standard Penetration Test (SPT) and laboratory triaxial test were used to evaluate the strength of the infilling material. All the instrument data and strength tests results were used to ascertain the performance of the stacked geotextile tubes containment bund.

1. Introduction

Land reclamation is one of the methods that most high population density countries employ to enlarge their land area, including Singapore [1]. Until today, Singapore has reclaimed approximately 150 km^2 or 25% of the original landmass [2]. In the past, the preferred infilling material for a land reclamation project in Singapore was sand due to its ease of construction and excellent performance. Recently, soft soil such as dredged marine clay and excavated soil from the construction site has become an alternative fill material for land reclamation projects due to the sand scarcity problem [3]. Those soils have high moisture content and behave like slurry in nature when hydraulically filled. Hence, it is a must to construct a containment bund along the edge of the land reclamation area to contain the soft soil fill material. Usually, the containment bund can be made up of merely a sand bund or geotextile tube filled with sand slurry. Then, again, the availability of a large amount of sand is always an issue. It may not be environmentally sustainable in the long term as well. Therefore, the construction of geotextile tubes filled with soft soil is becoming attractive, even though it has some difficulties. The problem with using soft soil as infilling material is it has high moisture content and low strength. Hence, the geotextile tube will have an excessive settlement and significant shape deformation after a long time. It is also noted that the dewatering process of the geotextile tube filled with soft clay may see some initial piping of clay particles through the geotextile sheet. Then, its dewatering rate will be reduced due to the binding of the filter cake at the interior perimeter of the geotextile tube [4].

An innovative way to minimise the outfall of using soft soil-filled material in a geotextile tube is to mix the soft soil with a small amount of cement before infilling it into a geotextile tube. This lightly cemented soft soil serves two purposes: it prevents the initial piping of fine particles and provides the required strength for stability in a shorter time. This concept was tested in a miniature geotextile tube study [5] and a pilot test on a single piece of actual-size geotextile tube filled with lightly cemented soft soil [6]. Both studies concluded that the concept of utilising lightly cemented soft soil as infilling material for geotextile tube is feasible. The geotextile tube in the tests was able to withstand the designed imposed loading with minimal deformation. Hence, lightly cemented soft soil-filled geotextile tubes were subsequently utilised to construct a containment bund in a mega reclamation project in Singapore. The objective of this paper is to examine the performance of this containment bund. Extensive instruments/sensors, including strain gauges, earth pressure cells and pore pressure transducers, were installed at the critical section. The behaviour of the geotextile tubes was analysed using field monitoring data during and post-construction phases. Besides, standard penetration test (SPT) and laboratory triaxial test were employed to evaluate the infilling material strength after two years. The strain development of the geotextile material, the stresses inside the filled geotextile tubes, and the strength development of the infilling material over time will be evaluated and reported in this paper.

2. Design of Containment Bund

At a reclamation site, an approximately 1 km long pyramidal shape containment bund was constructed. It was made up of numerous units of 40.3 m long geotextile tubes. The geotextile tubes were stacked up into a pyramidal shape in section view and placed in a staggered arrangement along the alignment of the bund. The pyramidal shape containment bund was made up of six (6) units of geotextile tubes stacked up in three (3) layers, as shown in figure 1. The first layer has three (3) geotextile tubes (GB1-L, GB1-R and GB1-C) placed side by side. The second layer has two (2) geotextile tubes (GB2-L and GB2-R), which were stacked above and positioned in-between the first layer's geotextile tubes. The third layer has only one geotextile tube (GB3). The height and width of a single filled geotextile tube used in this project are about 2 m and 5.29 m, respectively. The total height of the completed containment bund is roughly 6 m.

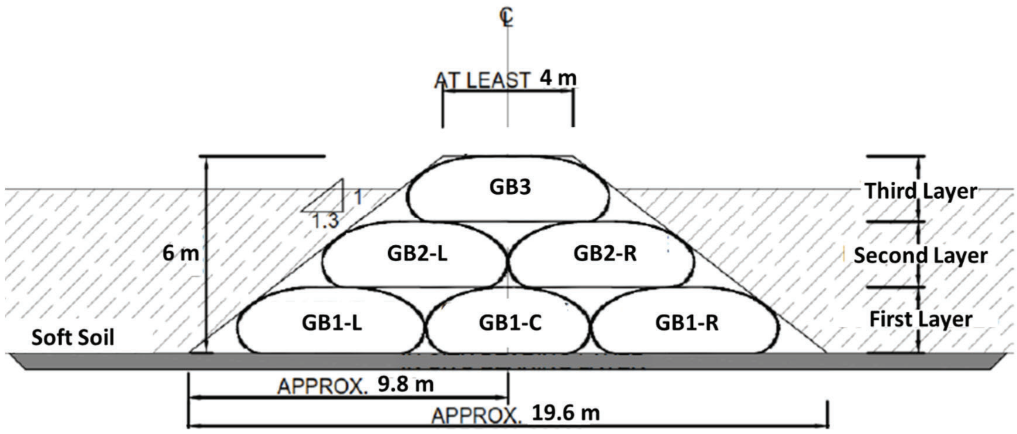

Figure 1. Schematic diagram of a stacked geotextile tubes containment bund in sectional view

2.1. Installation of geotextile tubes

As mentioned, each section of the containment bund was made up of three (3) layers of stacked geotextile tubes, where the first layer was made up of three (3) geotextile tubes placed side-by-side. The first layer's geotextile tubes were installed with a 1.5 m overlapping with each other to close up the gap that may create in between the geotextile tubes after filling. Figure 2 shows the installation sequence of the first layer of geotextile tubes. The construction started with the left geotextile tube (GB1-L), followed by the right geotextile tube (GB1-R). The centre geotextile tube (GB1-C) was installed last to fill the space between the completed left and right geotextile tubes. After completing the whole section with the first layer geotextile tubes, soft soil was backfilled on one side of the bund (i.e. called “contained area”) up to the same height as the installed geotextile tubes. The installation work of the second layer geotextile tubes continued only after the whole “contained area” was filled up. This construction sequence avoids any stability issue that may encounter by the geotextile bund during the soft soil backfilling work.

The second layer of geotextile tubes comprises two geotextile tubes (GB2-L and GB2-R), which were then installed from left to right and stacked on top of the first layer’s geotextile tubes. Similarly, backfilling of the soft soil on the “contained area” continued up to the same height as the second layer geotextile bunds.

Finally, the topmost layer of the geotextile tube (GB3) was installed, followed by the backfilling of the soft soil up to the final height.

The completed 6 m height containment bund could successfully function as a containment bund for the soft soil backfill in the “contained area” by following the construction sequence above. The whole 1 km long containment bund was constructed successfully.

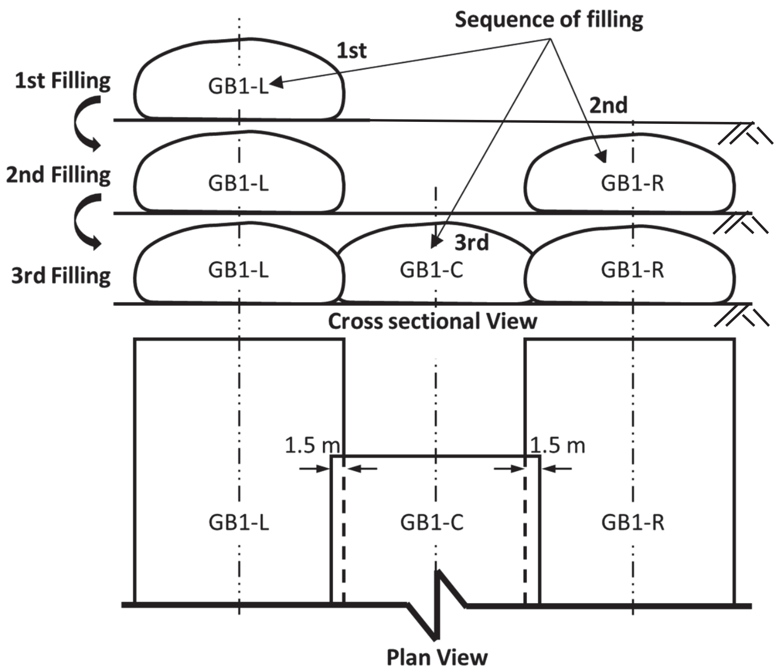

Figure 2. Installation sequence of first layer geotextile tubes

2.2. *Materials of geotextile tube*

The geotextile tubes used were stitched up with Polypropylene (PP) woven fabric. The circumference and longitudinal length of a geotextile tube are 12.6 m and 40.3 m, respectively. There were eight (8) injection ports located at an interval of approximately 5m on the top of the geotextile tube. The geotextile tube was designed to provide adequate strength and the ability to withstand harsh offshore conditions. Table 1 shows the properties of the geotextile material.

2.3. Infilling material properties - Lightly cemented soft soil

The infilling material used in this project consisted of soft soil and a small amount of cement. The soft soil was reused from the excavated soil from local construction sites of the basement excavation and tunnelling project. The soft soil contains mostly silt and clay, and the particle size distribution curve is shown in figure 3. It was mixed with water until a bulk density of 1.25-1.35 Mg/m^3, equivalent to a moisture content of 140 %. Subsequently, the Ordinary Portland Cement (OPC) was added to mix uniformly with the slurry soil. It was then pumped into the geotextile tubes in a slurry state.

Table 1. Material properties of the geotextile tube

Properties	Unit	Values	Test Standard
Wide width tensile strength (MD/CD)	kN/m	120/120	ISO 10319
Strain at max. tensile strength (MD/CD)	%	15/10	ISO 10319
Seam strength (CD)	kN/m	85	ISO 10321
CBR puncture strength	kN	14	ISO 12236
Drop cone perforation diameter	mm	10	ISO 13433
AOS O_{90}	mm	0.40	ISO 12956
Water permeability Q_{50}	$l/m^2/s$	15	ISO 11058
Abrasion resistance (strength retained)	%	75	ASTM D4886
UV resistance at 500 Hours (strength retained)	%	90	ASTM D4355

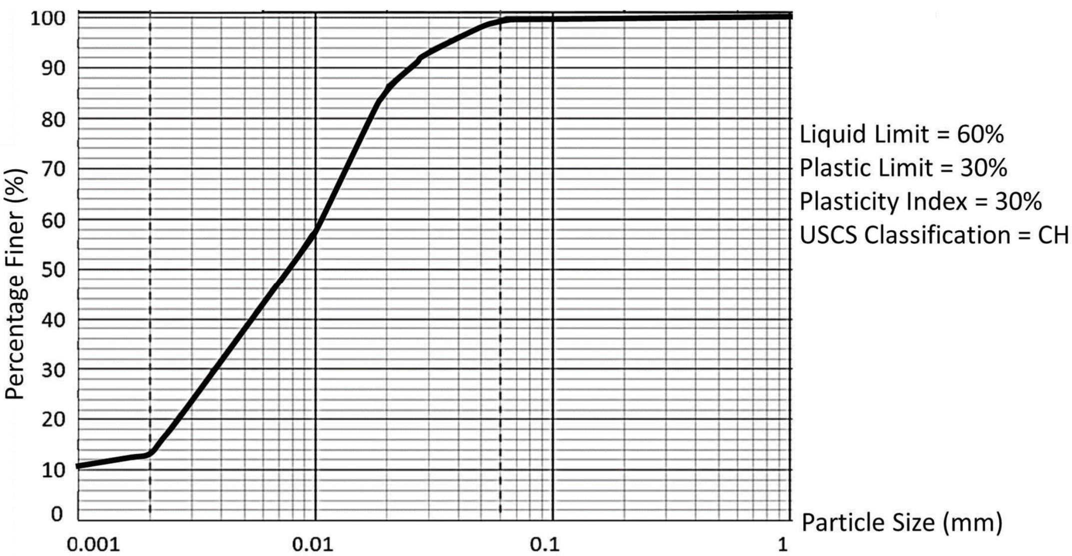

Figure 3. The particle size distribution of the fine-grained soil

Many types of research were conducted on the behaviour of cement mixed clayey soil in Singapore for deep mixing and jet grouting applications [7], [8] and [9]. On the graph of unconfined compressive strength versus cement content, it was proposed that two zones (i.e. "inactive zone" and "active zone") can be observed depending on the amount of cement content [9]. The "inactive zone" is referred to as the soil mixing with a low range of cement content, while the soil mixing of higher cement content is termed the "active zone". It was found that in the "inactive zone", cemented soil exhibited a lower increase rate of the unconfined compressive strength (qu) as compared to that in the active zone [9] &

[10]. With only 5-10% of cement content proposed in this project, it is within the “inactive zone”, and only a marginal amount of strength gain is expected. Nevertheless, it is still beneficial to have this cementitious material as it will bind the clayey particle together and reduce the initial piping, as well as provide sufficient strength for the overall bund stability.

The bulk density of this lightly cemented soil used in this project was 1.3 – 1.4 Mg/m^3.

3. Field Monitoring of Geotextile Tubes

Four (4) units of instrumented geotextile tubes were well monitored for their behaviour during and after the infilling process. The instrumented geotextile tubes were the first layer’s left (GB1-L) and the first layer’s centre tubes (GB1-C), the second layer’s left tube (GB2-L), and the top layer tube (GB3). Table 2 shows the installation timeline of the instrumented geotextile tubes for a better overview.

Table 2. Construction timeline of instrumented geotextile tubes

Instrumented Geotextile Tube	Installation Date
GB1-L	11th May 2017
GB1-C	12th May 2017
GB2-L	6th September 2017
GB3	13th November 2017

3.1. Instrumentation of geotextile tubes

Total pressure cell (TPC) and pore pressure transducer (PPT) located near the injection port was employed to measure the total pressure and pore water pressure, respectively. Also, strain gauges were attached, along the circumference, longitudinal and diagonal directions, at the inside surface of the instrumented geotextile tubes to monitor the strain mobilisation. Table 3 shows the instrumentation detail of the geotextile tubes. The instrumentation layout in the respective geotextile tubes is shown in figure 4(a) and 4(b).

Table 3. Construction timeline of instrumented geotextile tubes

Type of Instrumentation		Number of Instrument			
		GB1-L	GB1-C	GB2-L	GB3
Total Pressure Cell (TPC)		1	1	1	1
Pore Pressure Transducer (PPT)		1	1	1	1
Strain Gauge	Circumference Direction (CD)	11	-	8	8
	Longitudinal Direction (LD)	6	-	6	6
	Diagonal Direction (DD)	5	-	5	5

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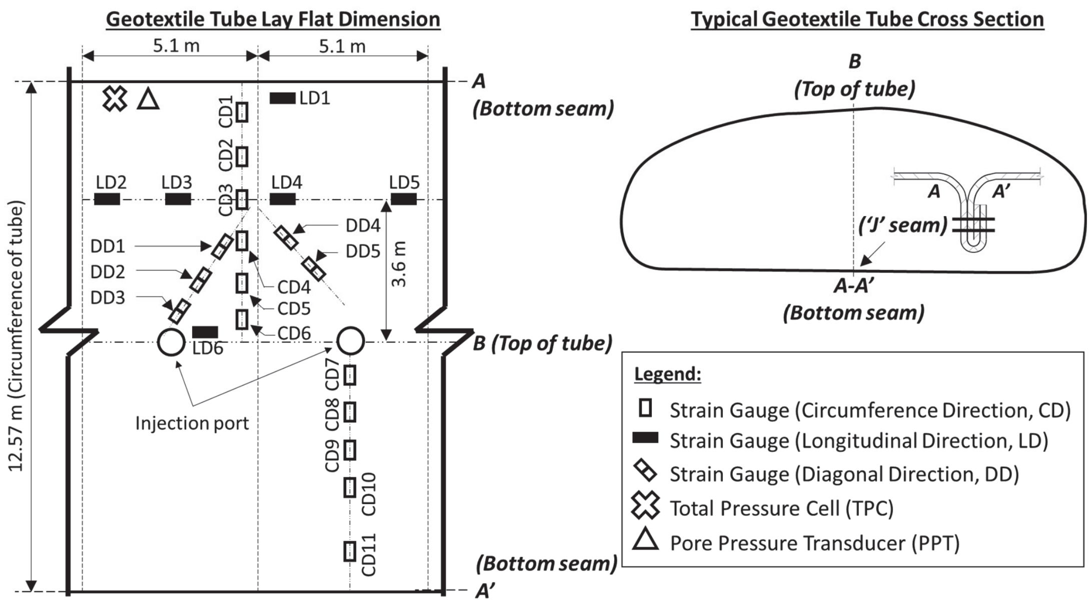

Figure 4(a). Instrumentation layout of GB1-L and GB1-C (TPC, PPT and DSG were only installed on GB1-C)

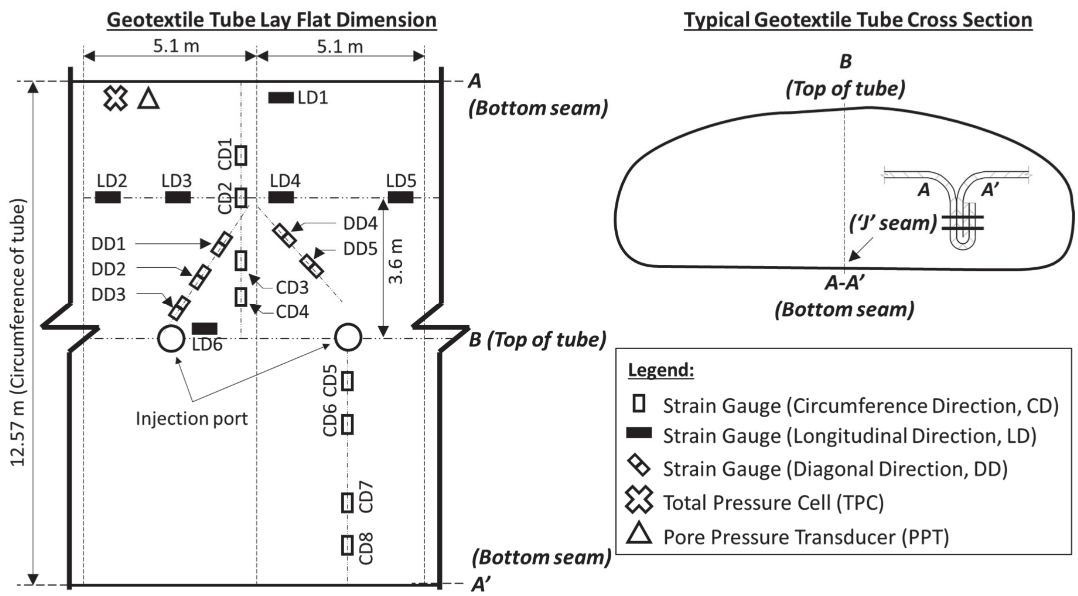

Figure 4(b). Instrumentation layout of GB2-L and GB3

3.2. Data recording and analysis of geotextile tubes

The pore pressure development in the four (4) instrumented geotextile tubes is shown in figure 5. In general, the pore pressure surged up at the very beginning of the infilling of the geotextile tube, which rapidly reduced after that. Subsequently, the pore pressure increased gradually as the backfilling of soft soil in the "contained area" progressed. From figure 5, it can be observed that the maximum pore pressure was recorded on the first layer geotextile tubes (GB1-L and GB1-C), followed by the second layer geotextile tube (GB2-L) and the topmost layer geotextile tube (GB3). This observation reflects well the increasing load from the topmost to the bottom layer geotextile tubes. For all curves, the highest pore pressure occurred after constructing the containment bund and backfilling of soft soil.

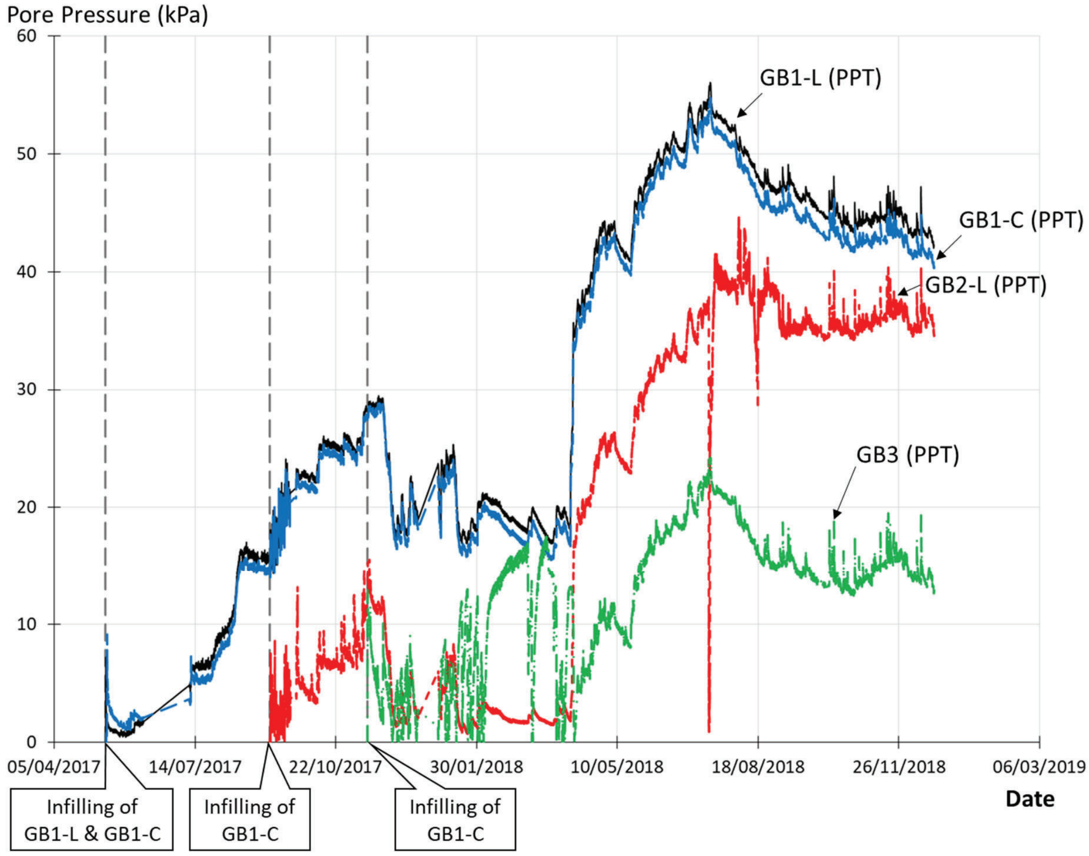

Figure 5. Pore pressure development in the geotextile tubes

Figure 6 shows the total pressure registered in the four (4) instrumented geotextile tubes. GB1-C experienced high pressure, up to ~300 kPa, whereas other geotextile tubes had lower total pressure throughout the entire monitoring period. As expected, the high pressure in GB1-C was due to the direct loading from the upper layer geotextile tubes. Although GB1-L is also located at the bottommost layer, it was not situated at the centre of the whole pyramidal shape bund, and hence, the pressure exerted was lesser than that of GB1-C.

The geotextile tube at the bottommost layer would likely experience a harsher condition from the analysis of these two pressure sensors. Hence, more critical design considerations should be considered for this layer of geotextile tubes.

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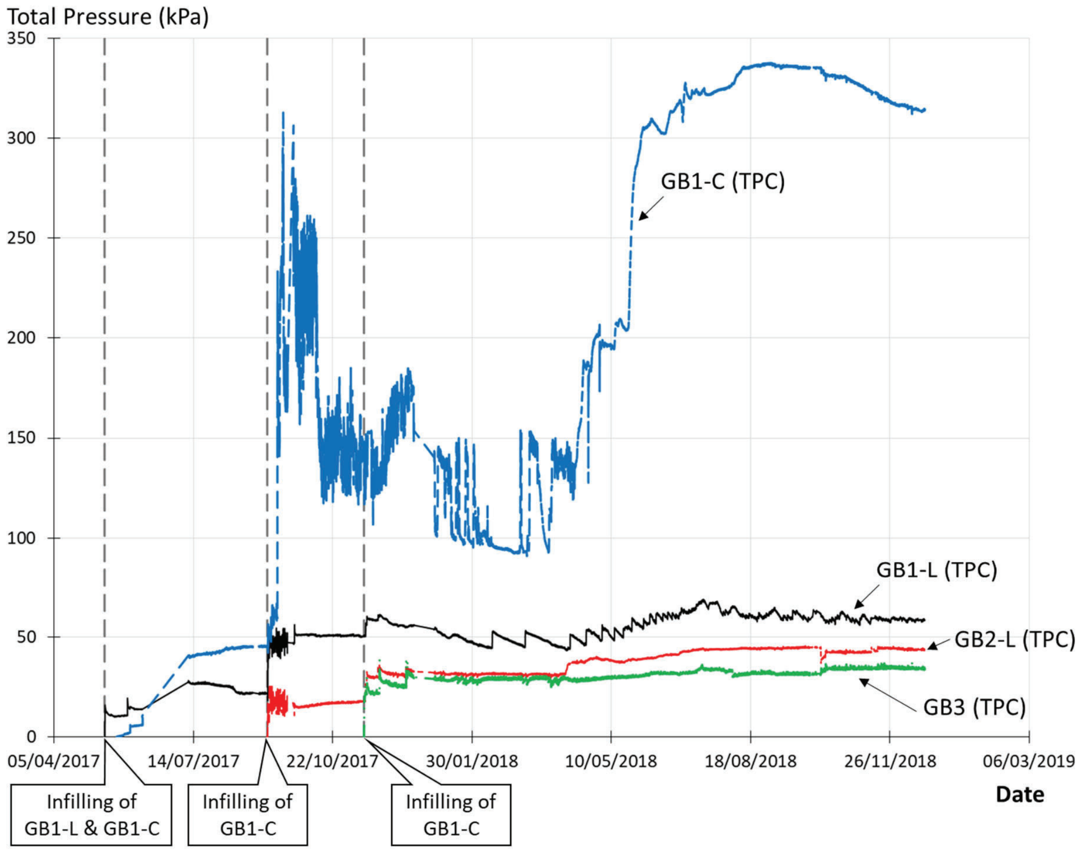

Figure 6. Total pressure development in the geotextile tubes

Figure 7(a), 7(b) and 7(c) show the strain development measured by the "critical strain gauges" of each geotextile tube in circumference direction (CD), longitudinal direction (LD) and diagonal direction (DD), respectively. This "critical strain gauge" is the strain gauge that registered maximum strain amongst all strain gauges in that direction on that instrumented geotextile tube. From Figure 7, it can be seen that during the infilling of each geotextile tube, a sudden surge of strain was observed during the high-pressure pumping process. The highest mobilised strain is about 14 %, measured in the diagonal direction (DD4) of GB2-L. Fortunately, the strain was not continued for an extended period. For circumference direction, the maximum strain, 9 %, was registered in GB3 at the location of CD8, which is attached at the highest curvature point of the circumference direction. It was also shown that the strain level was maintained until the end of the monitoring period. This is thus very critical to include this in the design consideration. On the other hand, the strain readings in the longitudinal direction were significantly lower than that in the other directions.

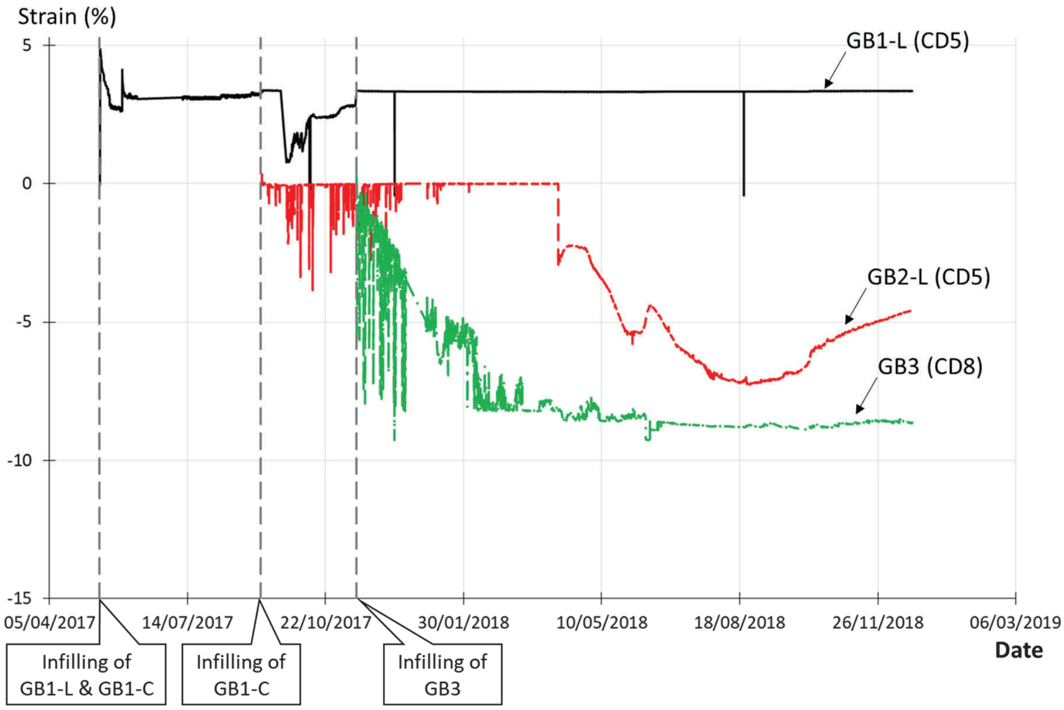

Figure 7(a). Strain reading in the circumference direction

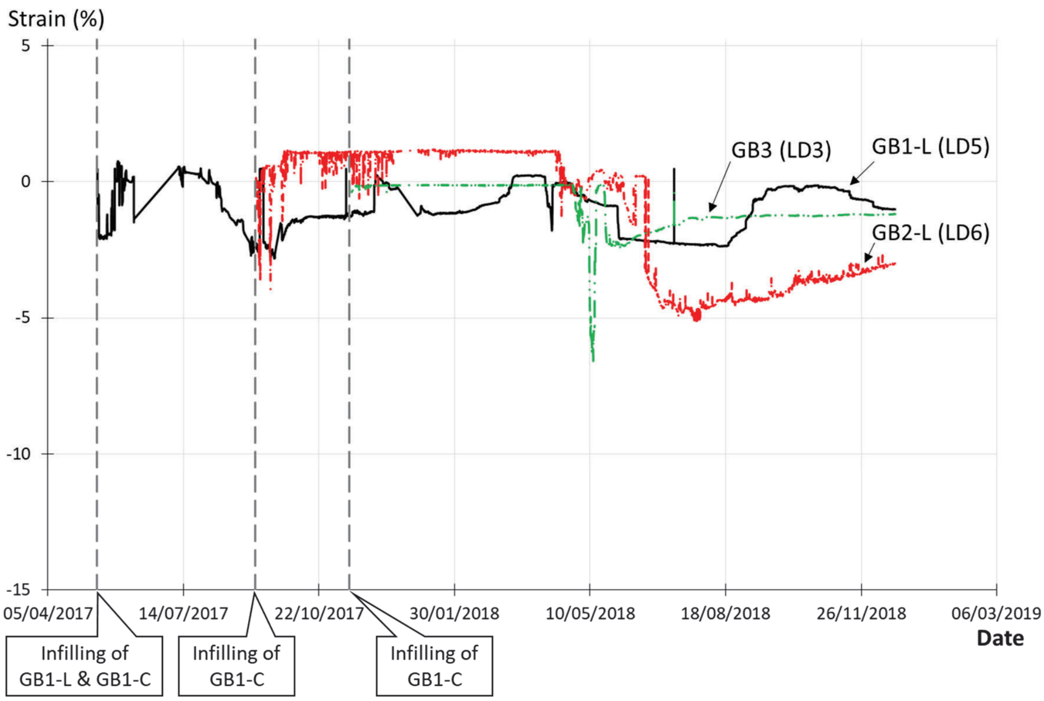

Figure 7(b). Strain reading in the longitudinal direction

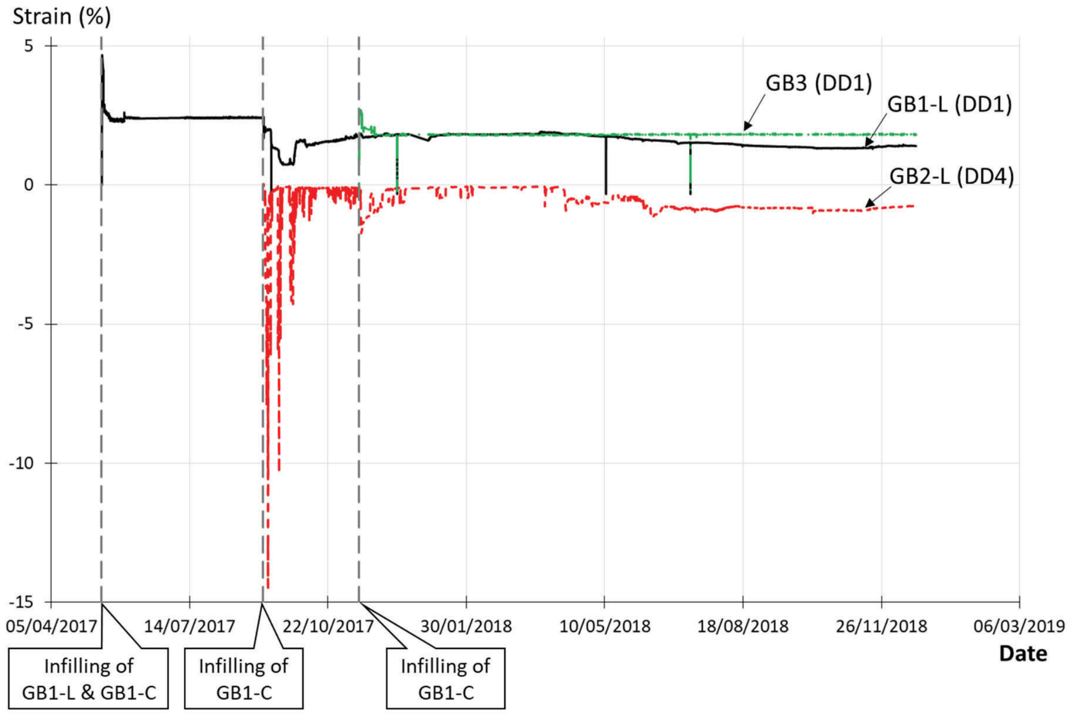

Figure 7(c). Strain reading in the diagonal direction

3.3. Post-construction site investigation analysis of geotextile tubes

After two years of installation of the containment bund, a standard penetration test (SPT) was carried out on the infilling material at 1.225 m, 3.225 m, and 5.225 m depth from the top surface of the GB3. Besides, core samples of 75 mm diameter and 1000 mm length undisturbed samples were extracted at two different depths from each layer of the geotextile tube. These UD samples were sent to the laboratory for strength determination using the Consolidated Undrained Triaxial test (CU). These in-situ and laboratory tests aimed to check the cemented soil strength developed inside the geotextile tube after two years. Figure 8 shows the detailed location of the SPT test and UD sampling locations.

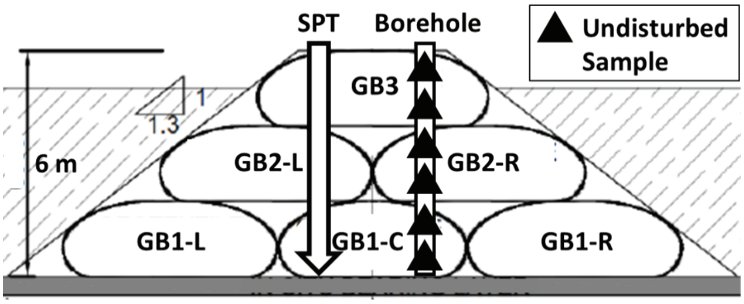

Figure 8. In-situ test and borehole detail location

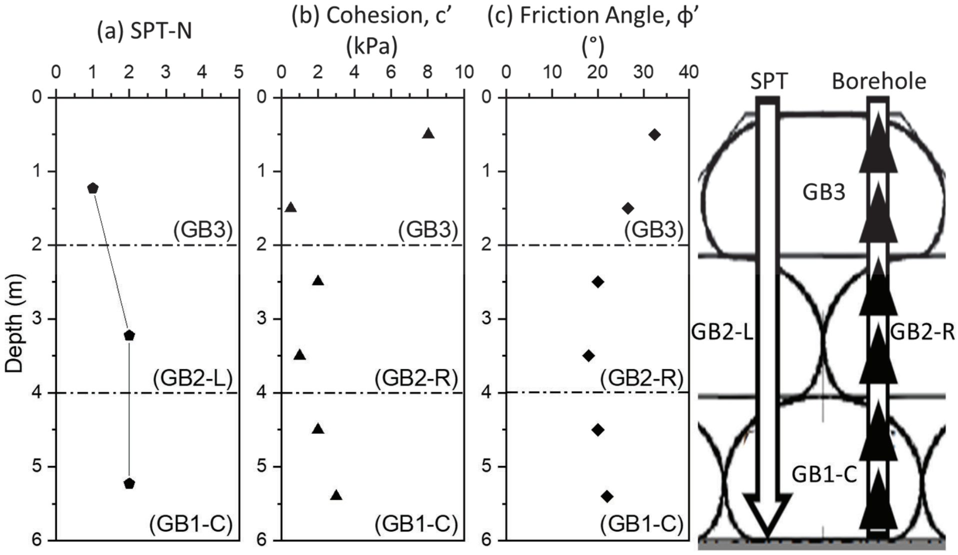

Figure 9(a), (b) & (c). SPT-N value, cohesion and friction angle of the cemented soil with depth

From the SPT results, as shown in figure 9(a), the N-value at the middle of each layer geotextile tube was found to be 1 to 2. The undrained shear strength, Su, of the cemented soil can be estimated using correlation (Su = 6.25N) as presented by [11]. Hence, the undrained shear strength was improved from zero at the slurry state to about 6-12 kPa at the end of 2 years. This value is indeed very close to the in-situ undrained shear strength of soft Singapore Marine clay [7]. It should be noted that, as illustrated in figure 9(a), the three SPT points were conducted in the middle of the respective geotextile tubes. In general, the infilling material in the central portion of a geotextile tube has been subjected to the lowest dewatering rate than the location nearer to the geotextile tube's top and bottom surfaces. Hence, the cemented soil at the other positions should have higher strength than that in the central portion of the geotextile tube.

Figure 9(b) and 9(c) show the consolidated undrained triaxial test results. GB1-C and GB2-R have quite similar effective cohesion, c' and friction angle, ϕ', which is in the range of 2-3 kPa, and 18°-22°, respectively. In contrast, GB3 has very low effective cohesion (c' =0.5 kPa) at the bottom and marginally higher (c' =8 kPa) at the top portion of the geotextile tube. Similarly, GB3's friction angle near the surface is 32 ° compared to that at the bottom part, 26°. The results show that the cemented soil at the topmost surface of the stacked geotextile tubes generally has the highest strength parameter. The observed behaviour may be due to the desiccation of the cemented soil, where the topmost portion is likely to receive lots of heat from sunlight.

The strength development of the infilling soft soil may not be too high, but it is indeed adequate to provide the needed stability of the overall containment bund section.

4. Conclusion

This paper presented the primary consideration and the construction procedure for the stacked geotextile tubes containment bund, of which the geotextile tubes were infilled with lightly cemented soft soil. The adopted design and construction procedure takes into account the effect of the lateral pushing force arising from the backfilling of soft soil by the side of the containment bund. This project adopted a lightly cemented soft soil as the infilling material for geotextile tube because of sand scarcity in Singapore and for environmental sustainability reason. This technique seems to provide sufficient strength for stability and avoid significant deformation of the geotextile tube. A section of this containment bund was instrumented to monitor its behaviour during and after construction.

The pore pressure and total pressure monitoring data show that the bottommost layer of geotextile tubes always experienced a higher loading. The loading is either from the stacked upper layer geotextile tubes or backfills soft soil in the "contained area" by the side. Different design requirements or considerations may be applied to a different layer of the geotextile tube, where the bottommost layer is more critical than the upper layers. The recorded strain readings indicated that the diagonal direction and circumference direction of a geotextile tube would experience a higher level of stretching and tension.

The SPT and CU strength test results show that the lightly cemented soft soil inside the geotextile tube had just gained sufficient strength over the two years. The increment in strength will help in the overall stability of the stacked geotextile tubes.

In conclusion, this project shows that stacked geotextile tubes filled with lightly cemented soft soil can effectively serve as a containment bund in land reclamation projects.

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