Model Deep Cement Mixing Specification for Hong Kong

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ABSTRACT

Reclamation outside Victoria Harbour is one of the multi-pronged approaches of increasing land supply in Hong Kong and tops the agenda of the current-term Government of HKSAR in order to build up a land reserve in the long run to solve the housing problem. The Government has been proactively pressing forward studies for such new reclamation projects as in Lung Kwu Tan and Ma Liu Shui, in addition to those for Kai Yi Chau Artificial Islands and North Lantau. This calls for cost-effective planning, design and construction practices of reclamation works in Hong Kong in order to expedite land production in meeting the vision set in the Hong Kong 2030+. The Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) has taken steps to work hand in hand with practitioners, academia and relevant government departments to consolidate the experience gained from the recent reclamation projects in the territory to enhance the design and construction practices. Focus has been put not only on enhancing the quantity, speed, efficiency and quality of reclamation works, but also promoting the adoption of the latest smart technologies and green construction materials to set a new norm for sustainable development. The first deliverable is the model specification for deep cement mixing (DCM), a prevailing ground improvement technique used in non-dredged reclamation. This paper discusses the rationales and considerations behind the enhancements on the DCM construction specification that could benefit future reclamation projects, and moreover, the planning of and actions taken by the GEO in developing a state-of-the-art while practical local design and construction guide for different reclamation methods and ground improvement techniques.
Keywords: Deep Cement Mixing

1 Introduction

Hong Kong had undergone a series of reclamation operations along the shorelines of Victoria Harbor since the 1850s to expand the Hong Kong Island and Kowloon Peninsula for accommodating a growing population, where these reclaimed lands underwent fast urbanisation. Reclamation has added about 6,500 hectares of land to the original land area of Hong Kong. Since the enactment of the Protection of the Harbour Ordinance in 1996, the pace of reclamation has been substantially slowed. In a bid to meet the ever-growing housing needs of society, the Government revives reclamation as an important strategy for the long-term land supply, as it can provide vast tracts of new land for development. Figure 1 summarises the reclamation works done in the past and the planned reclamation projects in the coming years. Moving on from the conventional dredged reclamation method, the reclamation techniques have evolved significantly over time, with new technologies and methods being developed to improve the sustainability and efficiency of land reclamation. The DCM method adopted in Tung Chung East Reclamation project, for instance, advanced the completion of reclamation by about 6 months when compared with the conventional drained method using prefabricated vertical drains and surcharging; saved around 6 million tonnes of fill material due to reduced replenishing settlement; and reduced 3,000 vessel trips passing through the north Lantau water channel near Brothers Marine Park which in turn

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resulted in less energy consumption, noise and air impacts as well as disturbances to marine habitats (HKIE, 2022).

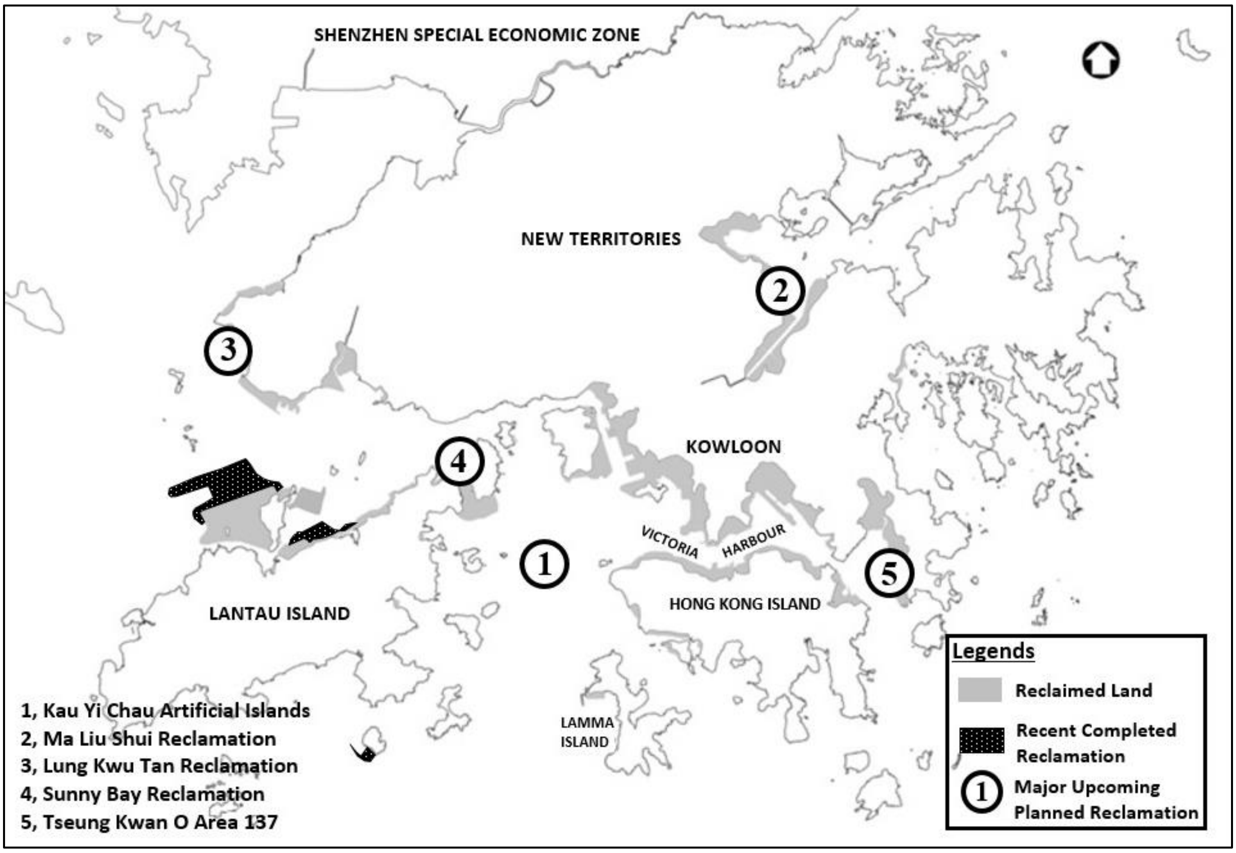

Figure 1: *Major upcoming reclamation projects (CEDD, 2019; PlanD, 2021 , CEDD 2020)*

Extensive use of DCM in reclamation started in around 2016-2017 for the Three Runway System and Tung Chung East Reclamation projects. At that time, the design and construction specifications were largely based on overseas practice and inevitably, conservative and cautious approaches were adopted by the designers and the authority. The experience gained in these large-scale reclamation projects provides an excellent opportunity for Hong Kong practitioners to obtain the domain knowledge in the application of DCM and pave the way for developing a local guidance document that would best suit the Hong Kong setting. As the first step, the GEO is currently developing a model specification and technical guidance notes for DCM works in Hong Kong through joint efforts with practitioners, academia and relevant government departments, which will improve the quality, cost and time required of DCM works. The DCM model specification will form part of the interim Design and Construction Guide with a particular focus on DCM method, which will be available tentatively by the end of 2023. The complete Guide covering broader ground improvement and reclamation techniques is tentatively scheduled for promulgation in mid-2025. In the following sections, key enhancement measures which are to be incorporated into the model DCM specification are briefly discussed.

2 Identifying Areas for Improvement In DCM Specification and Beyond

With the local experience from the recent local reclamation projects consolidated, several aspects of the use of DCM that could be improved have been identified. In addition to the model DCM specification, guidance notes are also produced to supplement the model specification, covering suggestions on key areas in the planning, design, construction and testing stages. The recommendations are prepared in consultation with local practitioners, academia and relevant government departments, with due consideration of the experience and lessons learnt from recent DCM applications in Hong Kong. Moreover, the guidance notes not only detail the rationales of the enhancements, but also aid in setting directions for the GEO to develop the technical guidelines.

The following key areas extracted from the model DCM specification and guidance notes are presented in the remaining parts of the paper.

a) Planning stage: Ground investigation strategy
b) Design stage: Requirement on coring and sampling frequency
c) Construction stage: Use of green binder materials, reuse of heaved materials, smart construction monitoring (digitalisation and automation)
d) Testing stage: Performance-based testing plan

3 Approach to Planning and Design

3.1 Ground Investigation Strategy

Issue identified: For a large-scale reclamation project involving DCM construction, sufficient ground investigation (GI) data for design is essential for smooth and fast construction. However, project delivery schedule is always tight and resources for carrying out marine GI works are usually limited. The designer often faces challenges in producing a robust design scheme with limited GI data. Moreover, some DCM projects in Hong Kong relied on electric current response of mixing rig and adopted post-construction GI works (i.e. performing cone penetration tests (CPTs) after completion of DCM elements) as quality control methods of confirming the sufficient embedment length of DCM element into the competent stratum (i.e. a soil layer that can provide sufficient support for the DCM element without excessive settlement). However, the challenges of this practice were that rig current readings could be easily affected by various site conditions and installation parameters (i.e. workmanship of DCM rig operator and local small obstructions below seabed level) and there could be risk of late revelation of problem by the post construction verification works; any remedial works required would result in a delay in site progress, especially when manoeuvring of marine plants in very often congested site condition was not easy.

Way forward: Sufficient time and resources should be secured in the project planning stage. Together with a proper GI strategy, e.g. phased marine GI as suggested in Port Works Design Manual (CEDD, 2002), acquaintance of sufficient GI information to pre-determine the toe level would be possible with minimal geotechnical risk, thus eliminating the late revelation of abrupt change in geology by post-construction GI works which may have time and cost implications. Nevertheless, it is still prudent to maintain real-time monitoring of the rig current during DCM installation which should only serve as a reference for the engineer on site to verify the pre-determined design toe level. The engineer should intervene only when obvious deviation from expected rig current profile is observed. The concept of pre-determination of DCM element toe levels will be incorporated into the model DCM specification.

The GEO is undertaking studies to explore the use of data-driven tools to leverage on existing geological knowledge and to develop a cost-effective GI strategy by using "machine learning" approach to adaptively optimise locations and quantity of GI works to determine the subsurface geology with minimal stratigraphic uncertainty through the most effective spatial distribution of borehole locations before construction. This concept, which could lead to substantial savings in both time and resources throughout the marine GI works at different phases before commencement of construction works, would later be incorporated into the guidance documents when the "machine learning" approach is developed through a series of hypotheses testing and verification. Should this AI-assisted approach be adopted in the future, this would mean GI planning would shift from "empirically specified" to "statistically based" which is more efficient with higher reliability. The reliance of post-construction verification works such as coring, CPTs and rig current readings could therefore be further minimised and more rational decisions could be made by the engineer in selecting the location of post-construction GI for verification.

3.2 Requirement on Coring and Sampling Frequency

Issue identified: In the absence of local guidelines and experience, the design of DCM works in recent projects was based on overseas guidelines and practices and the construction works were carried out in a more conservative approach to ensure the quality. With reference to recent local DCM projects, approximately 3% to 6% of DCM elements constructed along seawall area in a project were selected for coring. The frequency certainly tops amongst other international practices. Similar situation was also observed in sampling. A comparison between overseas practices and local experiences is given in Tables 1 and 2. As such, the specified coring and sampling frequencies are one of the many examples that designers should focus on to avoid excessive works.

Table 1: *Recommended/Adopted Coring Frequency in Overseas and Hong Kong*

Reference	Recommended/Adopted Coring Frequency
Federal Highway Administration Design Manual	2% to 4% of DCM elements constructed. At a minimum, five DCM elements should be cored, even for small projects (FWHA, 2013).
JTS 147-2017 Code for Foundation Design on Port and Waterway Engineering – Clause 9.3.4.6(3)	Minimum 3 cores or 0.5% to 1% of DCM elements constructed, whichever is greater (MTPRC, 2017).
Overseas publications	3% of DCM elements constructed (Li *et al.*, 2015)
	1 core per 1,000 linear meters of DCM elements constructed, where linear meter means depth along a DCM element (equivalent to 2% of DCM elements constructed*) (Daramalinggam *et al.* 2019).
	1 core is generally conducted for every 10,000m^3 of treated soil (i.e. volume of DCM elements). When the total volume exceeds 100,000m^3, 1 additional core should be conducted for every further 50,000m^3 (equivalent to approximately 0.2% to 0.9% of DCM elements constructed*) (Kitazume & Terashi, 2013).
Local projects	Approximately 3% to 6% of DCM elements constructed.

* Conversion is made by assuming each DCM element constructed is 20m in length and has a cross sectional area of 4.6m^2.

Table 2: *Recommended/ Adopted Sampling Frequency in Overseas and Hong Kong*

Reference	Recommended/Adopted Sampling Frequency
Federal Highway Administration Design Manual	At least 5 test specimens from each full-depth continuous core (FWHA, 2013).
Overseas publications	Samples from 5 representative depths (Daramalinggam *et al*., 2019).
	Core run returned from 3 representative depths and 3 samples from each core run (Kitazume & Terashi, 2013).
Local projects	1 sample per metre core-run along the full-depth continuous core or 10 tests per full depth core sample.

Way forward: A project-specific coring and sampling plan should be determined based on the following key considerations:

a) Project size and complexity;
b) Nature of supporting structures and magnitude of loading after completion;
c) Variability of sub-surface conditions;
d) Variability of deep mixing performance with respect to the level of control and detailing of specifications;
e) Variability of operational parameters and mix design;
f) Workmanship;
g) Confidence level of deep mixing performance; and
h) Economic consequence for subsequent rectification.

It is also worth noting that by plotting the strength test results of cored DCM samples against depth, the general strength characteristics of DCM material in relation to a geological profile can be observed as illustrated in Figure 2.

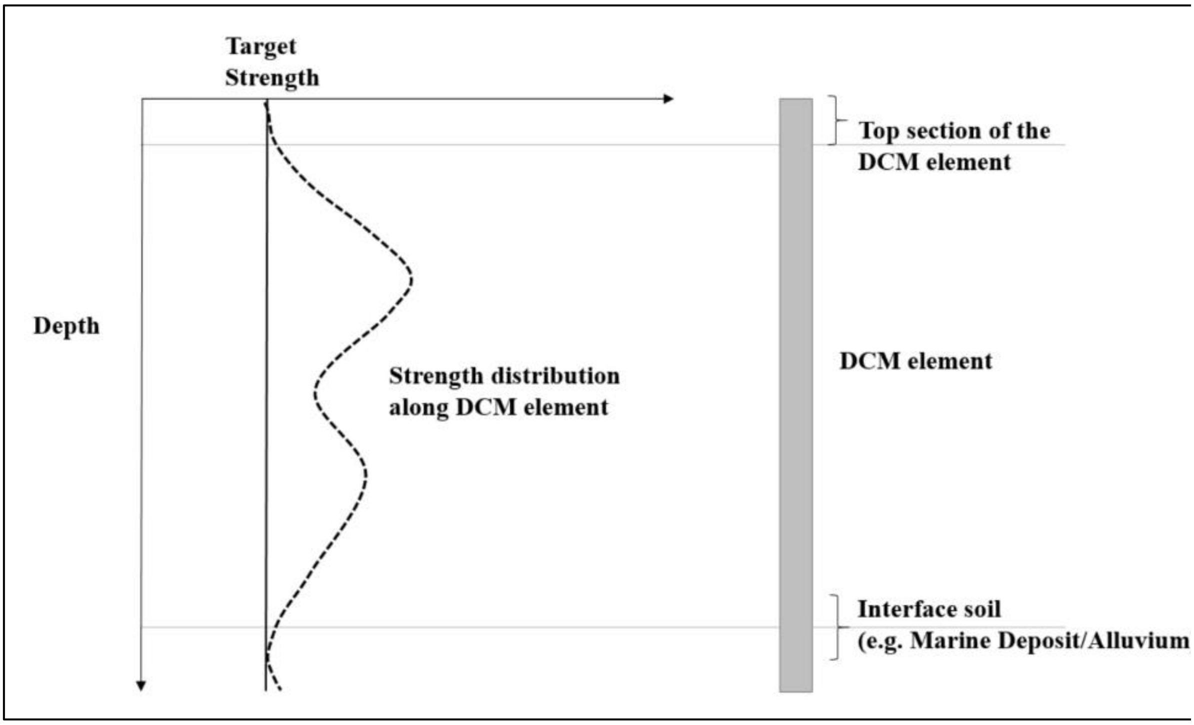

Figure 2: *Example variation of unconfined compressive strength of DCM material with depth*

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With reference to HKIE's Interim Guidelines on Testing of UCS of Cement Stabilised Soil Cores in Hong Kong (HKIEGD 2017), only the correction factors for UCS test results of specimens with a length-to-diameter ratio (L/D) of 1.5 to 2.0 are adopted. The GEO thus carried out further study in collaboration with the HKU (Chung *et al.*, 2022) and extended the L/D range to cover 1.0 to 1.5. With such findings, it is envisaged that greater flexibility will be allowed for engineers on site to select cored DCM samples for UCS testing.

Based on the international norm as shown in Table 1 and 2, general DCM material behaviors shown in Figure 2 and together with a more flexible sample dimension ratio available for strength compliance testing, the location and frequency of coring, as well as the depth and frequency of sampling should be carefully determined to cost-effectively uphold the quality of DCM works. The GEO would continue to study this subject with a view to optimise the coring and sampling frequencies and later incorporate recommendations into the guidance documents.

4 Application of Sustainable Materials and Smart Construction Technology

4.1 Use of Green Binder Materials

Issue identified: Ordinary Portland Cement (OPC) is a typical binder for strengthening of in-situ soils. Its performance and application have no doubt been verified by the construction industry across the globe and is widely adopted, particularly in concrete production. Due to its innate versatility and strength gaining characteristics as a binder material, OPC has been adopted as a binder material to mix with in-situ marine soils to form DCM elements.

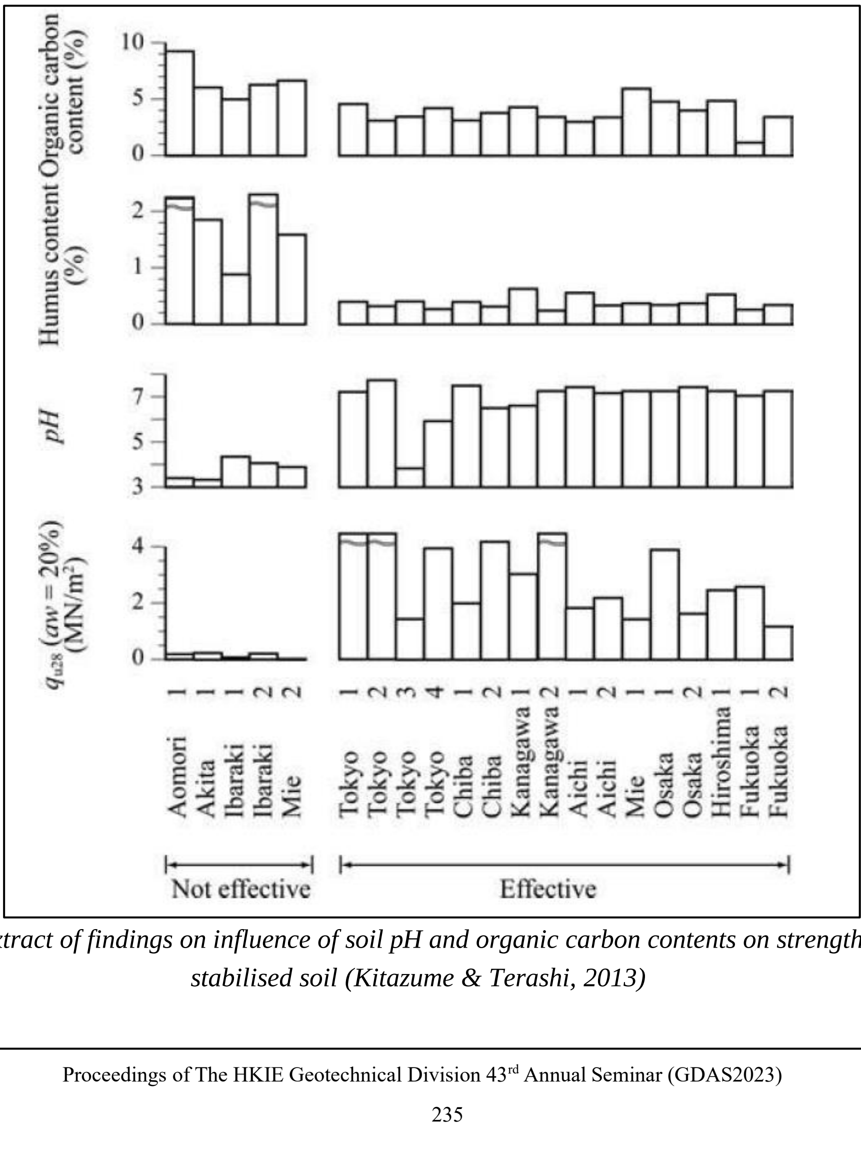

Figure 3: *Extract of findings on influence of soil pH and organic carbon contents on strength of cement stabilised soil (Kitazume & Terashi, 2013)*

However, in view of the large quantity of OPC required for DCM works and the associated high carbon footprint during OPC production, the sustainability of future DCM works should be reviewed. Moreover, the performance of OPC as a binder with in-situ marine soils at different ranges of pH values and organic contents are well documented in the literature (Kitazume & Terashi, 2013). In general, the strengths of soils treated by OPC at high acidity or high organic content tend to be low (see Figure 3).

Way forward*:* Portland Blast-furnace Cement (PBFC), which has been available in the market for a while, is a solution to this problem. PBFC is a homogeneous blend of OPC and Ground Granulated Blast-furnace Slag (GGBS). From the engineering perspective, the good performance of PBFC as a binder mixed with marine deposits or alluvium clay in Hong Kong has been proven in recent reclamation projects. Its performance even surpassed that of OPC (see Figure 4).

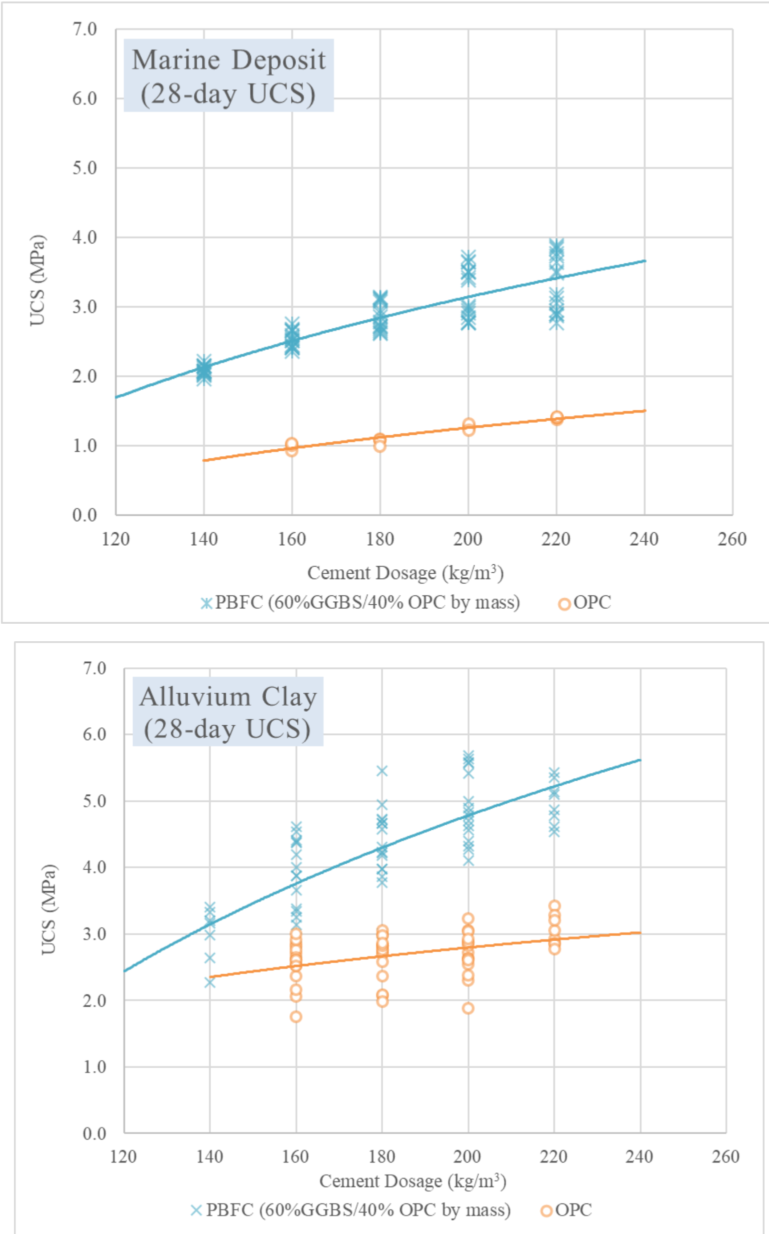

Figure 4: *Comparison of 28-day UCS of OPC and PBFC treated marine deposits and alluvium clay at different binder dosage* (Cheung *et al.*, 2021)

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PBFC because of GGBS is more resistant to acid and organic matters when compared with OPC (Lang *et al.*, 2020). From the sustainability point of view, GGBS, practically "carbon emission free", substitutes a portion of OPC in PBFC. The typical CO_2 emissions arising from the production of GGBS is approximately one sixteenth that of OPC only (Seymour, 2007). In the Tung Chung East Reclamation project, the use of PBFC with 60% GGBS content reduced CO_2 equivalent carbon greenhouse gas emission by around 600,000 tonnes (HKIE, 2022).

In view of the above advantages, adoption of PBFC in DCM works is recommended in the guidance notes. The GEO would also be looking into the possibilities of optimising the dosages of GGBS in PBFC as well as adopting other commonly available sustainable binder materials to replace OPC with an aim to further lowering carbon emission while keeping the required design strength achievable. Findings and recommendations on green binder materials would be duly incorporated into the guidance documents.

4.2 Reuse of Heaved Materials

Issue identified: Heaved materials, a mixture of marine clay, sand and cement formed at the top of DCM clusters after DCM clusters installation, is unavoidable. While the volume of the heaved materials accounts for approximately 70% of the injected cement slurry volume (Kitazume & Terashi, 2013), the volume of heaved materials could be substantial in large-scale DCM works. Typically, heaved materials are removed to prevent the formation of a weak layer in the seawall foundation because of its lower strength. However, the additional cost and time incurred from levelling of the seabed and removal of heaved materials off site are undesirable. Figure 5 illustrates the formation of heaved materials.

Way forward: The first step is to minimise heaving. In the previous projects, DCM cluster top level was terminated at 1m below the top of sand blanket as stated in the contract specification. However, heaving will raise the top level of the sand blanket resulting in getting the DCM cluster top termination level higher and higher. The requirement will be revised in the model DCM specification to terminating the DCM cluster top at a certain distance from a fixed datum, not necessarily the original seabed level, as specified in the drawing. Notwithstanding this, heaving is inevitable and removal of the heaved materials may be necessary in critical location, e.g. beneath the seawall structure. Appropriate treatment (e.g. mixed with suitable fill and/or binder) of the heaved materials can make them suitable for reuse as a fill material in the same main reclamation area. Such a treatment option will be desirable and thus incorporated in the DCM model specification. Chen *et al.* (2022) reported a full-scale test that had demonstrated the performance of the reused heaved materials resulting from high cement dosage, low water/cement ratio, low injection pressure and low blade rotation number near the top of the DCM elements could meet the design requirement as a fill material.

Further study would also be carried out by the GEO to investigate the type of green binder materials that are suitable for turning heaved materials into a suitable fill material. Findings and recommendations would be duly incorporated into the guidance documents.

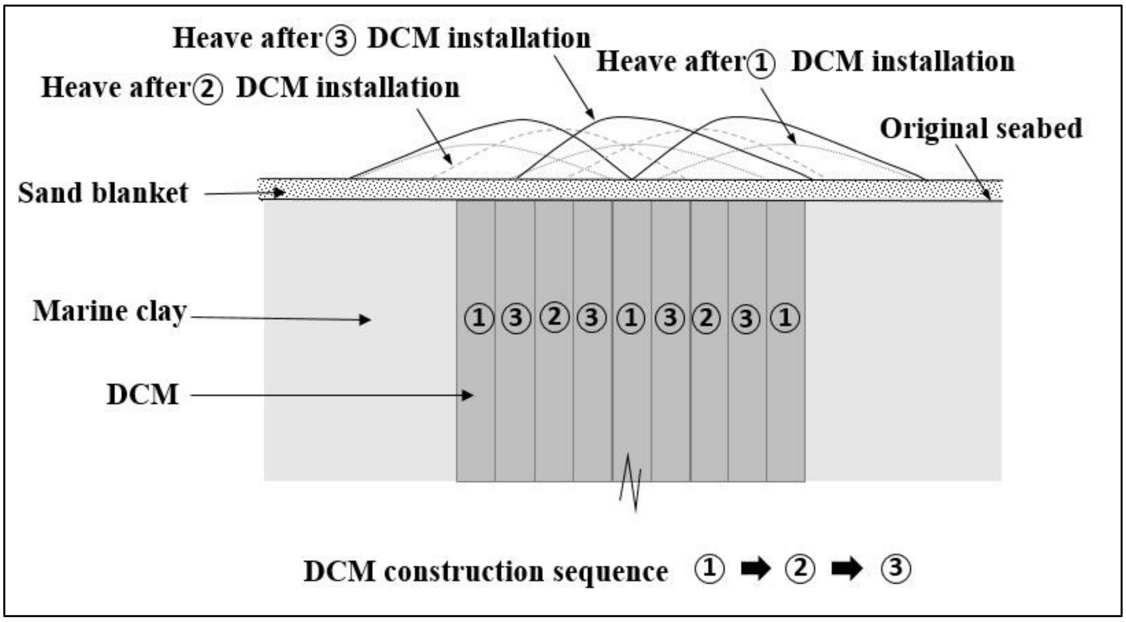

Figure 5: *Formation of heaved material above DCM clusters*

4.3 Smart Construction Monitoring (Digitalisation and Automation)

Issue identified: In a large-scale DCM project, effective data management and communication between the front line and the engineer in site office is often difficult. As such, delays are inevitable and hinder the engineer from providing timely responses to any non-conformity on site, leading to a situation that the quality of DCM works carried out at that instance heavily relies on the experience of the DCM contractor. With a substantial time lapse between DCM installation and data analysis by the engineer, additional maneuvering of DCM plants and time are therefore required in case additional or remedial works are identified. Moreover, without centralising the DCM installation data and analysis results, more resources and manpower from both the contractor and the engineer are expected for continuous monitoring to maintain the high quality of DCM works.

Way forward: With the aim of enhancing the efficiency and the quality of works, it is desirable to provide a project specific digital platform (PSDP) to serve as a common data environment to facilitate seamless and dynamic information exchange on DCM works between the contractor and the engineer. The concept is illustrated in Figure 6. The PSDP should have the following functions:

a) To serve as a hub for the real-time management of DCM works construction records and to facilitate the analysis of the quality of works;
b) To serve as a common data environment to facilitate seamless and dynamic information exchange between the engineer and contractor. In this regard, compatibility with the BIM model specified in the contract is recommended;
c) To monitor the progress of DCM works;
d) To quickly identify some suspicious non-compliance cases for those installed DCM elements not meeting the installation parameters;
e) To provide information to facilitate the engineer and contractor to make decision on the need for any necessary remedial actions; and
f) To support the development of digital twins for the project, if any.

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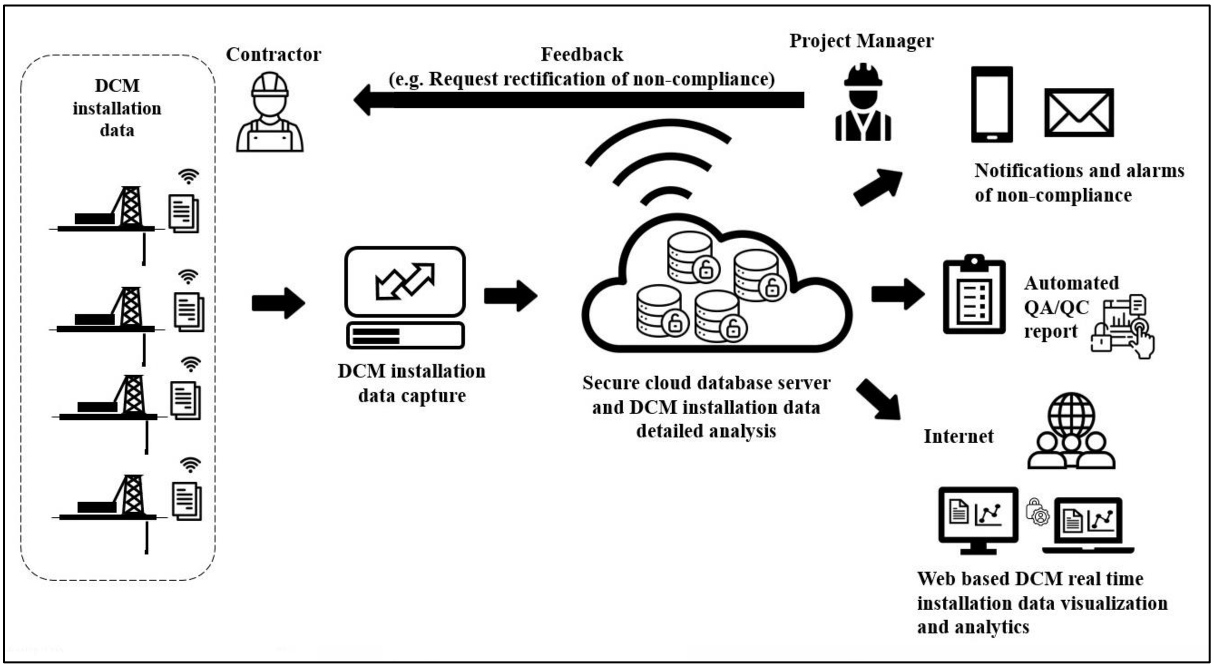

Figure 6: *Real-time monitoring of DCM installation data and feedback*

It is recommended that a set of detailed specifications and requirements on digitalisation (e.g. details on data handling and format standardisation, appropriate computer hardware, system software, servers, security, data backup system, power supply system, fixed broadband internet network communication services, testing requirements and all other necessary equipment, staffing and infrastructures to meet the functional requirements of the PSDP) should be formulated and included in the contract specification. If the situation permits, such PSDP should be developed during the detailed design stage to enable early setup and identification of any follow up actions to be included in the specification. The designer is recommended to work out the implementation plan as soon as the specifications are developed. The employer may also consider the procurement of supporting services to facilitate early establishment of PSDP, and collocating users' requirements for enhancing construction management. The detailed specifications and requirements on digitalisation would be further elaborated in the model DCM specification and guidance documents.

5 Incorporating the material behavior on DCM treated soil

5.1 Performance-based Testing Plan

Issue identified: With reference to Federal Highway Administration Design Manual on Deep Mixing for Embankment and Foundation Support (FWHA, 2013) and the experience in local projects, the design shear strength of DCM treated soil is derived from 28-day UCS with factors applied to cater for different scenarios, applications, strength variability and risk level. On the other hand, it has been well understood that the strength of the DCM continues to increase beyond the 28-day. To arrange the tests to be carried out on the 28-day, coring is recommended to be carried out from the 20th to 25th day for higher core recovery (FWHA, 2013). Under this rigid 28-day design requirement, the contractor always faced the difficulties of planning and maneuvering the coring plants and DCM plants to allow for the coring at the specified day. Moreover, the contractor may tend to, for instance, provide a conservative binder dosage in order to meet the target strength specified in the contract, resulting in a higher construction cost (reflected as a higher tender price).

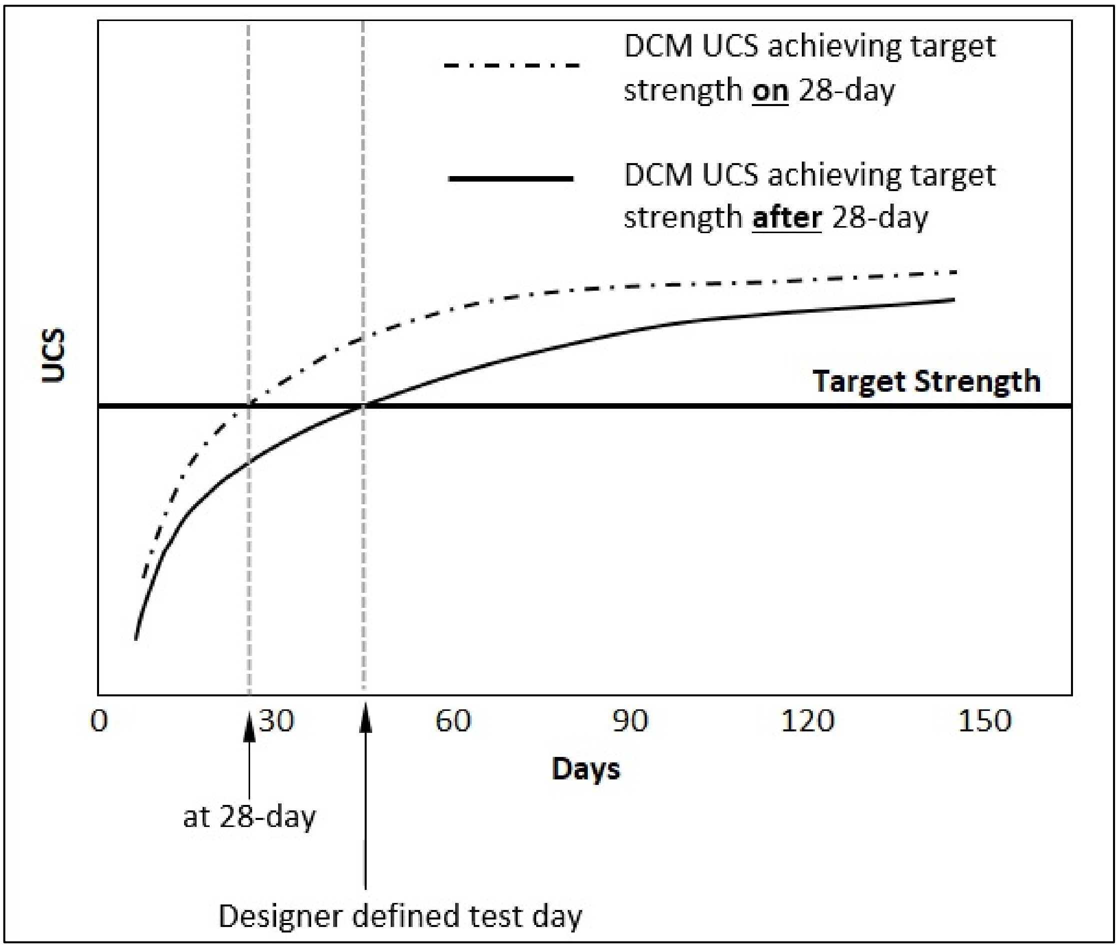

Figure 7: *Designer defined UCS test day*

Way forward: The effect of curing time on strength gain is well documented in the literature and local projects. Whilst the 28-day UCS is adopted in general, the designer may alternatively consider the curing time effect to enhance the cost-effectiveness of design. From the quality control perspective, it is preferable to assess the mixing performance as soon as practicable. In case of non-compliance, corrective measures can be executed and QA/QC system can be reviewed immediately. On the other hand, the tests may not necessarily be conducted on the 28-day from the geotechnical design perspective, unless the construction sequence warrants.

In essence, the periodical DCM plant site trial for performance verification and the associated selected cores could be tested for the 28-day strength as a quality control. The designer may specify the range of curing time and allow the tests to be carried out within a specified period as the design verification. Notwithstanding the above, it should be reiterated that the specified period should not be unreasonably early or late that renders core recovery being infeasible or any defect not recoverable. As an example, if the design shear strength is derived from 1MPa and the subsequent critical activity (e.g. construction of seawalls, reclamation filling, etc.) is anticipated for commencement in 2 months after the completion of DCM works, 1MPa could be taken as the target UCS and the testing period may be specified as from the 28-day to 40-day. The proposed approach not only allows flexibility in construction, but also provides an opportunity for cost savings in relation to the mix design. Figure 7 illustrates the concept with strength-time curves of DCM samples with different binder dosages. The concept will be incorporated into the model DCM specification and guidance documents.

6 Conclusion

The model DCM specification and guidance notes are just the beginning of an effort to enhance the DCM design and construction works in Hong Kong and the first milestone of the GEO to develop a comprehensive local reclamation design and construction guide. Despite these suggestions would only offer modest improvement to the DCM works, it is believed that significant cost and time savings and further reduction in environmental impacts would result in the upcoming mega-scale reclamation works.

7 Declarations

7.1 Acknowledgements

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