Marine Deep Cement Mixing: Cutter Soil Mixing Technique

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ABSTRACT

In recent years, marine deep cement mixing was widely adopted in Hong Kong as the ground treatment method for many mega reclamation projects. Compared to the traditional dredging method, the deep cement mixing method is renowned for its environmentally friendly and high-quality standard. The installation of the deep cement mixing works will generate less vibration to the surrounding and prevents bringing the toxic material into the open water. Also, the deep cement mixing can provide a stable foundation for the land formation and comparatively less settlement is expected. The Cutter Soil Mixing technique is a type of deep cement mixing method. It is developed based on the Hydrofraise Cutter technology, crushing the soil through two counter-rotary cutters, and simultaneously mixed with a slurry binder to achieve the contract required strength. This paper presents a recent ground improvement project in Hong Kong with the application of marine Cutter Soil Mixing technique. Several essential working parameters such as mixing factor, dosage design and the criterion to achieve the top of competent stratum for the Cutter Soil Mixing installation are discussed. In addition, real time supervision and monitoring system by using a set of sophisticated instruments are introduced. The environmental considerations and measures of the project are also presented in this paper.

Keywords: Deep cement mixing, Cutter Soil Mixing, GEOMIX, Low Headroom, Marine Works, Advanced Monitoring

1 Introduction

Deep cement mixing (DCM) technique is being used over decades to improve the properties of in-situ soil. Unlike other replacement or displacement methods, DCM mixes cement into the ground without generating large volume of spoil. The three critical success factors are efficiency of mixing, reliability of the mixed soil and sustainability.

Bachy-Soletanche, as a specialist geotechnical solution provider, has developed its patented DCM system (namely GEOMIX®). It is a deep cement mixing process using Hydrofraise Cutter technology which is also called Cutter Soil Mixing (CSM). Geomix has been used worldwide in various geotechnical applications such as retaining walls, cut-off walls, mitigation of liquefaction hazards and soil improvements. Since 2014, the first deep cement mixed soil block was constructed in Hong Kong by Bachy Soletanche Group Limited (BSG) to strengthen the soft soil as a plug in front of the launching shaft for two large diameter (remarkably 14m and 17.6m) Tunnel Boring Machines (TBM) to break-in. In the following years, DCM has been used extensively in the reclamations in Hong Kong and is recognized as one of the most environmentally friendly choices for ground improvement. It not only avoids the disturbance to the marine environment induced by dredging marine clay, but also shorten the time taken for the stabilization of newly reclaimed lands. This paper presents a recent Hong Kong project in which BSG has successfully completed the biggest size of CSM project ever, with over 92,000 nos. of marine CSM panels (over 5.1 million m^3 of CSM treatment), without exceeding the low head room limits set by adjacent operating airport. The team worked 24hours/7days in 33 months, started with 2 barges from Oct 2016 and increased to 16 barges at the peak production period.

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2 Background of the Project

The project presented in this paper is the soil improvement works using CSM technique to strengthen and stabilize the in-situ soft marine clay without dredging them away from the seabed. Avoiding any dredging prevented the adverse disturbance to the ecology of the sea environment in particularly the dolphins living close to the area of the proposed reclamation. Part of the proposed reclamation area had been used as the dump site for dredged marine clay which were packed in geotextile and known as Contaminated Mud Pit (CMP) in the past. This CMP may also be hazardous to the ecology. A protective system of silt curtain together with a real-time monitoring system of the appearance of dolphins have been adopted to achieve the environmental protection standard.

With respect to the headroom limitation (as low as 6.8m from the design highest sea level) in related to the aviation operation of the adjacent airport, all machines working on barges had been monitored by the tailor-made digital devices which were able to send alert and alarm warnings to the control teams if any booms of cranes or any parts excesses the height limit at the specific controlled locations.

Figure 1: Marine CSM working in low headroom condition

In order to shorten the stabilization time period as well as to reduce the residual settlement of the proposed reclamation to facilitate earliest commencement of the construction of seawalls and other permanent structures, CSM had been designed in pattern of individual rectangular panel of size of 2.8m x 1.2m (with cross sectional area of 3.36m^2) with different replacement ratio or in groups of overlapping panel walls to suit the corresponding load bearing and deformation performance requirements at different zones. Figure 2 below shows those different panel arrangements. The typical CSM treatment started from a thin layer of sand banket overlaid above the soft marine clay (from -6mPD to -15mPD, moisture content 75% to 95%), and penetrated through the soft Alluvium (soft to firm silt/clay, moisture content 30% to 75%). The termination criteria of CSM in the project was in general about 2m penetration of competent alluvium stratum (firm and stiff silt/clay, cone end resistance q-c of 1MPa to 2MPa), with a CSM treatment depth averaging 17m below the existing seabed.

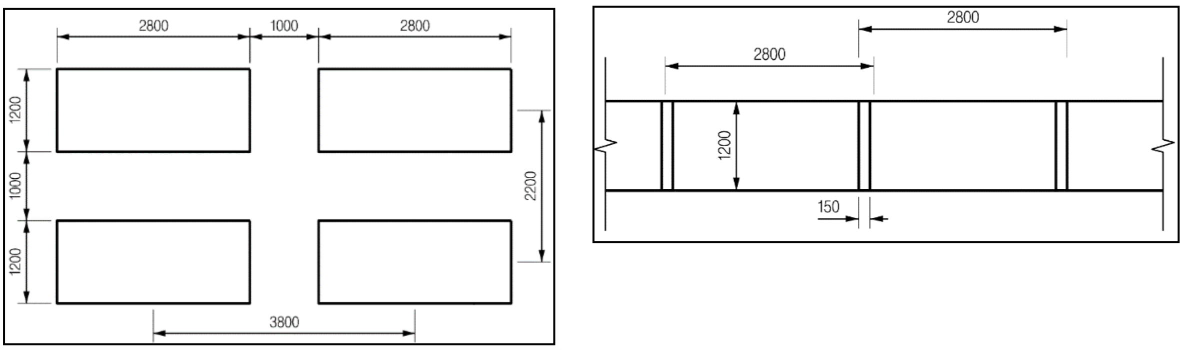

Figure 2: Typical CSM panel: Individual Panel (left) and Panel Wall (Right)

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The predicted properties of the CSM are measured and controlled under the contract quality plan by the Contract Required Unconfined Compressive Strength (CRUCS). In the project, 90% of the tested samples were required to achieve the minimum CRUCS of 0.8MPa to 1.2MPa, depending on the design requirement at various zones.

3 Marine Cutter Soil Mixing Technique

3.1 Introduction of CSM

The Cutter Soil Mixing (CSM) technique is a type of deep cement mixing method. It was developed by Bachy Soletanche derived from the Hydrofraise Cutter technology used in the construction of diaphragm walls. Figure 3 shows the Low Headroom Deep Cement Mixing tool (LHDCM) used on this project. On this equipment, the two counter rotary cutters disaggregate the in-situ soil, and simultaneously mix this soil with a slurry binder to produce a cemented compound with higher strength and stiffness than the original in-situ soil.

The cutter drums and the hydraulic motors were designed to optimize the mixing of ground in place with grout injected to reinforce the ground. As the hydraulic motors are embedded into the cutter drums and to be lowered to the treatment layer during mixing, it gives out direct power to the mixing operation and guarantees a very homogeneous material to be obtained under a relatively low cement consumption. In addition, as the mixing tool is mounted on the cable wire together with the Kelly bar, its center of gravity ensures very low deviation with good verticality and offset control.

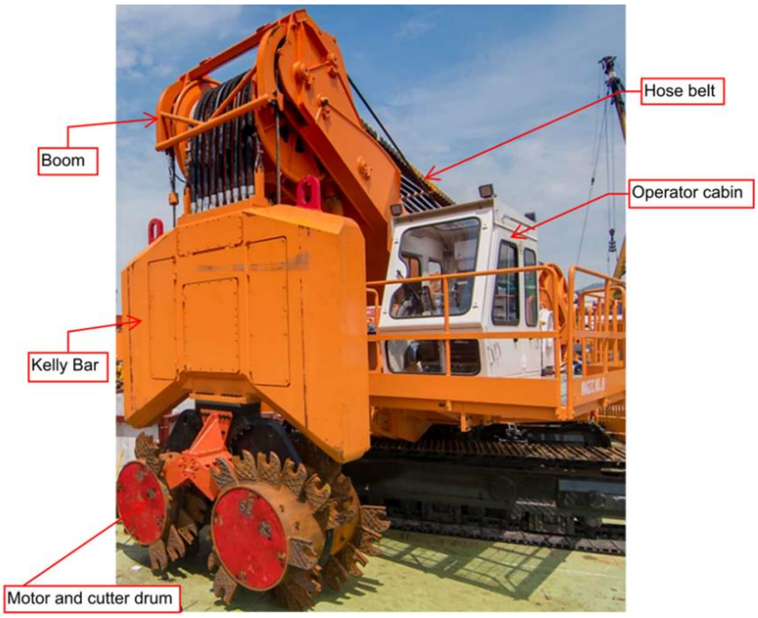

Figure 3: CSM Type Low Headroom Rig

In this project, with respect to the specific site condition, the marine base CSM rig was designed by Bachy Soletanche to work in a low headroom condition of as low as 6m in height, with the reachable depth of around 40m below deck. Moreover, based on the real situation, by extending the length of the hose belt and cable wires, the capacity of the CSM rig can reach a depth of 60m or over, while maintaining the same low headroom condition. The rig was flexible in height and compact in size, and fast in production as no connecting of drill rods was required throughout the entire CSM panel installation.

Each equipment was installed on a barge, together with a set of grout batching plant and horizontal silos, as shown on figure 4. Each barge was positioned with a system of winches and anchors with the assistance of a GPS positioning.

Figure 4: CSM Type Low Headroom Barge

On this project, the installation of a CSM panel was divided into two following phases:

a. Penetration Phase

The purpose of the penetration phase was to pre-mix the soil thoroughly and get ready for the withdrawal phase of the CSM operation. Once the CSM rig has been set up at the desired treatment location, the cutter started to penetrate and mix the in-situ soil with water injection. The incorporation of water was aimed to facilitate the mixing of the in-situ soil into a relatively homogeneous state, especially for the stiffer soil layer such as stiff alluvium. Thus, it was important to control the amount of water injection during this stage; too less water would make the soil difficult to mix with cement and hence decrease the degree of homogeneity, however, excessive water injection would weaken the final strength of the treatment.

b. Withdrawal Phase

After the cutters have reached the required bottom level of the CSM panel, the withdrawal phase began. During this phase, a cement binder grout was injected between the counter-rotating wheels and mixed with in-situ soil. The volume of cement grout delivered was determined to achieve the required strength. An extra volume of grout was required at particular depth in case excessive water volumes were introduced during the penetration phase. Same as the penetration phase, rotation speed, advancement rate of the cutters, together with the dosage design were pre-determined before commencement of the permanent works installation.

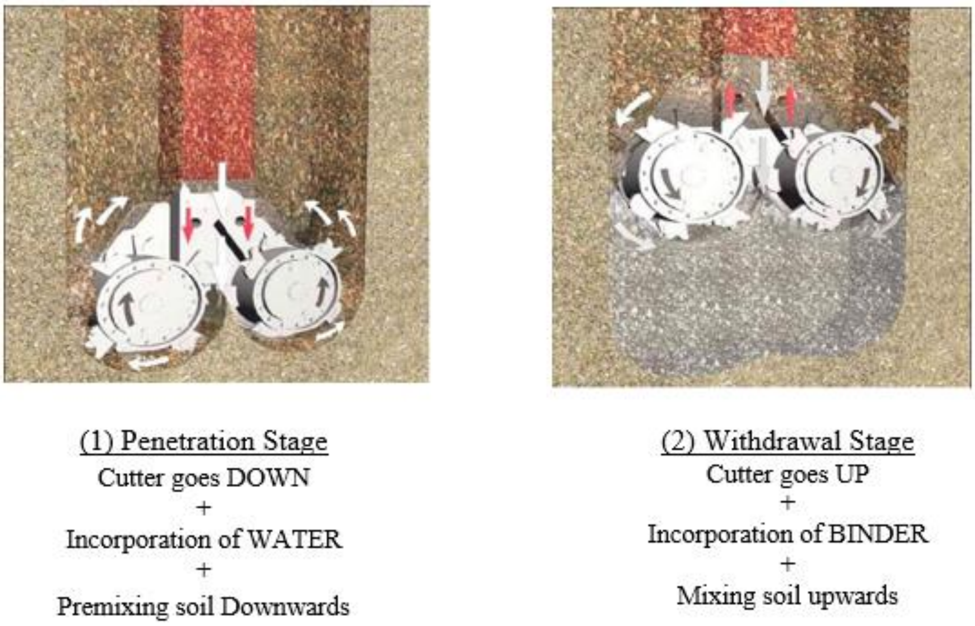

Figure 5: Mechanism of CSM operation

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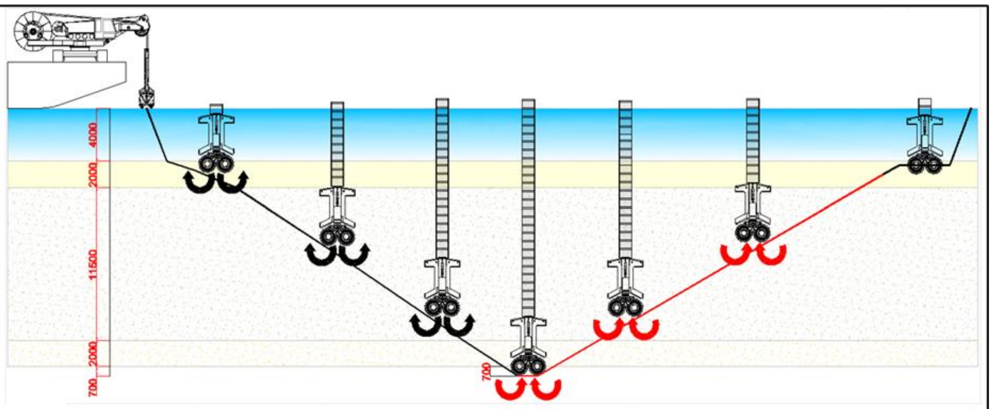

	1	2	3	4	5	6
Sequence	**Positioning**	**Penetration of soft layer**	**Penetration of stiff layer**	**Bottom cement slurry injection**	**Withdrawal with cement slurry**	**Rotate mixing wheels within sand blanket**
Procedure	Set mixing wheels to the exact position and confirm the vertical stability	Penetration by mixing wheels with normal rotation and moving speed	Cutter penetration until the Hydraulic pressure reaches Required bars for continuous 10 seconds. Go further 2m down to achieve the panel toe level	After confirm founding level, start cement slurry injection for replace seawater inside hose system. (30s ~)	After bottom cement slurry injection, withdrawal of mixing wheels with reverse rotation and injection of cement slurry until 1m below top of sand blanket	Upon completion of the LHDCM panel, lift up and rotate mixing wheels within sand blanket before raising into the water
	Mixing-down phase (seawater injection)			**Mixing-up phase (cement slurry injection)**		

Figure 6: Standard Installation Procedure of CSM

3.2 Working Parameters

Several working parameters were essential for the success of this operation and needed to be closely followed. In the below sections, these working parameters are presented and discussed.

a. Mixing Factor

The CSM tool is mainly composed of 3 main elements: cutting drums powered by the hydraulic motors, cutter blades and the scrappers. When a drum rotates, the scrappers fixed below the Kelly Bar interact with cutter blades and shear the soil to facilitate the mixing process. During one single rotation of each drum, the mixing effect by shearing occurs several times as each cutter drum carries several rows of 3 mixing blades each.

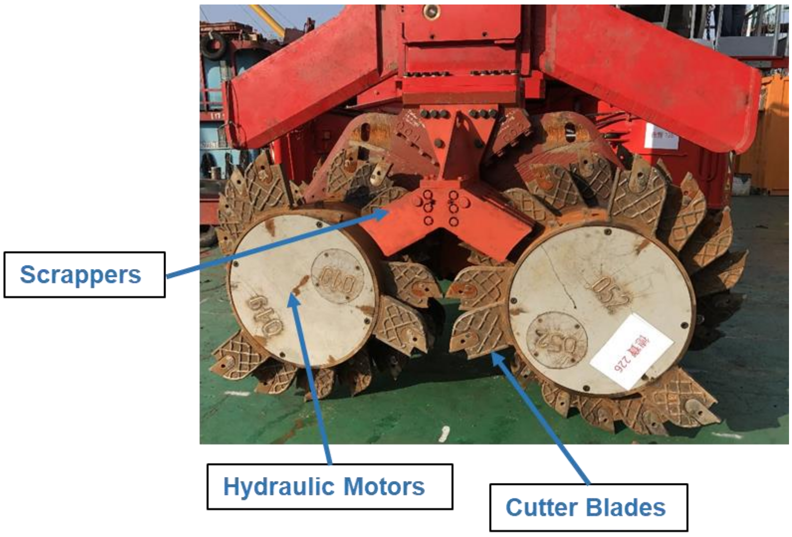

Figure 7: Configuration of a CSM tool

Unlike the standard auger-based DCM tools, the mixing factor with CSM equipment is not directly related to the quantity of blades used. Instead, based on Bachy Soletanche's experience in CSM works, the controlling criteria was the percentage of coverage of the cutter drum surface by sufficient cutter blades. The degree of mixing equation is given on Figure 8. The formula takes into account the advancement rates and the corresponding cutter rotational speeds.

$$T_{LHDCM} = \left(\frac{Nu}{Vu} + \frac{Nd}{Vd}\right)$$

Where,

T_{LHDCM}: mixing factor for LHDCM works

N_u: Rotation speed in rpm of the blades during withdraw

V_u: Mixing blade withdrawal velocity

N_d: Rotation speed in rpm of the blades during insertion

V_d: Mixing blade insertion velocity

Figure 8: Mixing Factor equation for CSM works

As the in-situ soil represents a significant part of the final mixture, the homogeneity of the deep cement mixed material may follow a log-normal statistical distribution of compressive strength driven by a ratio between standard deviation and average value, also called Coefficient of Variation (COV). As reported in the *Design of Deep Mixing for Support of Levees and Floodwalls*[1], the strength of the deep mixed ground has relatively high variability, with coefficient of variation ranging from 34% to 79%, with an average value of 56%.

Classically, any COV should be linked to a given value of mixing factor.

However, based on the experience of Bachy Soletanche's previous projects, the coefficient of variation for CSM works generally lies between 30% to 40%, with a corresponding mixing factor being achieved at various soil condition. The relatively lower COV credits to the mixing mechanism of the CSM tool, which is in direct contact with the soil and does not allow any soil particle to stay in place. This enhances the quality and homogeneity of the treated soil when treated with CSM.

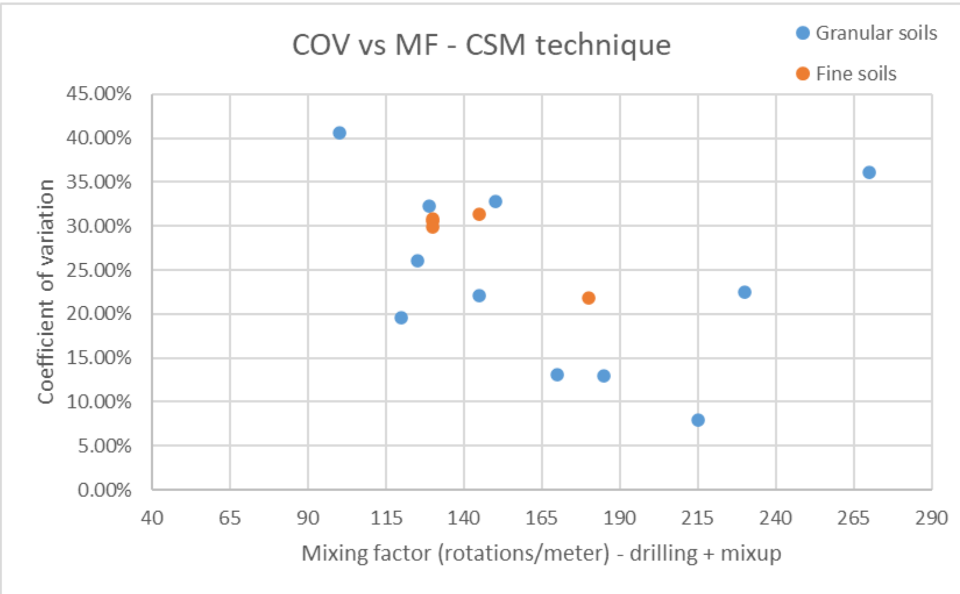

Figure 9: Few examples of COV vs Mixing Factor with CSM

b. Dosage Design

Dosage design is usually defined by the ratio between the dry binder mass incorporated into one cubic metre of DCM element. In practice, this value is related to the injection volume of binder to the treatment and will have a great impact on the final product strength.

Basically, the cement dosage depends on: (i) Type of cement and quantity of cement, (ii) Type of in-situ soil and its properties, (iii) the method of mixing treatment.

Few additional factors were considered when designing the cement dosage, such as the natural water content of the soil, organic content of the soil, water/cement ratio of the grout, level of confidence of the contract requirement uniaxial compressive strength to be achieved, the coefficient of variation of the mixing and the factor between the laboratory strength and the field strength.

A balance between all these factors was made to obtain the most appropriate dosage. As the dosage design is sensitive to site-specific factors, it was required to start with a laboratory test and to be followed by a site field trial.

In this project, various soil samples along the site area were obtained by Vibrocore at different depth. Properties tests such as Atterberg Limits, natural moisture content, bulk density, particle size distribution, pH value, organic matter content, etc. were performed. According to the ground investigation report, the soil samples were classified into 3 main categories: high moisture content marine deposit, low moisture content marine deposit and alluvium. Then various preset volume of seawater and binder grout were mixed with these soil samples to simulate the real mixing situation on site. According to the specification, 5 nos. of proposed dosages with different binder types were tested for a given Contract Required Unconfined Compressive Strength (CRUCS).

According to *The Deep Mixing Method*, Kitazume mentioned that "*usually the in-situ stabilized soil column has smaller average strength and larger strength deviation than those of the laboratory specimen*" and in the case of the land DCM, the field strength is generally about one-half to one-fifth for clay and about two-third for sand of the lab strength; while in the case of marine constructions, the UCS of in-situ stabilized soil is almost the same order with the laboratory strength.
A further coefficient of 15% was adopted in this project on the laboratory strength when designing of the cement dosage for the start of permanent works.

Field trials shall be carried out before the commencement of the permanent works to test the capability of the machine and to justify the design working parameters assumptions. Figure 10 below compares the unconfined compressive strengths (UCS) taken from cores samples inside one panel together with the UCS measured during the laboratory trials.

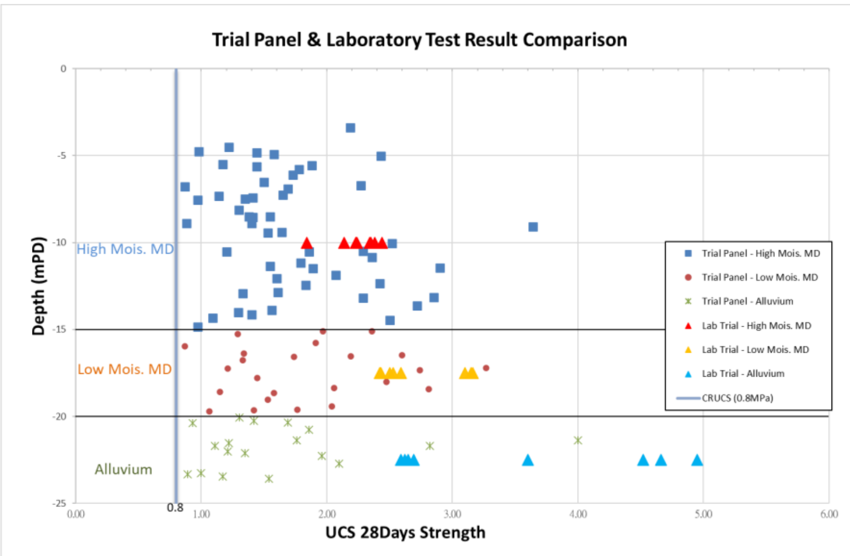

Figure 10: Test Result of laboratory test and field trial for a cement dosage

c. Top of Competent Stratum

In this project, all CSM panels were required to have a 2m embedment into the competent stratum, mainly classified as stiff alluvium with minimum CPT's cone end resistance > 1MPa.

Before commencement of the CSM panel installation, a site mapping of about 100nos. pre-CPT with approximately 100m distance apart from each other was conducted to determine of the design founding levels for each CSM panel. A contour plan with all the analyzed CPT results was then generated for construction purpose.

Besides, during the course of the CSM works, a test called trial insertion was conducted periodically to re-calibrate the performance of the CSM rigs and to justify the depth of each CSM panel to be or being constructed. The trial insertion system consisted of a CPT being performed at the test panel to compare with the CSM rig's response when encountering the top of the competent stratum. It was understood that the cutter wheels of the CSM machine would have a significant change of hydraulic pressure when encountering a comparatively stiffer material. With various trials at different locations on site, the relationship between hydraulic pressure with time and ground condition at the competent stratum could be established. This was a site-specific criterion and shall be assessed on each project.

3.3 Environmental

Compared to the traditional dredging method, CSM method was a more environmentally friendly method where the soil was mixed in-situ preventing toxic material of the contaminated soil being exposed into the water.

During the CSM installation, few environmental measures were implemented.

a. ***Sand Blanket:*** A layer of 1m to 2m thick sand blanket was placed on top of the existing seabed as an insulating capping layer. The purpose of the sand blanket treated as a capping layer was to prevent any excessive toxic material being released into the open water. Upon completion of each CSM panel, the cutter spent at least 5 minutes to rotate within the sand blanket to wash out and to remove the muddy mixture on the cutter before retrieving back on the deck. In addition, this capping layer helped to ensure the treatment quality for the top few meters of the soil as it prevented any excessive seawater being introduced into top of the treatment.

b. ***Silt Curtain:*** Primary silt curtain was equipped on each CSM barge. The primary silt curtain system was treated as the major protection. It was surrounding the CSM cutter and was lowered down to the top of sand blanket during each CSM operation. In case there was any exceedance of water quality level during the real-time water monitoring process, the woven geotextile fabric secondary silt curtain enclosing the barge itself was deployed.

c. ***Water quality monitoring:*** Apart from the silt curtain deployment, real time water quality monitoring is adopted for each CSM barge with in-situ continuous and on-site water quality monitoring data during the CSM works throughout the duration of the Contract. Monitoring locations are set up outside the boundary of the primary silt curtain. Sondes are used for continuous monitoring. Data such as salinity, pH value, dissolved oxygen, turbidity will be recorded every 5 minutes throughout the project.

d. ***Use of slag cement:*** The use of slag cement replacement was more sustainable to the environment as it had significantly reduced the amount of clinker, a major component of Ordinary Portland Cement. This lead to consume less energy for production and reduced by 380,000 tons the carbon footprint of the whole project. Moreover, as the strength achievement of slag cement was higher than that of OPC with the same dosage, we further managed to use less cement binder in the CSM treatment for the same final quality.

e. ***Mammal Observation:*** This project adopted and maintained 24-hour stations for implementing the Dolphin Exclusion Zone (DEZ) to minimize the impact on the Chinese White Dolphin. DEZ of 250m distance from the boundary of the works area was established during the CSM works. An innovative CCTV system was set up on the CSM barge to cover all sea surfaces within the DEZ as the monitoring stations. A group of minimum 2 numbers of well-trained dolphin observers were monitoring the process through a high resolution and zoomable network camera at a centralized monitoring office.

3.4 Supervision and Monitoring

As each low headroom barge working on sea was far away from the central site office, they were treated as a single remote site. A set of sophisticated instruments with the software developed by the team were installed on each CSM rig for data recording and monitoring to ensure the quality of the CSM works shall achieve the contract requirement.

Figure 11: Instruments on CSM rig

On each CSM rig, a customized interface with all necessary parameters presented in graphical format were displayed on screen and enabled the operator to keep track of the current working status and have a full control of the CSM installation. These displayed graphs and figures were designed in accordance with the working parameters in the contract requirement and specification. During the CSM operation, these visualized graphs and figures were shown in eye-catching color. In case of any requirement that are not being achieved, warning messages appeared on the screen to alert the operator for immediate corrective actions accordingly.

Figure 12: Graphs/figures during Penetration stage (left) and Withdrawal stage (right)

At the same time, the data was automatically transmitted to the Cloud where the whole installation process was recorded and saved. Real-time supervision works of all working rigs was centralized and monitored through the software at the remote main office. In addition to the front-line engineers, a team of monitoring engineers managed and supervised 24 hours per day to ensure the CSM works were in full compliance to the contract requirements. Hundreds of completion reports were automatically generated from the Cloud storage and cross checked before submission to the client within 24 hours after completion.

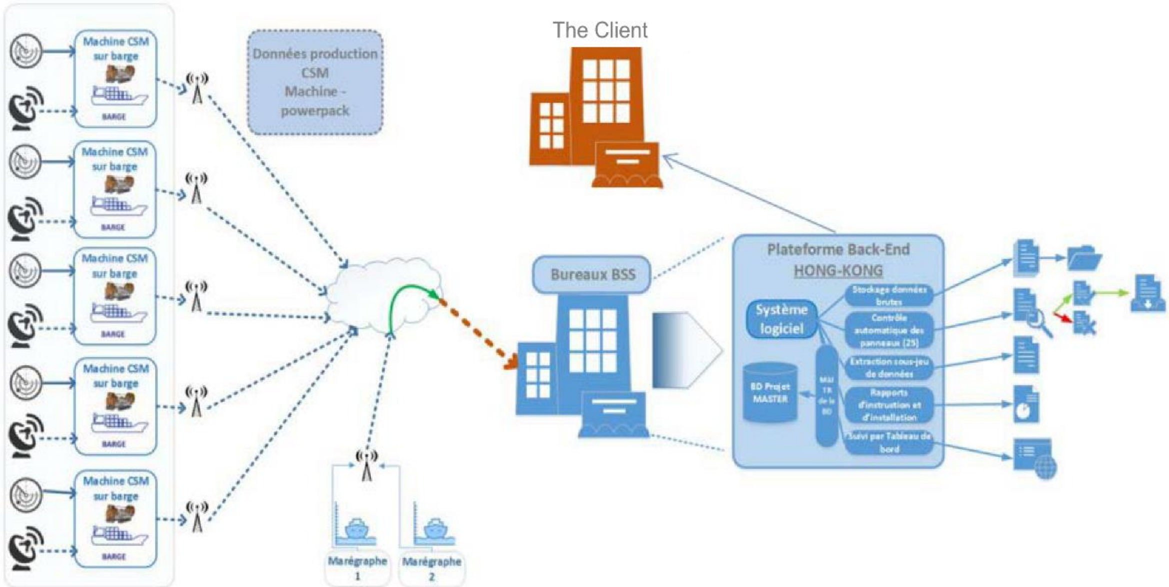

Figure 13: Transmission of data

In terms of analysis, data were retrieved from the Cloud for big data analysis. Throughout the CSM installation process, one line of data was recorded for every 1 second or 2 centimeters of the cable wire movement. The huge amount of data will be handled and organized by a database which allowed stability of data processing and provided a clear and structured organization of the data.

3.5 Quality

Upon completion of the CSM panels, testing works consisted of full depth core and post-CPT were carried out to justify the quality of the treated panel in terms of strength and embedment depth requirement.

a. Coring

Coring was performed to test the strength of the treatment installed by CSM. For the continuous CSM panel wall under the seawall footprint, continuous core sample was conducted at the 150mm overlapping joint of two panel walls; while the core was taken near the center of the CSM panel for those outside the seawall footprint. Under this project, the requirement of the full depth coring was required to carry out according to the following criteria:

Table 1: Contract requirement on coring frequency

Panel Location	Testing Frequency of Full Depth Core	
Seawall footprint	1 test for every 2 panels wall along the seawall chainage	1 specimen for each meter length of core
Outside seawall footprint	~1 core for every 250 CSM panels	10 specimens selected evenly per core

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Around 1,300nos. of core holes were conducted in this project. One of these coreholes is shown on Figure 14. About 95% of the overall UCS tested samples were over 0.8MPa at 28-day strength, which met the CRUCS of 0.8MPa with level of confidence of 90%. A view of the UCS measured on samples in given in Figure 15.

For the Coefficient of Variation, it was observed that at the upper and lower marine deposit, the COV were in the range of 30% to 40%, while the COV in the competent stratum was between 40% to 50%.

Figure 14: Corebox photo of a CSM treated panel

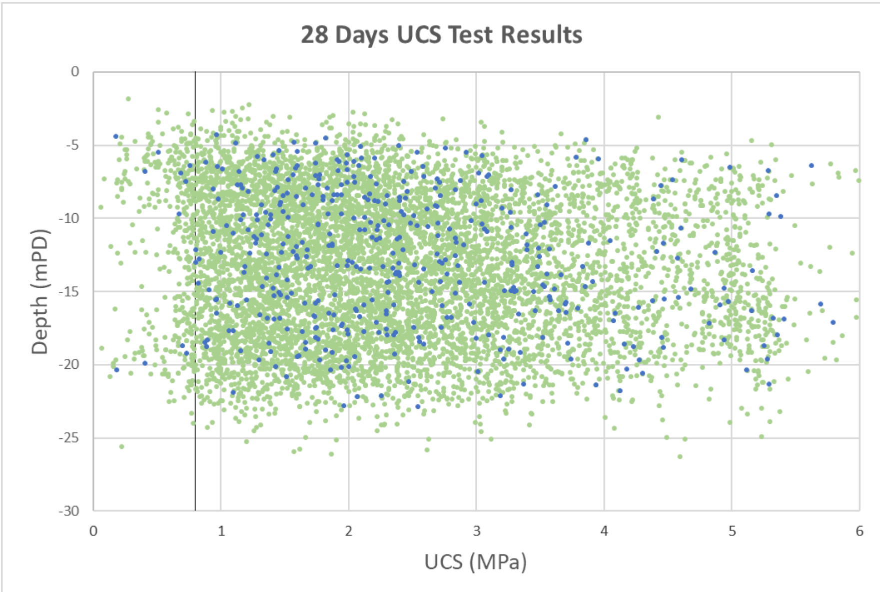

Figure 15: UCS test results

b. Post CPT

Post CPT was carried out at 600mm away from a constructed CSM panel as the proofing test of sufficient embedment into the competent stratum according the contract requirement. Under the contract requirement, the testing frequency is indicated in Table 2 below.

Table 2: Contract requirement on Post CPT frequency

Panel Location	Testing Frequency of Post Cone Penetration Test (CPT)
Seawall Panel	1 test for every 2 panels wall along the seawall chainage
Load Transfer Plate Panel	~1 core for every 100 CSM panels

Around 1,450nos. of post CPT were carried out and all of them were found deep enough with minimum 2m embedment into the competent stratum. In fact, the average toe level between the pre-CPT results, the as-built CSM panels and the post-CPT results were consistent. It further proved the effectiveness of the trial insertion system and the appropriateness of the criterion using the hydraulic pressure of the cutter to define the top of competent stratum.

Figure 16: CPT Test unit

4 Conclusion

The largest marine CSM project ever constructed in Hong Kong containing more than 92,000 panels have been completed. In this benchmarking project, not only the excellent safety performance of the team as continuously appreciated by Client via various safety prizes, but also the quality and environmental management systems are demonstrated to be successful.

The CSM barges and its supporting facilities are all tailor-made designed and fabricated to suit the low headroom requirement of the project.

All the data collected by the digitization monitoring system will flourish our database of Geomix CSM and become our valuable assets for future development of the technology in Hong Kong and worldwide. The contract arrangement, quality assurance framework and testing procedure developed for and improved throughout the project will form good example for the further reclamation projects.

5 Publisher's Note

AIJR remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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