Deep Cement Mixing (DCM) Method for Reclamation of Tung Chung East Reclamation – Construction Aspects

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ABSTRACT

Deep Cement Mixing (DCM) is an effective soil improvement technique widely used in geotechnical engineering. This technique involves the use of cement slurry to create cylindrical columns in the soil. These columns help to improve the strength, stiffness, and stability of the soil. DCM has been successfully applied in various projects, including marine infrastructure development. In the advanced work for Tung Chung New Town Extension (TCNTE) project, as a non-dredged construction scheme, deep cement mixing (DCM) method for ground improvement was used to strengthen very soft to soft marine sediment of clay to silty-clay materials in the project area for supporting seawalls and overlying fill material for ground formation. During the project, various types of DCM method and equipment were used according to the construction stage, purpose and site restraints in both marine and land work front. Different challenges were encountered and handled during the project such as low water, works near the noise sensitive area, severe barges interference by site congestion, low headroom and many others. Through the entire project, more than 6.2 million m^3 of volume of DCM was installed successfully which sets the record of world largest DCM application for a single contract.

Keywords: Deep Cement Mixing, Ground Improvement, Reclamation

1 Overview of Project

1.1 Project Introduction

The Tung Chung East (TCE) project is a reclamation project located in the Tung Chung New Town Extension (TCNTE), undertaken by the Civil Engineering and Development Department (CEDD). The project aims to create 130 hectares of new land adjacent to the existing residential area of Tung Chung new town.

Over the years, reclamation methods and ground treatment techniques have advanced significantly to meet technical requirements and social expectations. To promote sustainable reclamation method, the TCE reclamation project has adopted several measures, including non-dredged reclamation methods, specifically the deep cement mixing (DCM) method, and the use of construction and demolition (C&D) materials as the primary filling material. Given the pressing need for land, TCE reclamation is the first public works project in Hong Kong that has adopted the DCM method to expedite reclamation activities. During the project, various types of DCM methods and equipment were used based on the construction stage, purpose, and site constraints in both the marine and land work front.

For the general soil profile, the soil underlying the proposed reclaimed area typically consists of deep layers of very soft Marine Deposit (MD) and Alluvium (ALL). These superficial deposits are, in turn, underlain by an in-situ weathered granite profile, encountered at approximately 36m below the seabed. The description and thickness of the superficial deposits are presented in Table 1.

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Table 1: *Superficial deposits beneath the area of the proposed reclamation*

Stratum	Soil Type	Thickness (m)	Description
Marine Deposits (MD)	Silts/ Clay	10 ~ 17	Very soft to soft MARINE DEPOSITS CLAY and SILT, locally granular.
Alluvium (ALL)	Interbedded Clays/ Silts & Sands	10 ~ 21	Medium dense to dense silty fine to coarse SAND / Sandy clayey SILT (occasionally very stiff), interbedded with fine to coarse GRAVEL of rhyolite and quartz with cobbles.

1.2 Geotechnical properties of the soils to be treated by DCM

DCM method was utilized as a non-dredged construction scheme to improve the soft marine sediment consisting of clay to silty-clay materials in the project area, in order to support seawalls and overlying fill material for ground formation. This method involves treating the entire stratum of MD layer and a portion of the ALL layer within the column for each installation. The toe of the DCM column is terminated at the level of competent stratum (CS), which is defined as having a minimum 2m embedment depth in stratum with rolling average $q_c \geq 1.5$MPa, according to CPT results. This level is referred to as CS top level.

The water content of the original soil deposits, as measured with soil samples collected from the G.I, ranges from 70-110% for the upper 10m of MD and 15-45% for ALL layers. The bulk density of the alluvial layer is higher than that of the marine deposit layer, with an average value of 1.9tf/m^3 compared to the marine deposit layer's average value of 1.5tf/m^3.

Based on Atterberg limit test results as seen in the Figure 2, MD is classified as almost MH (Silt of High Plasticity) and ALL is classified as almost CL (Clay of Low Plasticity) according to the United Soil Classification System (USCS).

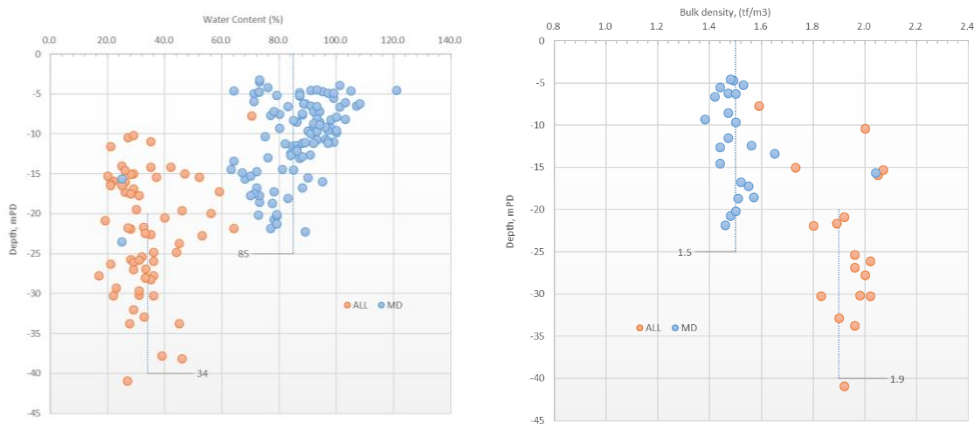

Figure 1: *Water content of MD and ALL*

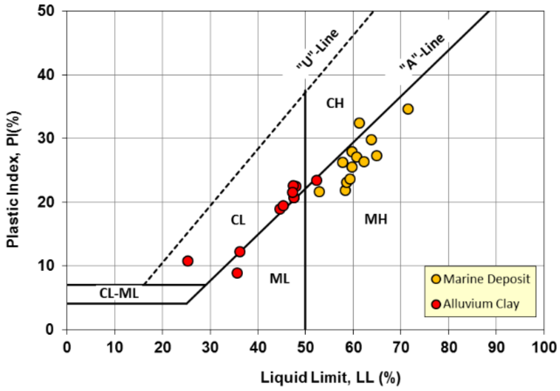

Figure 2: *Atterberg limit of MD and ALL*

2 Laboratory Mix Test

2.1 Test Conditions

DCM is a ground treatment technique and the design is site specific. The mixing parameters, such as the dosage of binder and mixing time are tested and verified for individual soil layers to ensure consistency of DCM quality. The test is first carried out in laboratory under control environment. The objective of the laboratory mixing test is to establish the soil properties, its mixability and binder dosage etc. Test specimens for the laboratory mixing test were prepared in accordance with the Japanese standard laboratory procedure on the preparation and storing of test samples of soil for dry and wet mixing methods (JGS 0821-2009) The time of mixing soil and binder slurry was determined to be 10min as recommended by Kitazume and Nishimura, 2009.

It is well-established that the strength of binder-stabilized soil using DCM is significantly influenced by the in-situ water content of the soils. The total water content in the treated soil mass, that is the in-situ water content plus the additional water in making of the slurry plus any additional water will make up the total water content in the end-product. This total water content to the binder ratio is found to be of relationship to the final strength of the DCM. Water content test is based on the procedures as recommended in Geoguide 3 (CEDD).

In the TCE project, there are two distinctive soil layers that are targeted for treatment using DCM. Soil samples from the MD and ALL layers were collected at the site using tube sampling, and the water content of the tested soils was controlled to represent those two soil layers in the mixing test. As the water content varies with depth and location across the site, the designer shall collect sufficient samples from different depth and location to provide reliable results.

To prepare the testing soils from the MD layers, the soils were screened by a sieve to remove larger size particles and mixed thoroughly in a soil box using portable hand-held mixing drills. The water content of the soils was controlled to the target water content, which was determined to be the average value of 85% in the original ground (refer to Figure 1).

On the other hand, the average water content of the ALL layers was found to be 34%, which is relatively low. It was often observed that the tamping of the mold with stiff binder-soil mixtures was not sufficient, resulting in failures to obtain proper test specimen conditions. A tailored made compact table, (Figure 3) standardize the compaction energy to ensure the samples are well compacted and to the same degree of compaction.

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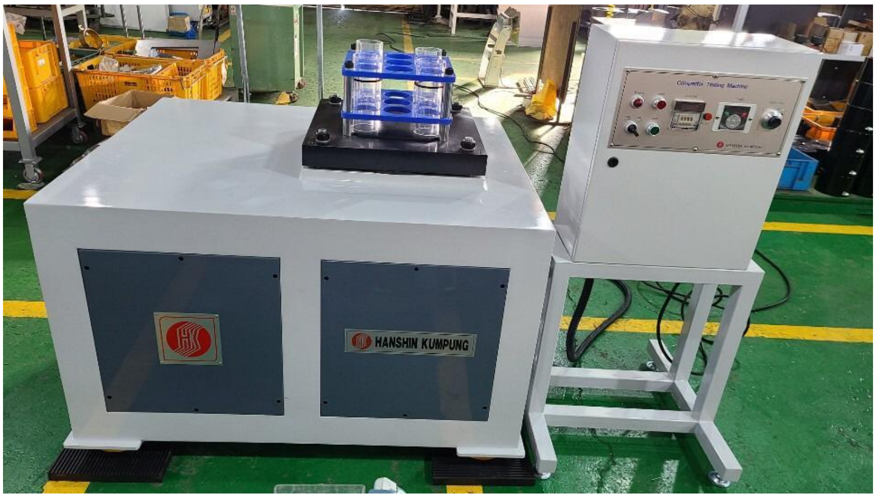


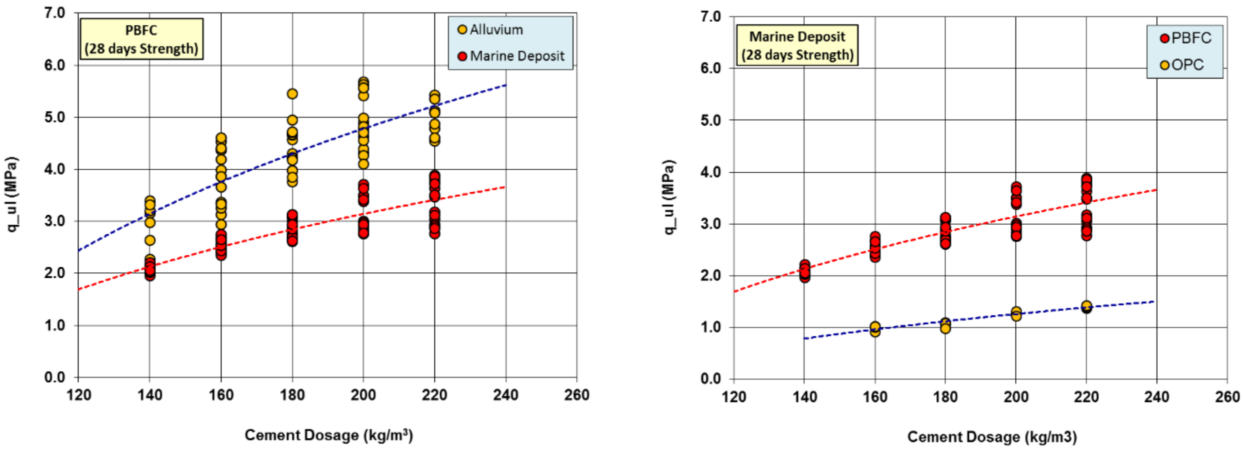
Figure 3: *Compaction table for DCM laboratory mix test*

Furthermore, considering the practical limitation of DCM rig penetration capability and to ensure proper mixing, it is not uncommon to adopt water injection to assist penetration and disturb of stiff ALL layer and achieve the desired penetration. It is envisaged that this injected water would result in an increase in the water content of this layer. Therefore, the water content of the ALL soils used in the laboratory mixing test was determined to be the average value of 40.0%.

2.2 UCS Strength Characteristics from the Laboratory Mix Test

The Unconfined Compressive Strength (UCS) test was conducted in accordance with ASTM D2166/D2166M-16. Figure 4 illustrates the relationship between the dosage of binder cement and UCS, as determined through laboratory testing of MD and ALL soils stabilized with Portland Blast Furnace Cement (PBFC) and Ordinary Portland Cement (OPC) and tested after 28 days of curing. Although there were some variations in the test results for specimens tested under the same conditions, the overall trend indicates that UCS increases with an increasing amount of binder cement.

Notably, the UCS values differ significantly between the MD and ALL layers, which strongly suggests that the water content of the soils may be a key factor influencing UCS under laboratory conditions, particularly when the degree of mixing is high enough for either soil type to avoid the effects of insufficient degree of mixing.

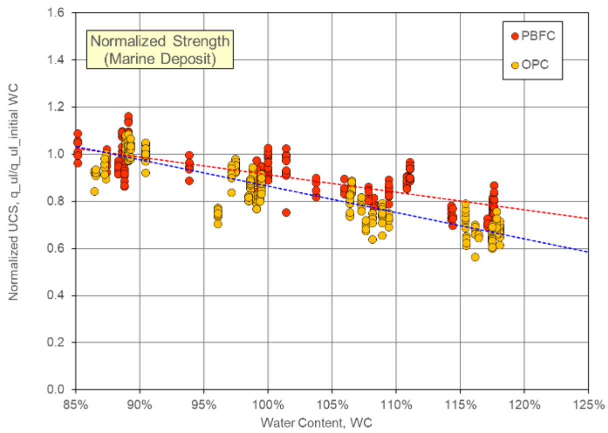


(a) UCS for MD and ALL (b) UCS for Biner Type

Figure 4: *UCS at 28 days for MD and ALL using PBFC and OPC*

As indicated by the results, the UCS of treated soils decreased with an increasing initial water content, regardless of the soil or cement type used. Of particular concern was the strength reduction of DCM in the upper soft soils within the MD layer. To further investigate this issue, additional UCS tests were conducted on MD soils with varying water content.

Figure 5 illustrates the relationship between normalized unconfined compressive strength and initial water content of MD soils using two different binders of PBFC and OPC. The results revealed that UCS decreased with increase of water content and that its decreasing rate is higher in case of using OPC compared to PBFC for the type of soils used in the test. Therefore, it is highly recommended that laboratory tests with various mixing conditions are needed for better planning of DCM before the field application.



where, $q_{\_ul}$: UCS by laboratory test with increasing water content
$q_{\_ul\_initial\ WC}$: UCS by laboratory test at initial water content

Figure 5: *Relationship between normalized UCS and water content of stabilized Marine Deposit (MD)*

3 Marine DCM

3.1 Mobilization of DCM Barges into the Site

The TCE reclamation project required the construction of a 4.9km long seawall, which was crucial to support the reclamation materials needed to form the new land. As the foundation of the seawall was designed with DCM walls and slabs, the DCM installation for the original ground under the seabed had to be conducted in marine conditions. Before starting marine DCM works, a sand blanket was laid on the original seabed along the footprint of the DCM foundation. This was done to provide a safe environment for water quality protection and to cut off direct exposure to seawater during DCM construction for the treatment of surface soils along the seabed. To achieve the target depth of DCM treatment, high-mast marine DCM barges, which were 52~53m above the water level, were selected. In total, six marine DCM barges with the same configuration were used for this task. All these DCM barges were equipped with multiple rigs that allowed the installation of three DCM clusters at the same time, as seen in Figure 6. The spacing between the rigs was adjustable to suit the design requirements.

As illustrated in Figure 7, each DCM barge was equipped with 6 cement silos of 70~80 ton capacity each for the storage and supply of the dry binder to the mixing plant. In the mixing plant, a batch of the binder was weighed and dropped into the mixer where seawater was added proportionally at the predetermined water-binder ratio (normally 80-100%). This fresh mixture of binder slurry was then transferred to the agitator, and this process was repeated until the required volume of binder slurry was

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reached for one DCM cluster installation. The flow of binder slurry was controlled by the measurement of a flow meter attached to each slurry pump, ensuring accurate injection at the discharge outlet of the mixing blade system.

LM-1	LM-2	YP-1
		
DJ-6	DJ-7	ESC-51
		

Figure 6: *Marine DCM barges used in TCE project.*

Meanwhile, due to the physical constraints of the site, the high-mast DCM barges had to pass under the existing Tuen Mun Chek Lap Kok (TMCLK) link viaduct during mobilization. To meet the height restrictions for passing under the TMCLK bridge, the barges had to be lowered with the rigs fitted at a height lower than 21m. Once they had passed under the bridge, the barges were reassembled.

Before mobilization, the rigs and leaders were dismantled, and the backstay tower (also known as the A-frame) was demounted and lifted onto a flat barge to be separately towed for assembly by a crane barge, as shown in Figure 8. For some of the DCM barges, due to their original barge layout, the backstay tower could not be lifted. In such cases, the front laying method was adopted, as shown in Figure 9.

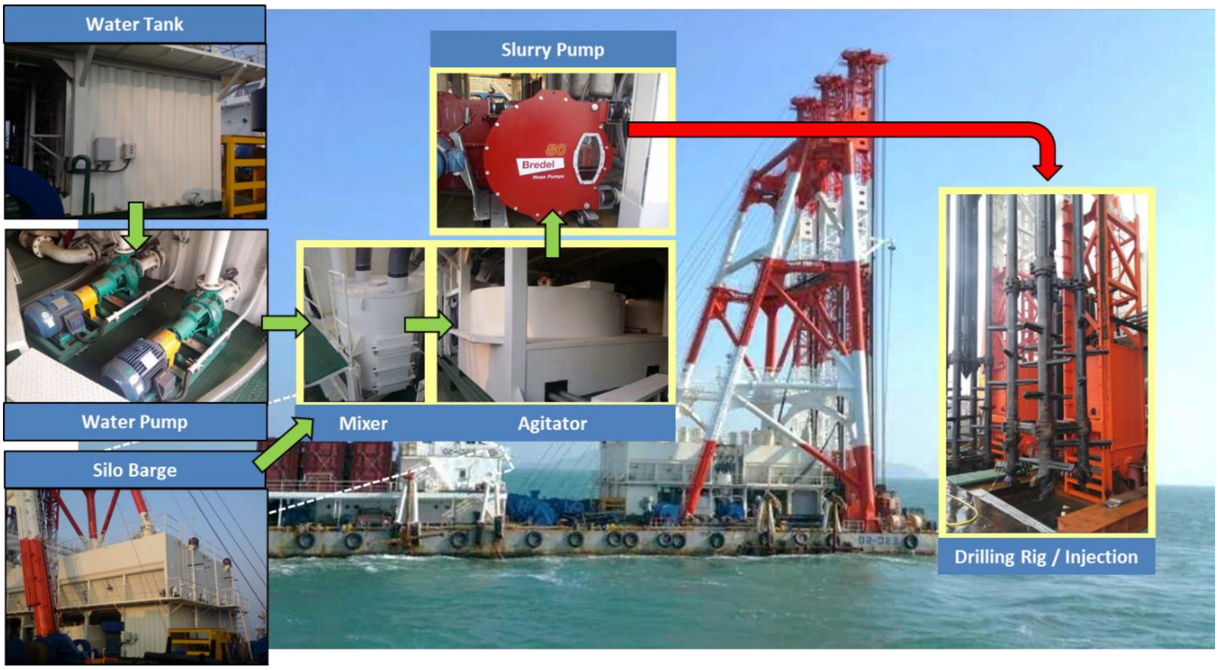

Figure 7: *Binder slurry supply for marine DCM barges*

Figure 8: *Towing of barges into the site passing under TM CLK Link*

(a) Dismantling of back stay and placing on a flat barge for towing

(b) Front inclining of back stay

Figure 9: *Dismantling and inclining of back stay for towing into the site*

3.2 Marine DCM Works

During the marine DCM operation, certain site restrictions were in place, such as the need to work in close proximity to the existing residential area(Figure 10). To comply with Environmental Permit, working hours were limited to 12 hours per day, from 7 am to 7 pm, and all necessary noise reduction devices and measures were prepared and equipped to minimize noise impact in the sound-sensitive area. The noise generated from the working barges was subdued and minimized to the best extent possible. The major sources of noise were covered by noise mats, including the Auger motors of each rig and the mixing plant used for preparing and supplying binder slurry. The generator engine rooms were enclosed by steel housing and panels to further reduce noise emissions.

Figure 10: *Marine DCM barges on work close to residential area*

In the DCM application, the 4-shafts DCM blade system consists of blades mounted on a steel rod shaft that are rotated to mix the soil and injected slurry and each cylindrical column per shaft has a diameter of 1.3 meters so that the dimensional area of treatment by each DCM cluster becomes 4.63m^3. The extent of a DCM cluster from the original seabed is varied in the range of 18~30m according to the required thickness of MD and ALL layer for improvement. The binder slurry can be injected from the bottom nozzle of the blade rods for penetration injection and from the top injection outlet for withdrawal injection.

Figure 11 shows the illustrated installation cycle diagram for a single cluster by marine DCM. After the DCM barge is positioned to the designated location, via Real-Time Kinematic GPS control, the DCM rig starts to penetrate down into the ground while the blades are rotating.

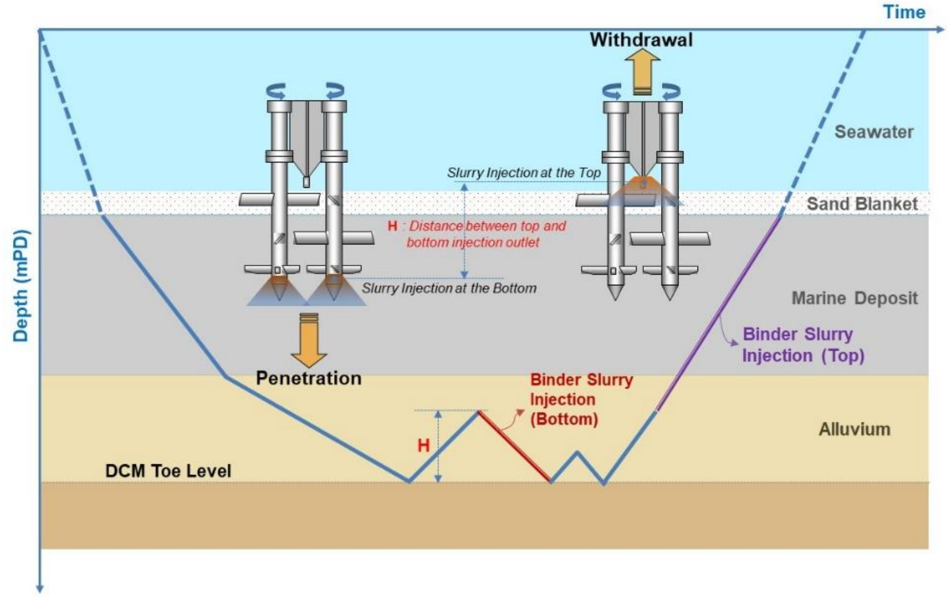

Figure 11: *DCM installation cycle diagram*

Once the penetration at the bottom end of the blade system (Zero-level) reaches to the design toe level, the blade system is then raised by "H" (the distance between top and bottom injection outlet points) as indicated in the Figure 11 so that this range of thickness is treated by "penetration injection". After the treatment of this portion of the cluster profile is completed, the outlet of binder injection switches from the bottom to the top so that the "withdrawal injection" is maintained to continue to treat the remaining part of soils up to the design top level of a DCM cluster.

The penetration rate of the mixing shaft may vary depending on the ground stiffness. The typical range of penetration rate is between 0.5m/sec to 1m/sec. The degree of mixing is dependent on the vertical movement of the mixing tools and the rotation speed of the blades. These two key parameters are presented in an index form, "Blade Rotation Number (BRN). BRN for DCM is defined in EN 14679:2005 and also in FHWA-HRT-13-046;

BRN = (Total number of mixing blades) x ($Np/Vp + Nw/Vw$)

Where, Np : Rotational speed during penetration (rpm)

Vp : Velocity of mixing blade during penetration (m/min)

Nw : Rotational speed during withdrawal (rpm)

Vw : Velocity of mixing blade during withdrawal (m/min).

During the process of penetrating the ground with the DCM rig, the rotation of blades fully disturbs the original soil structure. The main purpose of this penetration is to confirm if the rig can reach to the design toe level, therefore until the design toe is confirmed, no binder slurry is injected. Through the penetration rotation, the soil is remolded and will improve the mixability of the soil with the cement slurry.

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The resistance of the soil to the rotation of the blades at certain RPM can be estimated by measuring the current (Ampere) of the electric auger motors. This provides an indication of the ground stiffness encountered during the penetration of the DCM rig.

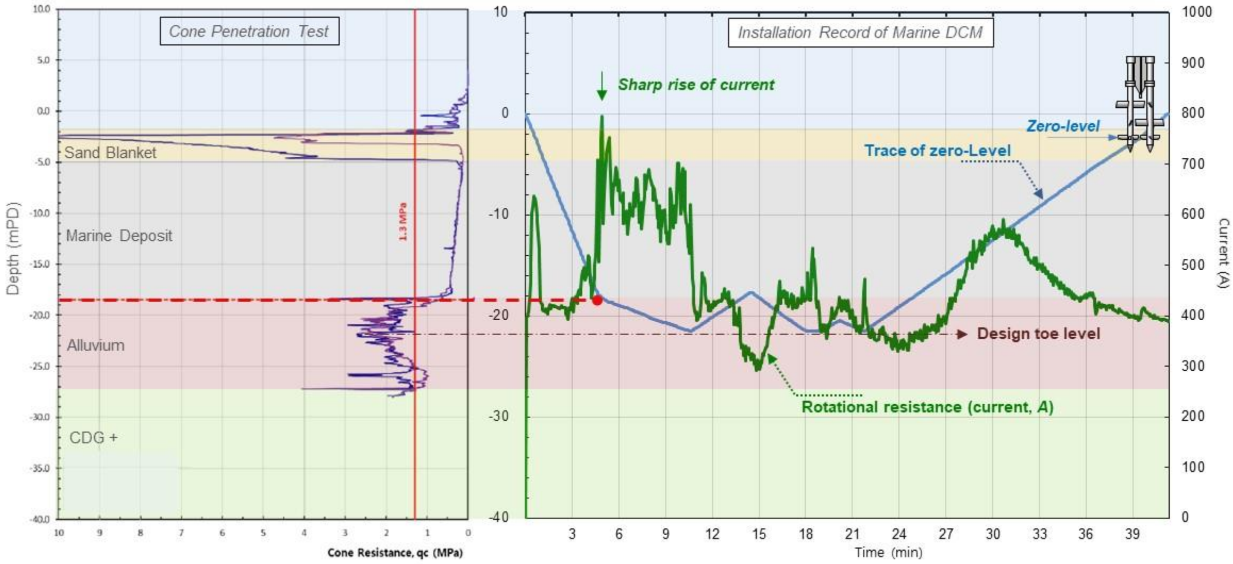

Figure 12: *Example of installation record for DCM cluster*

Figure 12 shows an example on the track record of DCM installation obtained from one of the DCM clusters by marine DCM. The rotational resistance of the auger motor is compared with CPT(Cone Penetration Test) values obtained from the original ground before DCM installation, it is understood that the trend of this resistance is well fit with the CPT results. This indicates that relatively accurate understanding of soil layer profiles can be obtained during the installation of DCM by the operator.

From Figure 12, it also can be seen that slightly before the bottom end of blades reaches the top of alluvial layer, the current started to build up with increase of resistance and the dramatical increase of current indicates that the blades encountered the Alluvial layer. With such measurement, the DCM operator can estimate the ground condition so that the operator can correspond timely with appropriate controlling of rig penetration by regulating the RPM of auger motors or by handling the lifting of the rig by the main wire, or by water injection so that they can provide proper mixing condition for good quality of DCM treatment.

In addition, installation criteria were established in case the rig cannot reach the design toe level or it is interfered with during the penetration. The DCM operator can refer to the cycle record as illustrated in Figure 12 to make decisions based on such predetermined criteria.

4 Land DCM

4.1 Land DCM Machines

Land DCM method was used to treat the soils at area where DCM barge could not access, due to shallow water. Around 47,000 clusters of DCM were installed using 17 land DCM machines, making it one of the largest land DCM installations for a single reclamation project.

The maximum reach of the land DCM was 31~32m from the ground level varying between +3 to +4mPD based on the site conditions. The land DCM machine has similar configuration as the marine DCM rig, that is a multi-auger system which combined four individual motors with a capacity of 110kW each, allowing the machine to construct DCM clusters with the same size as those used for marine

DCM. The multi-auger system provided powerful rotational torque, allowing it to penetrate large depths and overcome complex ground formations with intermediate stiff layers or hard materials. This was the first attempt that four auger motors of large capacity were combined for a single cluster formation.

Due to the weight of the rig being over 35 tons, the base machine had to be sufficiently large for safe operation. The DCM rig of the land DCM was mounted to the leader of a crawler type pile driver, and the rig was lifted by the main winch with steel wire rope.

In comparison to the marine DCM, the land DCM typically used the penetration injection method due to the complexity of attaching additional injection pipe and hose lines. It was also considered that this attachment could add excessive overburden weight to the rig, which was not beneficial for safe operation. Figure 13 shows the typical cycle diagram for the installation process by land DCM. After the rig is fully penetrated to the target depth of improvement, the rig is lifted to the designed top level of a DCM cluster to start the binder slurry injection at the bottom of the blade system. The rig is then lowered at the predetermined rate of penetration, RPM of blade rotation, and rate of slurry injection to form the DCM cluster.

Unlike the DCM barge, there are separate cement silos, mixer plant and pumping stations set up remote from the DCM machine and this fixed location has to be selected considering site conditions such as interference to the other works nearby due to long term occupation of the plant facilities within the area, method for daily supply of cement/binder to the storage silos and maximum distance between the plant and the DCM machines. The mixer plant and silos can be facilitated on the marine barge or on the land as it is illustrated in Figure 14 and the pumping station is setup for the longer supply of binder slurry by relaying the pumping between the mixer plant and the DCM machine.

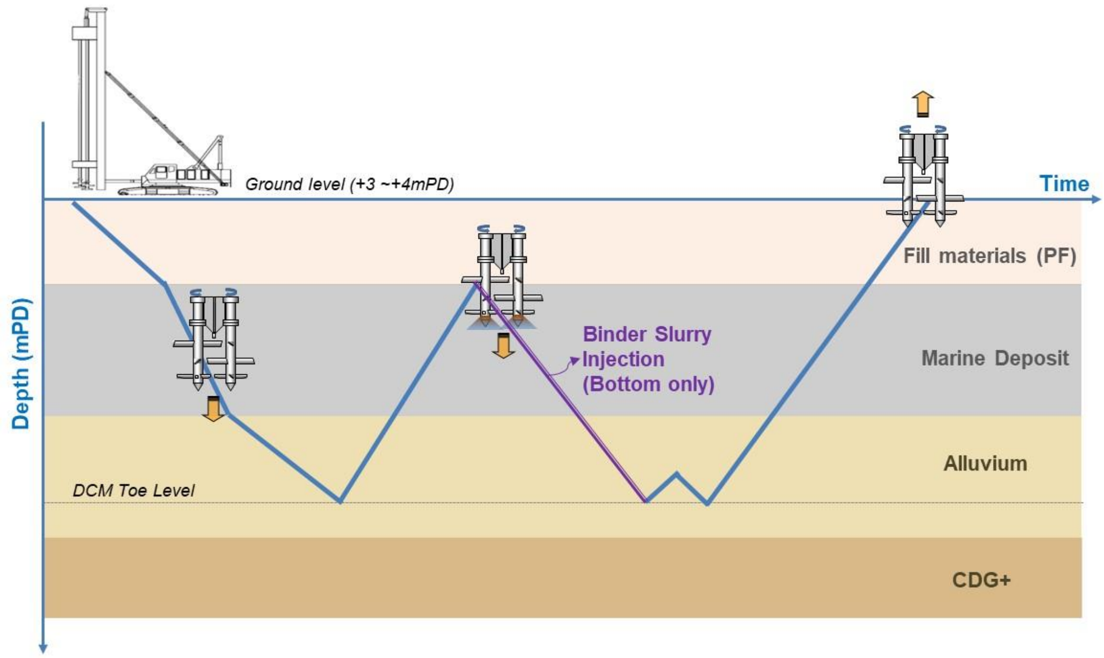

Figure 13: *Cycle diagram for land DCM installation*

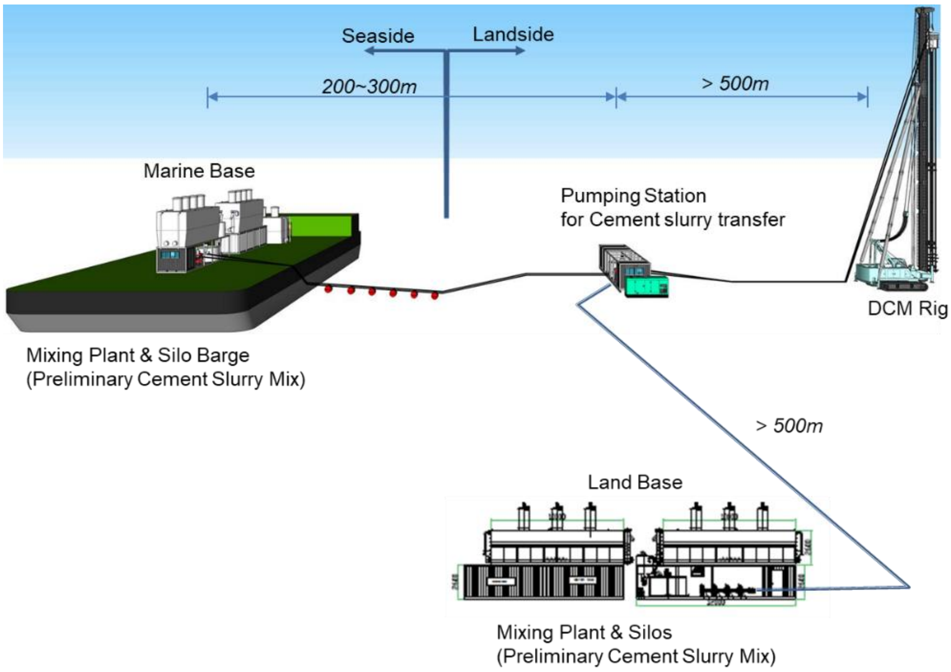

Figure 14: *Arrangement of land DCM application*

When the supply of cement/binder is planned by marine transport, the area near to the vertical seawall is more advantageous for the plant facilities. The binder slurry that is prepared in the mixer plant is transferred by slurry pumps in the mixer plant or pumping station through high-pressure hoses that were extended up to 500m. However, for easier quality control and for preventing from clogging of high pressure due to long lead time by long pumping distance, it is preferred to keep the slurry pumping distance from the mixer plant to the DCM machine to within 300m. Figure 15 shows the site scene for land DCM operation.

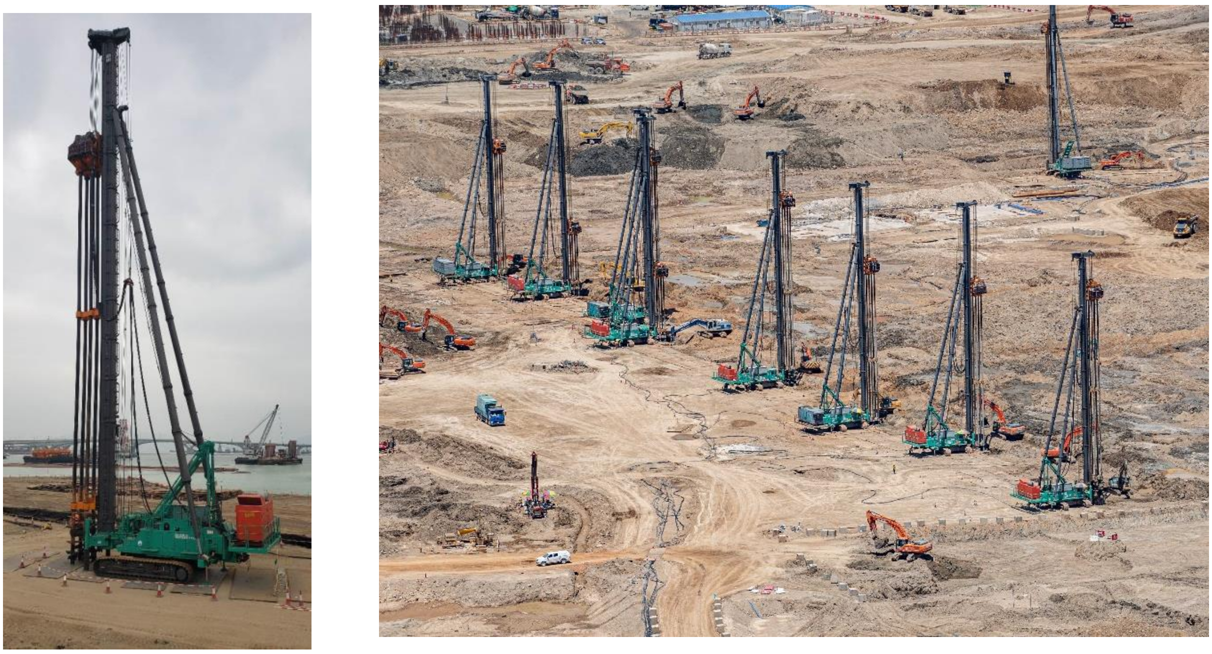

Figure 15: *Land DCM machines and its working on land*

5 Low Headroom DCM

Figure 16 illustrates a construction site located beneath the TM-CLKL viaducts, where the maximum allowable headroom is approximately 17m above mean sea level. This height restriction makes it impossible to employ standard DCM barges in this low headroom working condition. Initially, wire-mounted Cutter Soil Mixing (CSM) barges were planned for the area, but this approach posed significant challenges, including limited working space, the need for multiple working barges to complete the required volume of DCM within the allowed time, and safety concerns due to the operational status of the bridge.

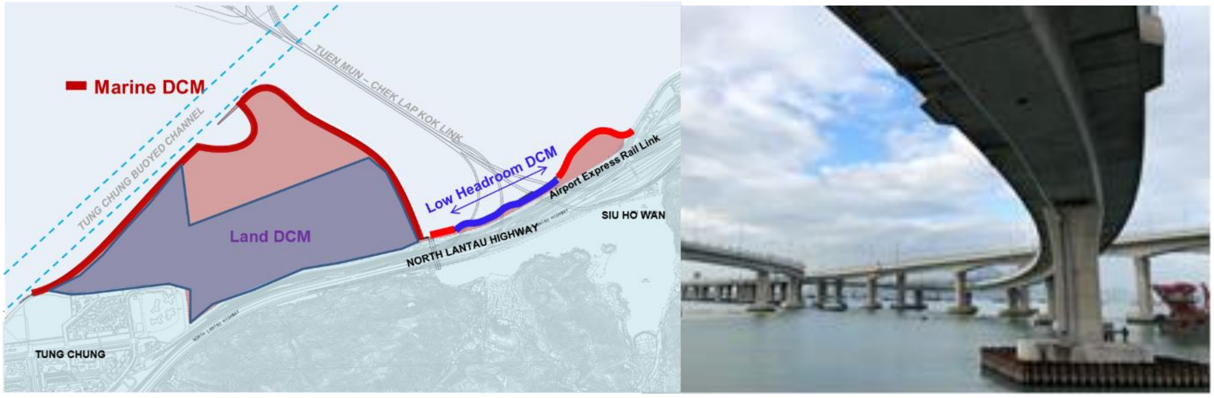

Figure 16: *Area for low headroom DCM*

To address these challenges, a proactive decision was taken in the middle of the project to develop a custom-made "low headroom DCM barge." This innovative barge featured a telescopic retractable rod design that was combined with a standard marine DCM application method. This solution enabled the barge to safely enter the low headroom area and install DCM treatment down to the design level by extending the rods up to four stages (Figure 17).

This novel system represented a significant achievement for the project team, as it was the first of its kind and demonstrated their advanced technical capabilities.

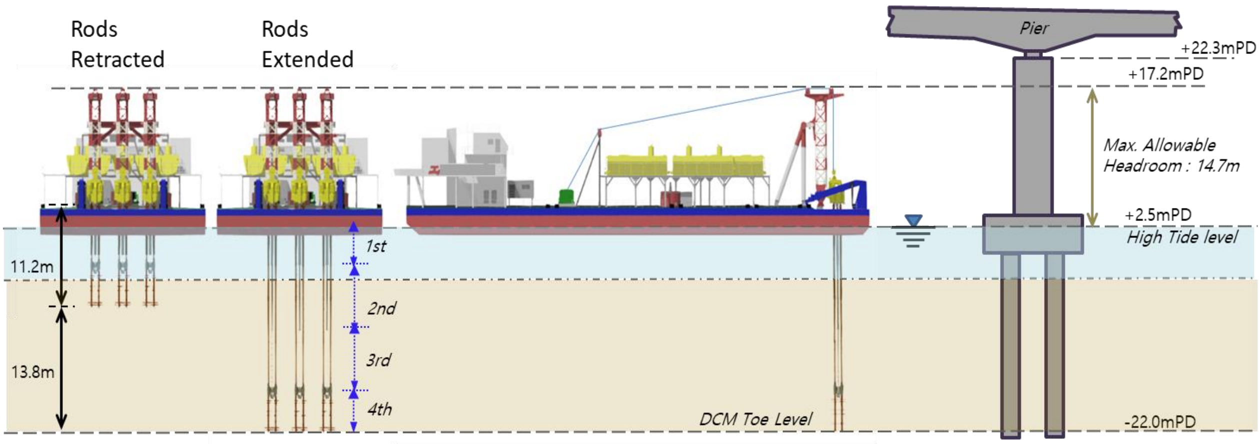

Figure 17: *Low headroom DCM barge with 4 stage retractable rods*

The new design not only overcame the stringent site conditions but also improved the overall productivity and flexibility of barge deployment. Unlike the conventional CSM system, which can only mount one set of wheels on a barge, the retractable telescopic design allows for up to three retractable rods to be equipped on one barge (Figure 18). This enables three DCM columns to be completed simultaneously, resulting in a significant increase in productivity, with a treated volume (per insertion)

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170% of that achievable with conventional CSM machines. Furthermore, the total number of DCM installations required to build the same design foundation for seawalls was reduced.

Figure 18: *Two low headroom barges working under the TM-CLK Link*

As a result of this innovative design, the number of working barges needed for the project was dramatically reduced from the anticipated seven barges to only two, while productivity was enhanced. The novel low headroom barge successfully completed ground treatment works in the extremely congested area in a timely manner, ultimately reducing the overall construction time by 35%. Additionally, as a result of this design, the potential risk of barge collisions was significantly reduced, and it had less effects on the environment of the adjacent water during construction.

6 Obstructions To DCM

A limitation of DCM method is the ground obstructions, including cobbles and boulders. The mixing shaft is able to push individual obstruction sideway during the penetration through the rotation of the mixing blades. Modern DCM rigs, individual mixing shafts could be operated individually, that is they can rotate, not rotate or rotate in reversed direct. Through the operation of experienced DCM operator, individual obstruction in most cases could be push sideway to facilitate the continuous penetration and mixing action of the mixing shafts. When larger size obstructions or in case of thick layer of cobbles and gravels, the penetration capacity is limited. Repeated up and down motion of the mixing shaft may be able to assist the penetration.

Sometimes, additional water injection would be able to ease the penetration through obstruction. The pre-insertion test and site trial insertion is useful means for the operator to experience the ground response before carrying out permanent DCM works. Other means of ground treatment method may be required, example jet grouting, depends on the design requirements and assessment of the toe levels actually achieved.

7 Conclusions

The Tung Chung East (TCE) reclamation project is the first public project to adopt sustainable method – DCM, and represents the large-scale reclamation utilizing a diverse array of deep cement mixing (DCM) techniques as non-dredging ground improvement method, including marine DCM, land DCM, and low headroom DCM. Prior to commencement of the main works, laboratory mix tests were conducted to evaluate the characteristics of the soils to be treated using DCM. These tests utilized soil samples extracted from the project site, and revealed significant variations in the unconfined compressive strength (UCS) characteristics of the Marine Deposit and Alluvium layers, which were found to be influenced by binder types, dosages, and water content of the original soil.The marine DCM works utilized high-mast marine DCM barges equipped with multiple rigs for seawall foundations, while the land DCM installation process employed more than 17 land DCM machines to improve the soft soils beneath the reclaimed land with public fills. A custom-made "Low Headroom DCM barge" was specifically designed to overcome site-specific constraints related to working under the viaduct of TM-CLK Link. This innovative solution utilized a four-stage retractable rod system, ultimately resulting in reduced construction time and enhanced worker safety. The Tung Chung East reclamation project stands as a prime example of the successful implementation of deep cement mixing (DCM) in large-scale reclamation projects.

8 Declarations

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