A Study of Heaving Material Resulted from Deep Cement Mixing Construction

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Abstract

The deep cement mixing (DCM) method has been used to form foundations for some of the marine structures in Hong Kong. Injection of cementitious slurry into the seabed will inevitably cause the seabed to rise, resulting in a raised soil-and-cement mixture above the top of DCM clusters, which is referred to as heaving material in this paper. The amount and characteristics of heaving material are influenced by several factors such as soil type, improvement depth and area ratio, cement-water ratio, cement injection pressure and workmanship. Due to its weaker strength, heaving material is conventionally dredged to avoid forming a weak layer in the DCM foundation. This paper aims to investigate how to retain heaving material in the DCM foundation system to avoid both causing pollution and incurring additional costs due to dredging. It has four objectives, namely: firstly, to study its formation mechanism; secondly, to investigate its shear strength characteristics, through the results of various lab and in-situ tests; thirdly, to discuss design and construction considerations concerning heaving material; and finally, to discuss the results of a full scale test involving heaving material. It is shown that heaving material may be retained provided it can meet design requirements.

Keywords: Deep cement mixing, Ground improvement, Reclamation, Marine deposits

1 Introduction

The DCM method involves in-situ treatment of soft soils by mixing in cementitious and/or other materials to form a column of solid element, hereafter referred to as the “DCM Cluster”. The ground may be fully or partially treated with DCM, depending on the design area ratio, and is referred to as the DCM treated ground. This technique has been widely used to improve soft marine deposits for the construction of marine structures such as seawalls and breakwaters.

Injection of cementitious slurry into the seabed will inevitably cause the seabed to rise, due to ground volume increase, resulting in a raised soil-and-cement mixture above the top of DCM clusters, which is referred to as “heaving material” in this paper. The generated volume and the characteristics of heaving material are influenced by several factors such as soil type, improvement depth and area ratio, cement-water ratio, cement injection pressure and workmanship. Due to its uncertain engineering properties and its weaker shear strength than that of a DCM cluster, heaving material is conventionally dredged to avoid forming a weak layer in the DCM foundation. However, dredging is not only time consuming and costly, but also prone to causing marine pollution due to diffusion of its fine particles during the dredging and dumping process.

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For example, if a marine DCM project involves installing 10,000 DCM clusters (each cluster having a depth of 30m and an area of 4.62m^2), the volume of heaving material will be approximately 970,000m^3, based on the assumption that it is about 70% of the injected cement volume. Significant resources will be required to undertake dredging work and environmental measures which will involve installing silt curtains, amongst others, to minimize suffusion of fine particles. This will no doubt negate the DCM application and prolong its construction duration, resulting in delays of subsequential construction activities.

This paper aims to investigate how to retain heaving material in the DCM foundation system to avoid both causing pollution and incurring additional project costs due to dredging. It has four objectives, namely: firstly, to study its formation mechanism; secondly, to investigate its shear strength characteristics, through the results of various lab and in-situ tests; thirdly, to discuss design and construction considerations concerning heaving material; and finally, to discuss the results of a full-scale test involving heaving material.

2 Formation Mechanism and Key Characteristics

To prevent fine particle diffusion, a 2m thick sand blanket is conventionally placed on the seabed prior to DCM construction. During the cement injection process, the marine deposit will be gradually extruded upwards and mixed with cement slurry, consequently pushing upwards the original seabed and hence the sand blanket. The material located directly above the top of DCM clusters and between the design DCM top level and the top of sand blanket after DCM is referred to as heaving material in the present study, as depicted in Figure 1.

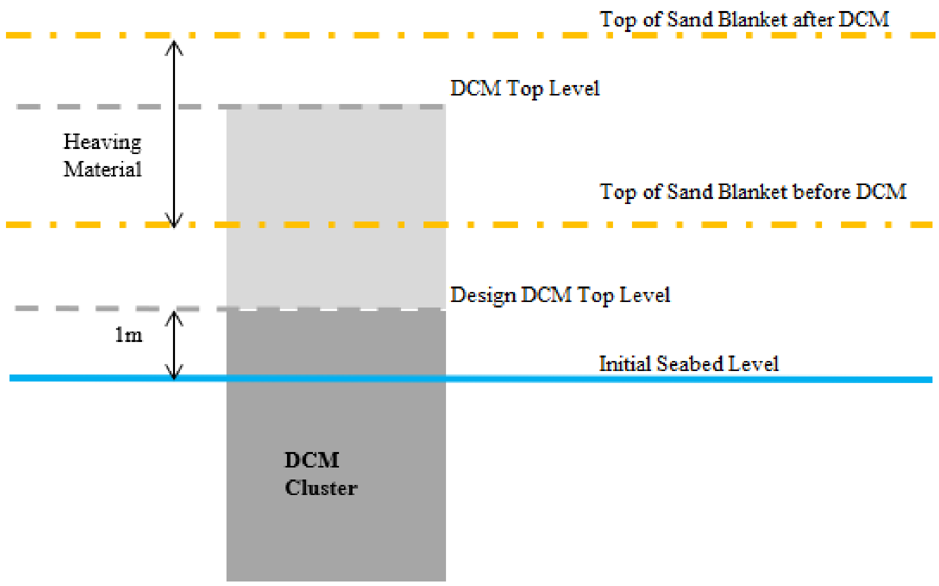


Figure 1: Definition of DCM heaving material

According to past experiences, the volume and properties of heaving material are influenced by a number of key factors including the in-situ soil properties, improvement depth and area ratio, cement dosage, workmanship and construction sequence.

The volume has close correlation with the particle size distribution of in situ soil. A clayey soil tends to induce a larger volume due to its higher incompressibility as compared with a sandy soil. The improvement depth also plays an important role; the deeper the improvement depth, the larger the volume because more soils are replaced by cement slurry. Similarly, the larger the improvement area ratio, the larger heave volume.

The Japanese solidification treatment research committee has proposed an empirical equation to calculate heaving thickness based on DCM cluster depth. Building office of Kansai airports has suggested that heaving thickness can be estimated as 5 to 10% of improvement depth for grid type or wall type DCM based on their experiences. Some researchers believe that the dominant factor affecting heaving volume is the injected cement volume based on detailed investigations into past projects. Some researchers, for example EuroSoilStab (2014), have reported that heaving volume accounts for 70 to 80% of the injected cement volume. In the revetment project of Port of Yokohama, the measured heaving volume was about 108% of cement injection and maximum heaving thickness was about 3m (DCM dosage:160kg/m3; water cement ratio:0.6; improvement depth:24 to 32m). In the revetment project of Kansai airports Phase II, heaving volume varied from 58 to 73% of cement injection and maximum heaving thickness was about 3.4m (DCM dosage:180kg/m3; improvement depth:33m). Heaving thickness is also affected by DCM construction sequence in that heaving material from earlier DCM installation can spread sideways to areas where DCM clusters are to be installed later.

Confining pressure of treated soil plays an important role for DCM mixing quality. A low confining pressure cannot effectively prevent leakage of cement slurry and maintain an ideal curing condition for DCM mixture. As compared with DCM clusters, more cracks can be observed from cored samples taken from heaving material, which can affect its intactness and strength. As heaving material lies above the original seabed, its confining pressure is low or even zero, resulting in poor mixing quality.

3 Shear Strength Characteristics

A series of site trials, involving installing DCM clusters and the associated post-DCM Unconfined Compressive Strength (UCS) tests and CPT tests, have been carried out under the current study to investigate the shear strength characteristics of heaving material. For the trials, the design of DCM clusters aims to achieve a UCS value of not less than 1.2MPa.

UCS values are plotted versus depth in Figure 2. While the majority of UCS values are much greater than 1.2MPa for DCM clusters, thus meeting the design requirement, they fall below 1.2MPa for heaving material, although being generally above 0.45MPa, except for the top 1m which consists of predominately sand. The likely reasons are, where heaving material is formed: (1) the confining pressure is low; (2) sand content is high due to the existence of the sand blanket; and (3) due to leakage of cement slurry and bad curing condition, cementing stress is not enough to bond cement slurry, soft clay and sand together as a unit.

Shallow in-situ CPT tests have been undertaken through the heave zone down to the top of DCM clusters. Figure 3 shows a typical plot of the measured CPT net cone resistance along depth. It can be seen that the cone resistance tends to increase with depth in the heave zone and is generally greater than 5MPa, except for the top 1m which consists of predominately sand.

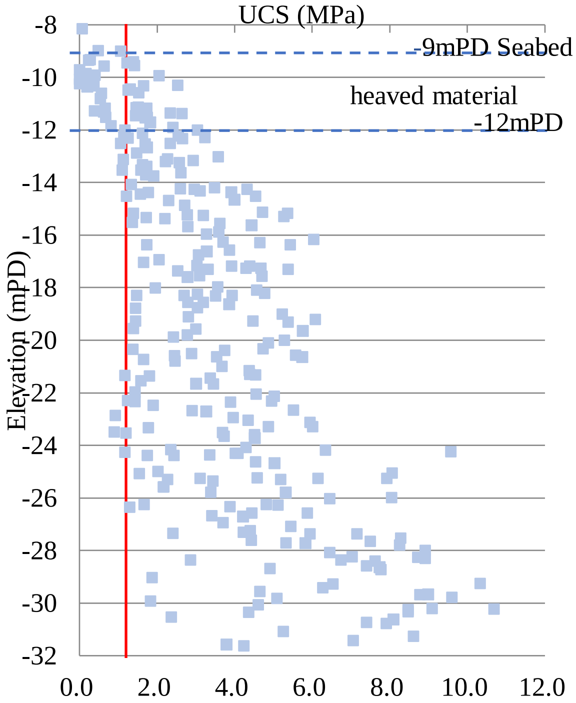


Figure 2: Plot of UCS values along DCM depth

When the CPT results are interpreted using the well established empirical methods, it can be observed that the behavior of heaving material is similar to that of a granular material. Figure 4 plots the inferred friction angles using the correlations proposed by Robertson & Campanella (1983) and Kulhawy & Mayne (1990). It can be seen that the friction angles at the DCM heave zone generally range between 45° and 52°, with some limited data showing about 40°, except for the top 1m. For the top 1m, the frication angles are generally greater than 30°.

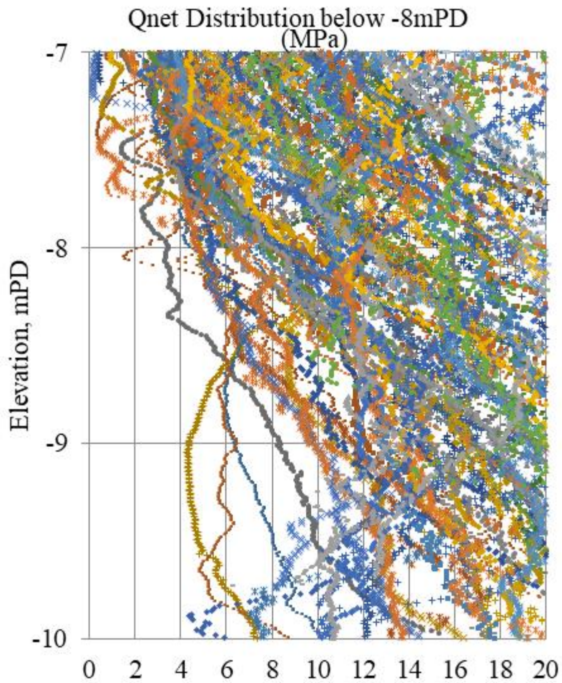
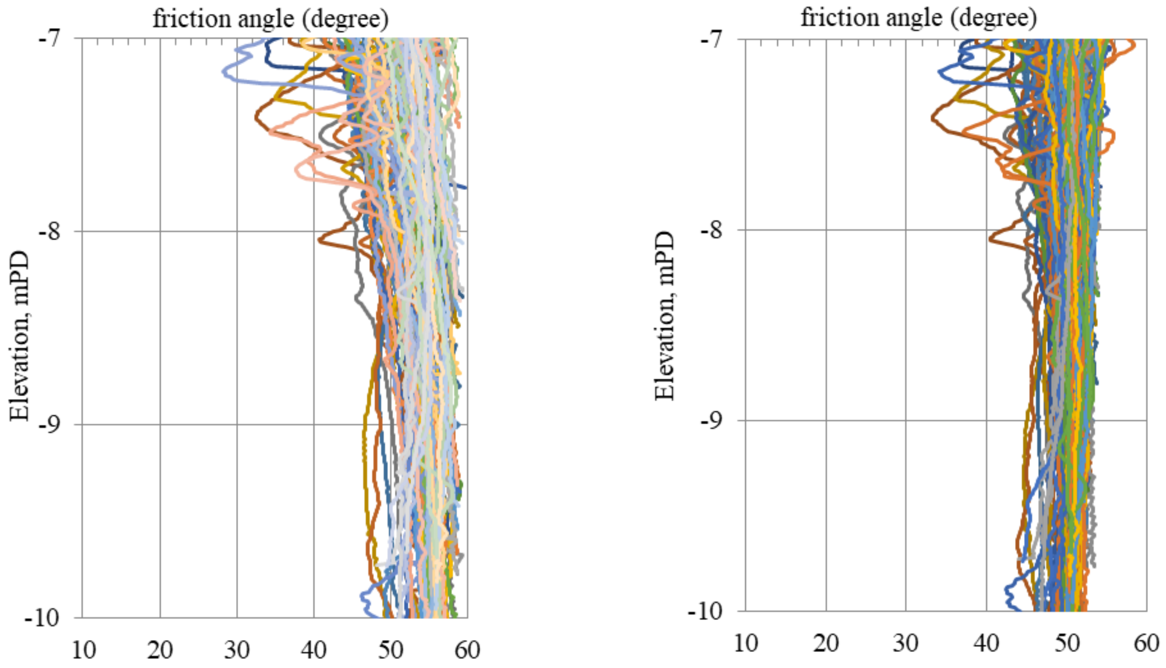


Figure 3: Plot of CPT net cone resistance along depth



(a) using Kulhawy & Mayne (1990) method (b) using Robertson & Campanella (1983) method

Figure 4: Plot of friction angle inferred from CPT results

To further understand the heaving material behavior, direct shear tests have also been carried out on the heaving material samples following the method modified from ASTM D5607-02. Some tests are carried out on samples with a pre-sheared plane to introduce a defined failure mode, which is considered to be representative of residual shear strength because the DCM cement bonding is completely destroyed. Other tests are on intact samples to provide the peak shear strength.

The test results are shown in Figure 5, while the deduced shear strength values are presented in Table 1.

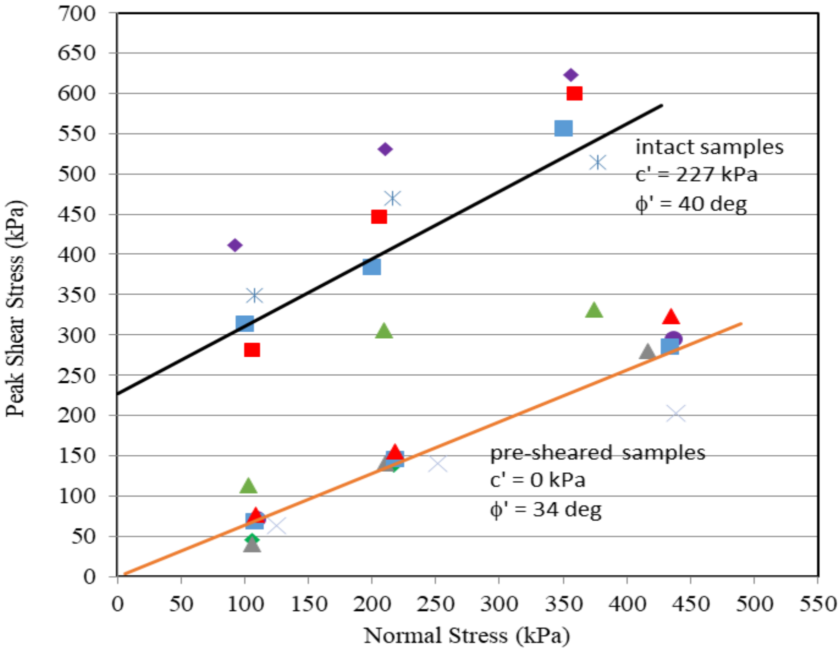


Figure 5: Plot of direct shear tests

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Table 1. Shear strength parameters deduced from direct shear tests

Shear strength	Cohesion c (kPa)	Effective frictional angle f (°)
Peak shear strength	227	40
Residual shear strength	0	34

4 Design And Construction Considerations

This section will discuss, from design and construction perspectives, how to assess whether heaving material can be retained in a DCM foundation system and how to improve its engineering properties if it is to be retained.

4.1 Design Considerations

Whether heaving material can be retained in a DCM foundation system depends on whether it has the required shear strength and stiffness parameters which can meet the design requirements of a foundation. For a seawall or breakwater structure, the design requirements will include achieving satisfactory safety factors against sliding, overturning and bearing failure of the foundation, while limiting settlement and lateral movement of the structure. If heaving material has the required engineering properties to meet design requirements, then it can be retained in the DCM foundation system. Otherwise, it will need to be either dredged or further treated.

Based on the test results discussed above in Section 3, it is proposed to adopt the values presented in Table 2 as the design geotechnical parameters for the heaving material under the present study. These shear strength parameters can be used to check sliding, overturning and bearing. The corresponding Young modulus values have been estimated using relevant correlations or past experience.

These parameters will be used for the full scale test discussed later in Section 5.

Table 2. Adopted geotechnical design parameters for heaving material

Heave zone	Undrained		drained		
	Young's modulus Eu (MPa)	UCS (kPa)	Young's modulus E' (MPa)	cohesion c' (kPa)	Friction angle φ' (°)
top 1m(1)	-	-	10	0	30
below top 1m	162(2)	450	20(3)	50(4)	34

Notes:

(1) The adopted parameters for the top 1m heaving material are the same as those for sand blanket;

(2) The adopted undrained Young's modulus is assumed to be 300 times UCS following the recommendation given in FHADM for DCM clusters;

(3) The adopted drained Young's modulus is the same as that for a rubble mound consisting of rock fill;

(4) The adopted drained cohesion of 50kPa is considered to be conservative based on the test results presented in Table 1.

4.2 Construction Considerations

If a heaving material is to be retained, then efforts should be exercised to improve its engineering properties.

The challenge of cement mixing for heaving material is to inject cement slurry within heaving material and achieve good mixing quality under low confining pressure. To fulfil this objective, construction parameters of high cement dosage, low water cement ratio, low injection pressure, low water injection and low BRN are recommended to minimize leakage of cement and maximize the cementation. Due to the variations of DCM rigs and cement supply systems, the specific construction parameters are not discussed here.

During the mixing process, stringent quality control and monitoring should be undertaken to ensure that the required strength can be achieved in the soil. Field trials should be carried out to obtain or verify design parameters, mixing designs (such as optimal site-specific soil to cement ratio, water cement ratio, etc) and construction methods (such as blade rotation number, etc).

5 Full Scale Test

As part of the present study, a full scale test involving loading a 31m by 32m DCM improvement area has been carried out. The heaving material following DCM construction was measured to be about 2.1m thick and was decided to be retained in the DCM foundation based on stability and settlement analysis results.

The design UCS value for DCM clusters is 1.2MPa and the design geotechnical parameters for heaving material are the same as those presented in Table 2 which have shown to meet the stability, settlement and lateral movement requirements of the loading platform.

5.1 Test setup

Prior to DCM installation, a 2m thick sand blanket was placed on the existing seabed. With a 50% improvement area ratio, a total of 123 numbers of DCM clusters, about 20m deep, were then installed, followed by the placement of a 1.6m thick rubble mound which was used as a loading platform. Loading was applied to the loading platform on a 15m by 15m area, at the centre of the DCM treated ground, through a gradual placement of precast concrete blocks amounting to a total height of 10.8m. This is equivalent to a uniform loading of about 340kPa corresponding to a mean lower low sea level of +0.4mPD. The DCM layout and a typical section of the test setup are illustrated in Figure 6. A site photo showing the loading concrete blocks is presented in Plate 1.

6 numbers of Shape Array Vertical (SAAV) Inclinometers and 3 numbers of yield point Multiple Rod Extensometer have been installed to monitor the settlement and lateral movement of both the loading platform and the DCM body. All the instruments were connected to a data logger fixed on a prefabricated steel platform which is located about 5.8m away from the test area, as indicated in Figure 6a.

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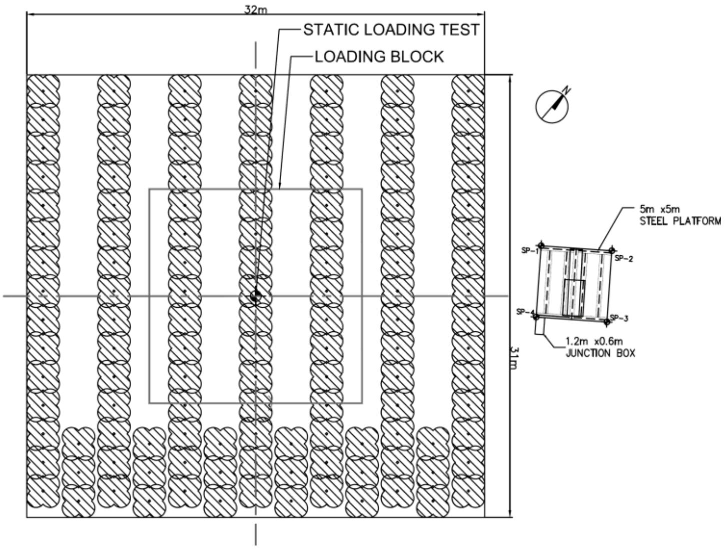
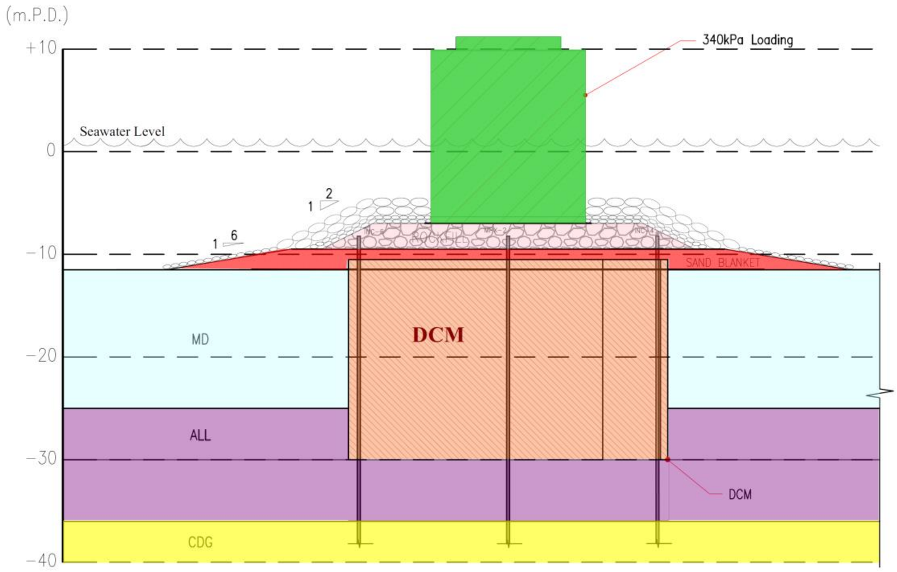


(a) DCM layout



(b) typical cross section of test setup

Figure 6: DCM layout and test setup

Plate 1 - Site Photo of loading concrete blocks

5.2 Test Results

Throughout the test the loading platform was observed to have remained stable. The settlement and lateral movement were measured at different depths, from the loading platform downward, and then compared with their theoretical predictions. In the present paper, only compression of both the DCM body and heaving material is discussed below.

Plaxis 3D has been employed to model the loading process and predict compression of the DCM and heaving material. Heaving material was assumed to be under an undrained condition due to the relatively short test period. The measured and predicted results are presented in Table 3.

Table 3. Comparison of measured and predicted compression

Material	Compression (mm)	
	measured	predicted
DCM treated ground	1.4	38
DCM heaving material	1.5	22

As can be seen, the predicted compression value is much smaller than the measured, for both the DCM treated ground and heaving material, indicating that the theoretical assumptions are on the conservative side. Based on these results, it can be concluded that the heaving material can satisfy design requirements and hence can be retained in the DCM foundation system.

6 Conclusion

A series of lab and in-situ tests including a full scale static loading test have been carried out under the present study to investigate whether heaving material, resulted from DCM construction, can be retained in the DCM foundation system.

Lab tests include UCS and direct shear tests on samples taken from heaving material, while shallow CPT tests are conducted through the heave zone down to the top of the DCM clusters. The test results

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have shown that the shear strength parameters of heaving material are much less than those of the DCM clusters but may still be able to meet design requirements.

The results of the full scale static loading test which involves loading a 30m by 30m DCM treated area, with an improvement area ratio of 50%, have indicated that the heaving material can meet design requirements and hence can be retained in the DCM foundation system for the loading test.

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