The Use of Deep Soil Mixing Technology Over The Ocean In Singapore's First Polder

C.K. Lee
Arup
Chee-Kien.Lee@Arup.com

C.C. Ng
ONE SMART Engineering
davidng@onesmart.com.sg

C.W. Ong
ONE SMART Engineering
ong@onesmart.com.sg

ABSTRACT

The Dutch have been honing their land reclamation technology using polders since the 12th century. The Singaporean Government then looked to the Dutch and adopted the empoldering technique when they decided to protect their Tekong Island from rising sea levels, while expanding their useable land area to the north of the Tekong Island. Such a technique allows for the conservation of sand resources in land reclamation activities. This paper explores the construction of the Stormwater Collection Pond in Tekong Polder, specifically delving into the engineering aspects of the deep soil mixing (DSM) technology. The deployment of the DSM technology was made possible via purpose-built barges fitted with cluster DSM augers that were long enough to reach the seabed, cement mixing plants, among other heavy machineries. Positioning of the barge on the ocean to deliver the DSM columns at the desired position also demanded the use of accurate and precise positioning technologies. Sensors fitted on the barge allowed the as-built information of the DSM clusters, such as coordinates, termination depth, and auger logs such as cement injection rate, auger rotation speed, etc to be uploaded to a platform as part of the building information modelling (BIM) initiative to facilitate the production of as-built drawings among other engineering key monitoring parameters. While cement reinforced soil can be considered as an advanced material, uncertainties in the in-situ soil mix demanded meticulous monitoring and quality control. Some rudimentary understanding of the DSM will be discussed in this paper, while shedding light on the challenging construction methodology of DSM over water.

KEYWORDS: Polder, Deep Soil Mixing, Reclamation, Cement, Dam, Barge, Mixing Plants, GPS, Building Information Modelling (BIM), Advanced Materials, Construction Under Difficult Environment, Sand Resource Conservation

1. Introduction

The Singaporean Government is reclaiming land at the north-western tip of its Tekong Island using the impoldering technique, and they have looked to the Dutch to adopt their expertise in view of the Dutch's centuries of expertise (Verruijt, 2001). Such a move by the Singaporean Government also capitalises on the impoldering technique's potential savings of the sand quantity required to reclaim land, as illustrated in Figure 1.

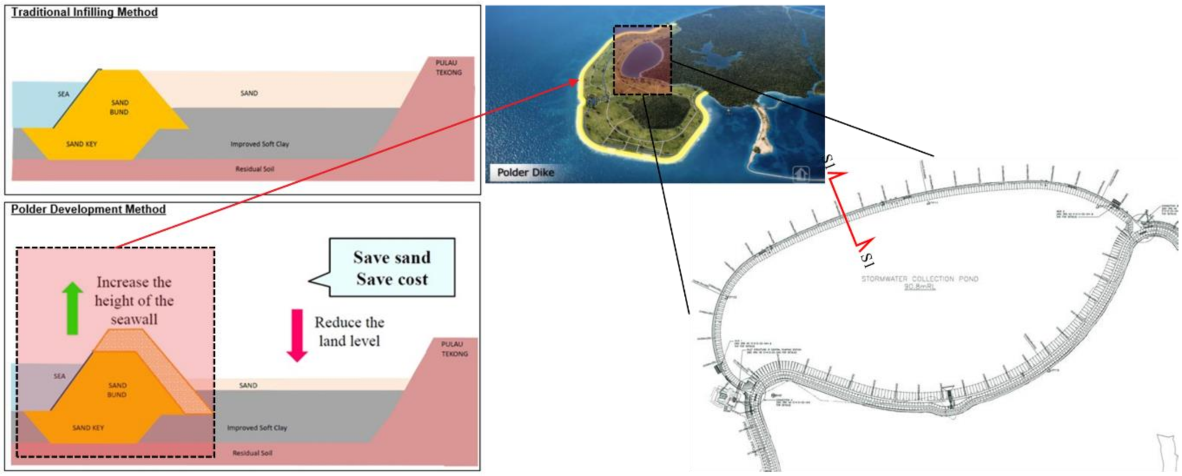


Figure 1 Comparison of traditional infilling method and impoldering method for land reclamation for Tekong Island. Figure taken from HDB's website (Joint Press Release by MND & HDB: HDB to adopt new land reclamation method at Pulau Tekong, 2016)

Within the reclaimed land, a stormwater collection pond is being constructed, with details as shown in Figure 1. The construction sequence involved performing ground treatment works (with the perimeter dike having been completed first), followed by the installation of the DSM clusters forming the edge of the stormwater collection pond, before the excavation to the pond invert level and furnishing of the pond. This paper shall delve into the design and construction of the DSM clusters, expounding on the construction methodologies, design considerations, and some test results for the characterisation of the DSM.

2. Background and The Use of DSM

The local geology, design considerations, construction challenges and techniques, are discussed in this section.

2.1 Local Geology

Figure 3 shows the local geology of Tekong Island, whereby the intended polder construction takes place in predominantly the Sajahat Formation. The Sajahat Formation is an unfossiliferous, regionally metamorphosed formation found on Tekong Island, among other localities in Singapore. It is unconformably overlain by fossiliferous Permian conglomerates with an angular unconformity. To date, there has been no conclusive evidence of the age of deposition of the Sajahat Formation, but it has been speculated that the Sajahat Formation is probably late Permian in age (Pan, Oliver, Chu, Goh, & Wei, 2018).

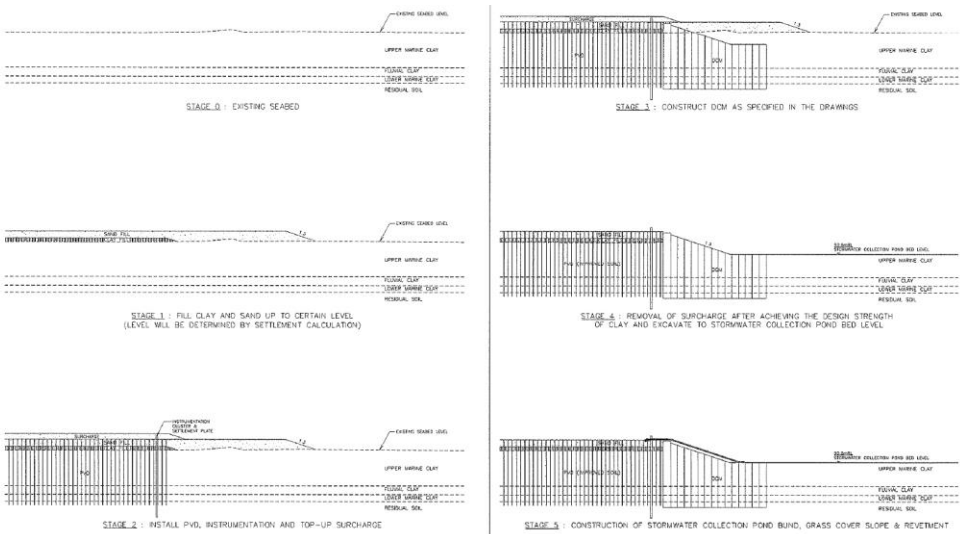


Figure 2 Construction sequence of the polder, taken near Section S1. The formation of the dike at the edge of reclaimed land is not shown here.

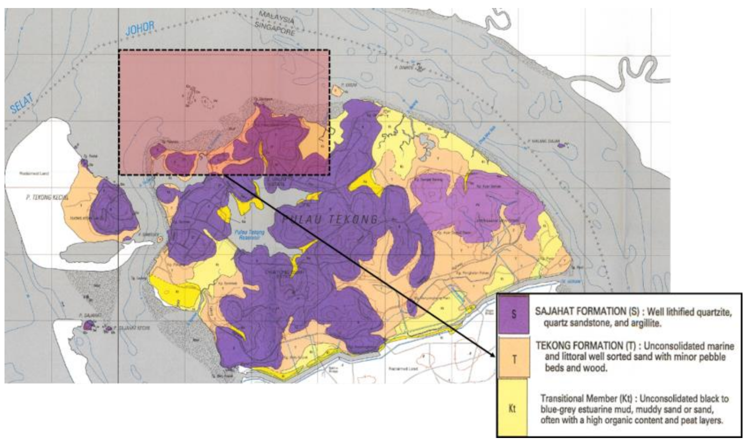


Figure 3 Geology of Tekong Island (Pulau Tekong, Geological Maps of Singapore, 2008). Note that the intended polder construction is expected to take place predominantly in the Sajahat Formation (S).

2.2 Geotechnical Conditions

The geotechnical conditions near Section S1 (as shown in Figure 1) is considered in this paper. Near Section S1, a trial DSM panel was constructed, with two boreholes sunken side-by-side adjacent to the panel. The trial DSM panel comprises DSM clusters constructed using various parameters, as tabulated in Table 1.

Table 1 DSM trial panel constituents

Mixing method	Cement Content (kg/m^3)
Penetration Injection	120
	140
	160

Retrieval Injection	120
	140
	160

The geotechnical parameters are tabulated in Figure 4, which shall be referred for the subsequent DSM engineering characterisation. The borehole sticks are shown in Figure 5, which shows a consistent soil profile across the DSM trial panel. Generally, with the mean sea level taken as 100mRL, the sea bed level lies on 96mRL. The Upper Marine Clay (UMC) can be found from the top of the sea bed (96mRL) to 89mRL, below which Estuarine Clay (E) of approximately 1m thick can be found, followed by Fluvial Clay (F2) of approximately 4m thick. The Lower Marine Clay (LMC) can be found from 84mRL to 77mRL, within which Fluvial Sand (F1) of approximately 3m thick occurs as a sand lens within the LMC. Below the LMC, Residual Soil (RS) of the Sajahat Formation can be found, from 77mRL and below. This stratigraphy is common in the sedimentary rock formations in Singapore.

2.3 DSM Implementation Over The Ocean

DSM ground treatment was implemented as a means of strengthening the stormwater collection pond's side slopes, in terms of the slope stability as well as the permeability. Essentially, the DSM forms a mini dam along the perimeter of the stormwater collection pond. As the polder construction was still underway during the construction of the DSM columns, the ground level was still submerged under the ocean. An illustration of the sea levels and seabed level are given in Figure 5. As such, a purpose-built barge was required to construct the DSM columns over the ocean, shown in Figure 6. The designed DSM configuration is shown in Figure 7. A cell block configuration was adopted, with a targeted area replacement ratio of 50%. In view of the large replacement ratio, with clusters of DSMs required to fulfil the area replacement ratio, the DSM Barge was fitted with three columns of mixers, each of which comprises four individual DSM auger flights, among other ancillary equipment such as cement mixing plant, fuel tank, compressor, power generators, etc. Each of the columns and auger flights is independent of each other, whereby in certain conditions, only 2 flights are required, instead of all 4, the 2 required flights can be deployed independently.

During construction of the DSM cell blocks, a GPS system together with a geo-referenced layout of the DSM blocks guide the DSM barge into position. As the DSM clusters are progressively installed, the as-built information of the DSM is uploaded to a web-based system. This information contains the as-built coordinates of each individual DSM clusters, including the easting, northing, top and bottom levels, as well as the mix parameters, such as cement injection rate, blade rotation speed, mixing depth. As such, the abovementioned information, along with any relevant construction records could be retrieved easily from the web-based system given the knowledge of the DSM number, or a particular group of DSM installed on certain days, by certain machines, and/or with certain parameters where a systematic defect could be correlated to. This information is used by the engineers onshore for construction monitoring, quality control and checking works. As part of the initiative to incorporate Building Information Modelling (BIM) into the project, a workflow was adopted to retrieve the as-built coordinates of the DSM to produce as-built drawings of the DSM clusters. This aided the engineers in conducting routine DSM cell block stability analyses under service conditions to the appropriate design codes. As for construction monitoring, as seen from Figure 8, if there had been abnormally high motor output wattage to maintain the auger rotation speed, it could be suspected that an obstruction had been encountered on site; vice versa, had there been an abnormally low motor output wattage, while the auger rotation speed remained the same (or did not reduce significantly), it could be suspected that a particularly soft pocket was encountered. Following which, additional tests such as core tests could be prescribed at that DSM to investigate the cause of such anomaly.

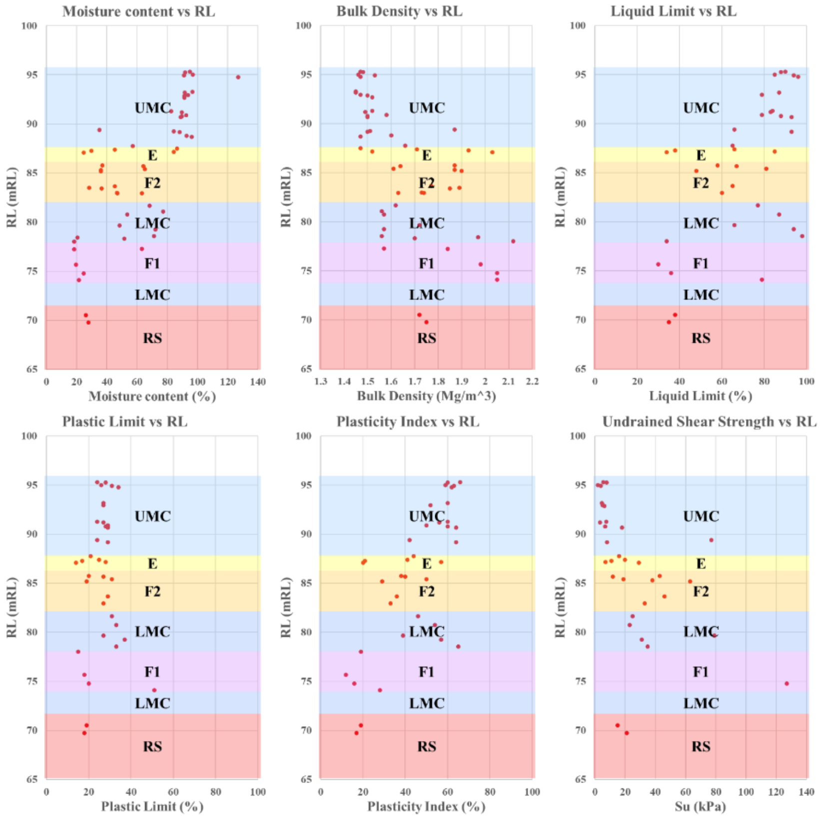


Figure 4 Geotechnical parameters from the nearest boreholes to the DSM trial panel.

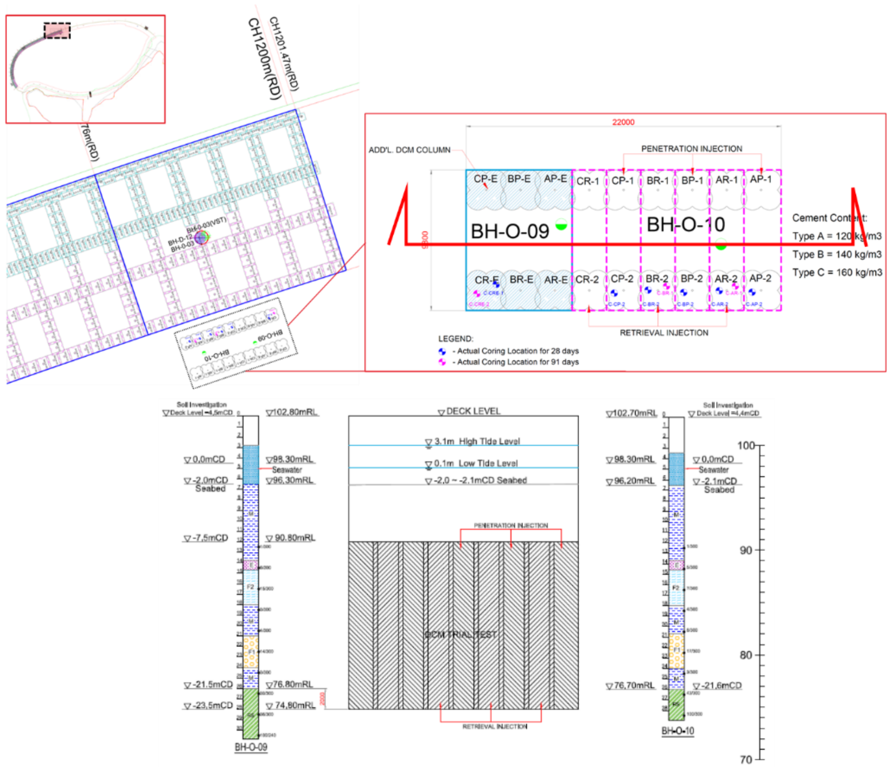


Figure 5 Location of the Trial DSM Panel, constructed adjacent to the working DSM walls.

Figure 6 View of the purpose-built DSM Barge from another vessel travelling towards the DSM Barge.

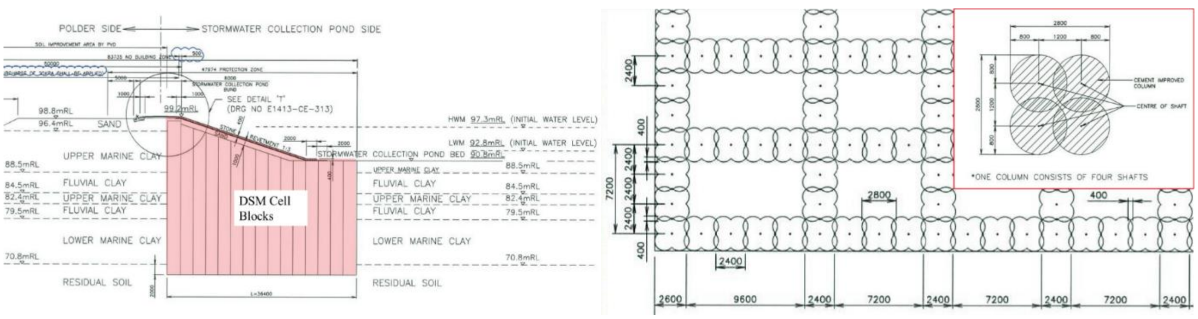


Figure 7 The use of DSM Cell block as a "mini dam" for the stormwater collection pond.

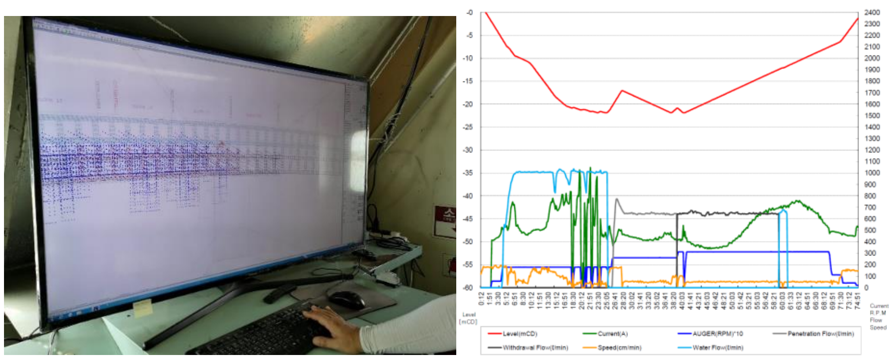


Figure 8 Acquisition of data as seen on board the DSM Barge. Left: DSM As-Built Positions. Right: Mixing parameters such as cement flow rate, water flow rate, auger position, auger rotation speed, etc.

3. Engineering Characterisation of DSM

Some attempts to characterize the DSM according to the native soil type is made in this chapter.

3.1 Laboratory Trial Mix

Prior to the DSM trial panel construction, laboratory trial mix was conducted to guide the mix parameters required for the field trial. While it comes as no surprise that higher cement content results in a higher unconfined compressive strength (UCS) of the DSM samples (Miura, Horpibulsuk, & Nagaraj, 2001) (as shown in Figure 9), some nuances affecting the mix results such as the native soil type's engineering properties are investigated. Similarly, for the same soil type and across decreasing cement contents, the UCS of the laboratory DSM trial mix is unsurprisingly reducing, as shown in Figure 10. The study then looked towards the effect of soil type, or particularly, the engineering properties of the native soil, on the UCS of the laboratory mixed DSM samples.

Based on the conducted mixes using the native soils of UMC, F1, and RS, the plasticity indices of these soil types were determined from Figure 4. The plot of DSM UCS versus Plasticity Index (PI) is shown in Figure 12. Congruent with the trend observed in Figure 11, with increasing PI, the UCS of the DSM samples reduces. The same trend persists across the 28-day and the 91-day cured DSM samples. Unfortunately, there were insufficient samples to fill the PI gap between 25% to 60%. Nonetheless, it can be deduced that the reduction in UCS with increasing PI will be asymptotic past a large enough PI.

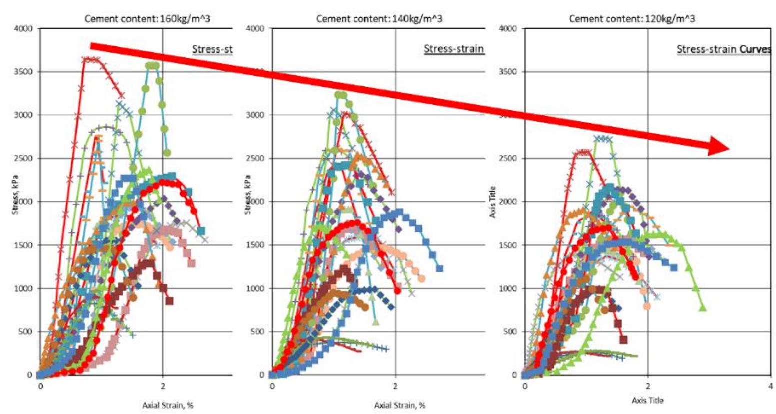


Figure 9 Aggregated laboratory DSM trial mix results for all soil types, separated by cement content.

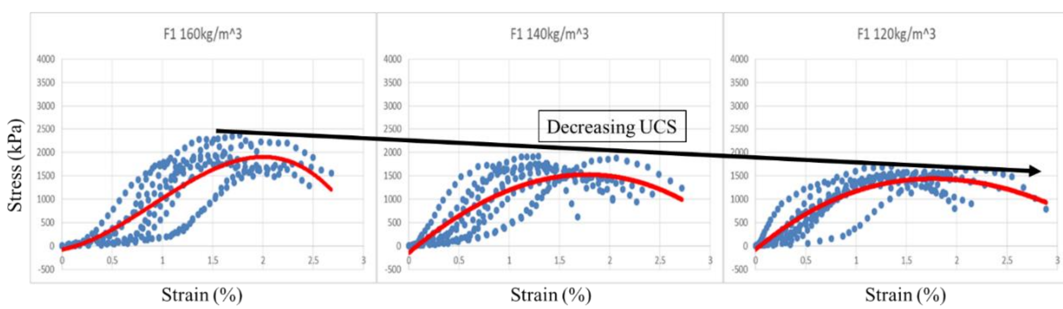


Figure 10 DSM Laboratory trial test results for F1 soil type, across various cement contents.

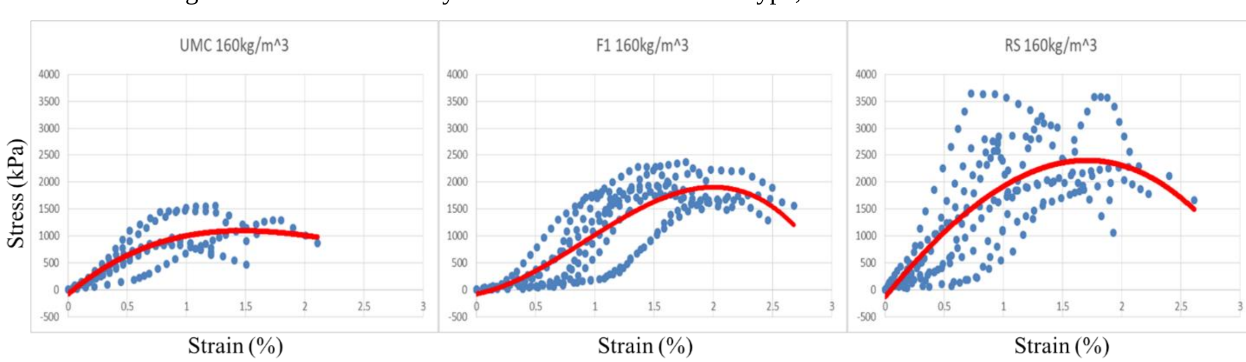
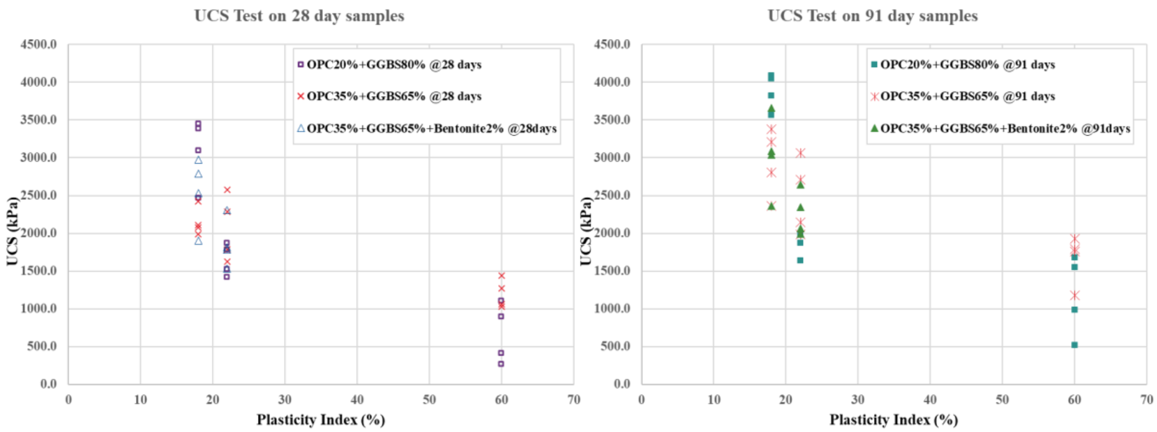


Figure 11 DSM Laboratory trial test results for the same cement content across various soil types.



*Note: The actual PI of the native soil was determined based on the SI results as discussed in 2.2.

Figure 12 Comparison between UCS and plasticity index of laboratory mixed DSM samples. Left: UCS results after 28 days of curing, Right: after 91 days of curing.

3.2 Wet Sampling

Wet sampling refers to the cement-soil mixture samples collected during the field trial panel mixing process. The UCS tests on the wet sampling specimens were conducted on 7-day cured samples only. As summarized in Table 1, the samples were collected from both penetration and retrieval injection construction methods, using various cement contents. Similar to Figure 12, an attempt to visualize the UCS vs PI of the DSM wet sampling specimen was conducted, as shown in Figure 13. However, the previously deduced correlation of decreasing UCS with increasing PI seems to have broken down. In addition, the wet sampling specimens collected from the penetration injection construction method showed markedly lower UCS values as compared to those from the retrieval injection method.

It is therefore imperative to visualize the information from another perspective in an attempt to reveal the cause for this break down. The UCS is thence plotted against the reduced level, as shown in Figure 13. It has then become apparent that, the UCS of the wet sampling specimens collected near the toe of the DSM, despite being mixed with RS which has a low plasticity index, suffered a marked reduction in UCS.

3.3 Core Tests from DSM Trial Panel

Cores from the DSM trial panels were retrieved, as per the locations indicated in Figure 5. These cores were then subjected to UCS tests and triaxial permeability tests.

Consistent with the findings from 3.2, the relationship between UCS and the native soil PI breaks down. As shown in Figure 14, there is no discernible trend between the DSM core sample strength and the native soil's PI. As such, a similar approach in reviewing the core sample UCS from the perspective of mixing depth was adopted, as shown in Figure 15. Upon close inspection, it can be found that the DSM constructed using retrieval injection suffered a lower 28-day UCS near the DSM toe levels, relative to the soil layers above, which also contradicts with the findings from Figure 12. The same trend is carried over in the 91-day DSM core strength tests. While the DSM 28-day UCS near the toe level of the penetration injection method did not show a marked increase relative to the soil layers above, it is also not conforming to the trend suggested in Figure 12.

As for the permeability of DSM columns, a general trend that could be observed was the decreasing permeability with increasing native soil PI as shown in Figure 14. It is worthy to note that some outliers were omitted in Figure 14, whereby near the DSM toe level, the permeability of DSM was 1 magnitude higher.

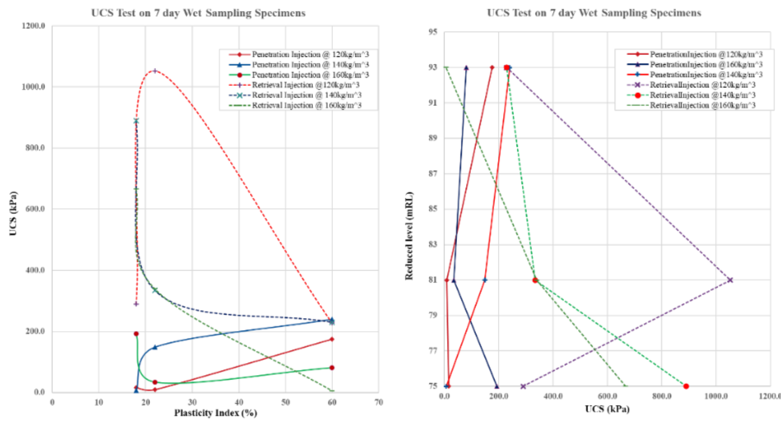
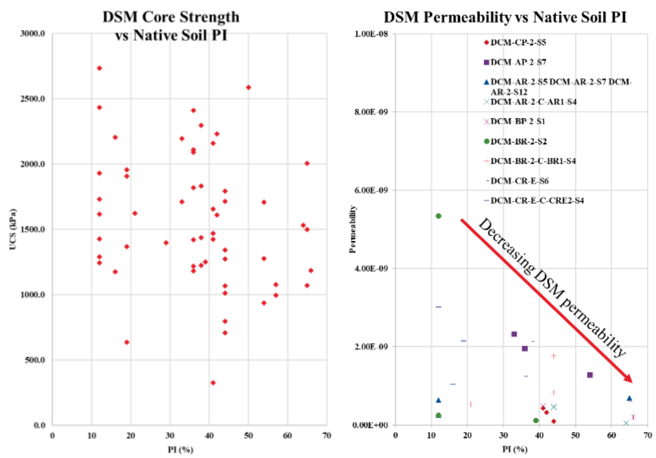


Figure 13 Wet sampling specimen, left: UCS vs PI, right: UCS variation over depth.



*note: the PI in this chart was taken from the nearest available PI results, as shown in Figure 4.

Figure 14 DSM Core sample key performance parameters correlation with native soil PI. Left: UCS vs PI. Right: Permeability vs PI.

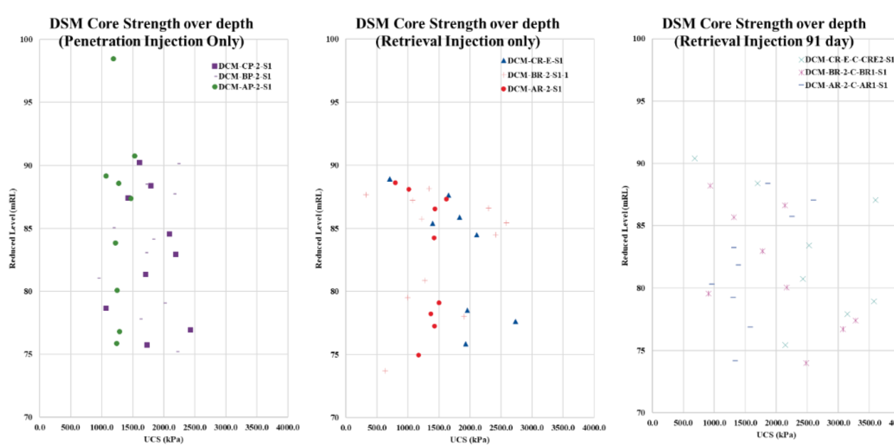


Figure 15 DSM core sample 28-day strength over reduced level. Results of samples retrieved from various construction techniques, namely penetration and injection retrieval, are shown. 91-day strength is only available for the retrieval injection method.

4. Discussions

4.1 Inference of the DSM mix results

It is evident in the foregoing that the relationship between DSM UCS and the native soil's PI established in the laboratory mix in section 3.1, as well as other research findings (Kitazume & Terashi, 2013) (Bian, Zeng, Ji, Xie, & Hong, 2022) breaks down during the site implementation, as seen in the wet sampling and core tests from field trial DSM in sections 3.2 and 3.3. Some possible reasons for this could be due to the workmanship of the DSM, particularly near the toe of the DSM columns where the UCS values are relatively lower. This issue is particularly pronounced in the retrieval injection as opposed to the penetration injection, as the DSM UCS is seen to be rather uniform throughout the entire retrieval injection DSM core samples.

When benchmarked against available research results (Mitchell, 1976), (Muhunthan & Sariosseiri, 2008), as shown in Figure 16, the laboratory trial mix UCS vs Cement Content regression line gradient falls below that of the lower bound (gradient=275) as proposed by Mitchell (1976). The regression line gradient of the 28-day core sample test from the trial DSM panel falls (gradient=180) below that of the laboratory mix (gradient=221), while the 91-day core sample (gradient=239) barely matches the lower bound proposed by Mitchel (1976).

Despite research findings that suggest concrete mixed using sea water gaining early strength faster within the first 28 days but loses strength after 91 days of curing (Wegian, 2010), (Guo, Chen, Zhao, Admilson, & Zhang, 2017), however, as seen in Figure 15 there is no appreciable reduction in UCS of the 91 day DSM samples. Nonetheless, it could not be ascertained whether the DSM UCS would reduce given a longer curing period.

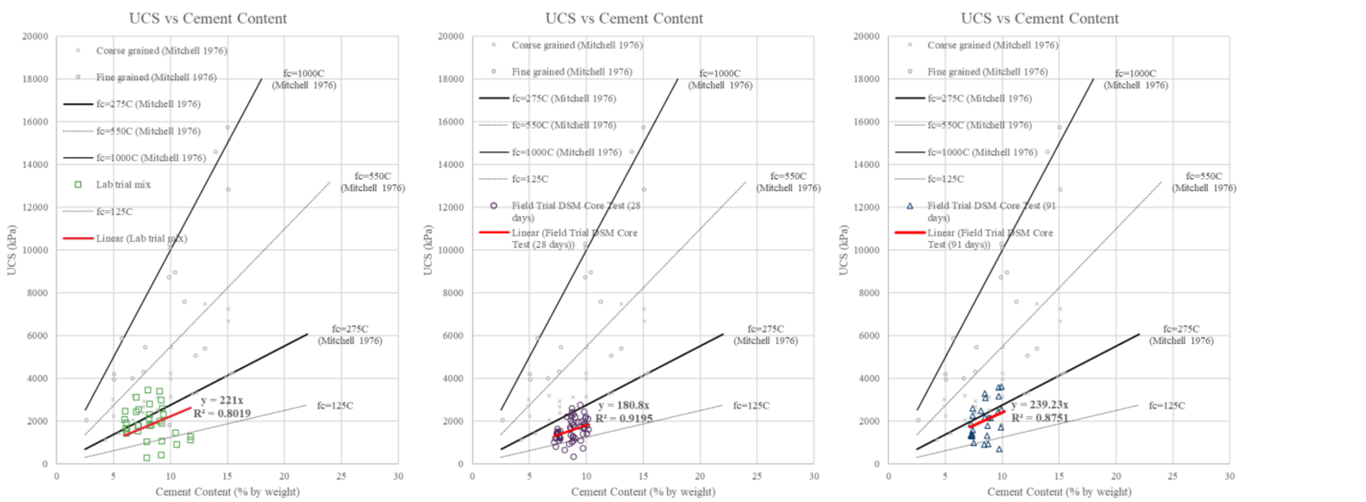


Figure 16 DSM UCS vs cement content (% by weight) after Mitchell, 1976.

4.2 Application and analysis of DSM cell block

Despite the myriad of factors that can affect the DSM mix quality in the foregoing observations, one of the most crucial and most simple base to assess the DSM mix quality is the shape of the yield locus, whereby there is a consistent shape of the yield locus regardless of the cement mix ratio (Xiao, Lee, & Chin, 2014). The UCS parameter can be correlated with the yield locus based on the following deductions:

$$q = \sigma_1 - \sigma_3$$

In unconfined compression tests, $\sigma_1 = 0$, hence,

$$q_{ult} = \sigma_1 = UCS$$

With the above relationship, the assessment of the DSM cell block configuration as shown in Figure 7 (based on a 50% area replacement ratio) can be conducted using numerical analysis. The simple approach would be to assess the DSM internal stress states to not exceed the designed UCS values, as well as the predicted movement. Such an assessment is not dissimilar to that studied by (Ng, Chew, & Sukri, 2019). Further assessments such as on the brittleness of DSM (Sariosseiri, 2008) would be beyond the scope of this paper.

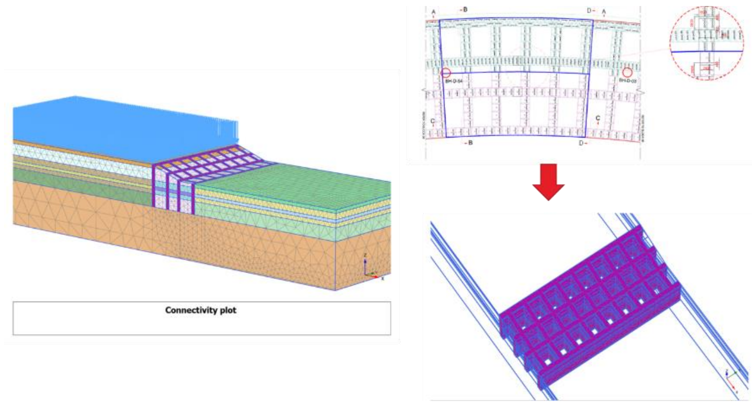


Figure 17 3D numerical analysis of the DSM cell block

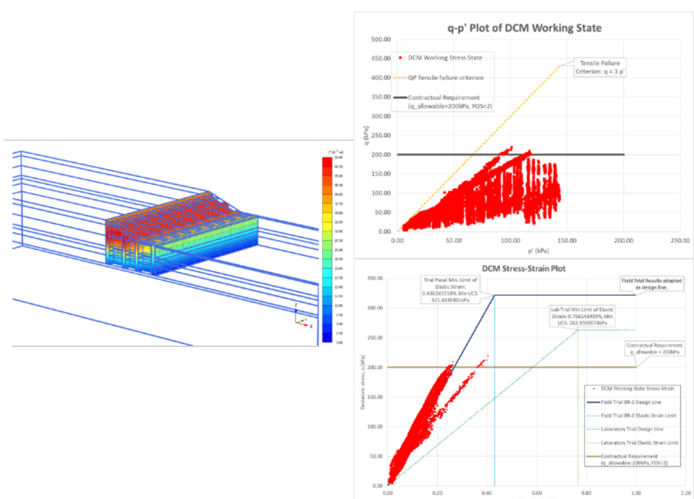


Figure 18 Assessment of DCM internal stress under service loads.

5. Conclusion

It has become apparent that while there are appreciable correlations for DSM UCS to the cement content and to the native soil parameters (Muhunthan & Sariosseiri, 2008), (Sariosseiri, 2008), (Bian, Zeng, Ji, Xie, & Hong, 2022), other factors during actual construction works, such as workmanship, technique, curing conditions, among others, play a major role in the outcome of the DSM mix results. As observed in the foregoing, the technique used may well determine the DSM quality particularly near the toe level. There is also little carry over of concrete characteristics to DSM in terms of mixing and curing conditions. Care should be taken by the designers when implementing DSM, in terms of site monitoring, quality control, and testing regimes. Moreover, where the implementation of DSM is performed in challenging conditions, such as over the ocean, the use of technology to aid in the monitoring works will become indispensable. With the advent of sensing technologies, BIM, and the Internet of Things (IoT), it is the author's wish that the implementation of DSM, from design to construction to construction monitoring, could be automated.

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