Deep Cement Mixing –The Experience in Tung Chung East Reclamation and Challenges Ahead

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ABSTRACT

Reclamation has been the most tenable land supply in the interest of the public. Today, around 27% of Hong Kong people are living on reclaimed land formed in the past decades. Over the past few decades, reclamation methods and ground treatment techniques have been advanced to meet the technical requirements and social acceptance at different times. In response to the increasing environmental awareness of the public, non-dredged reclamation methods in association with Deep Cement Mixing (DCM) has been introduced in Hong Kong. Tung Chung East (TCE) reclamation, as one of the ongoing projects adopting this novel technology, has showcased a role model on assimilation and adaptation of this new technology in tackling ever changing challenges in the construction industry. The success of the project markedly attributes to the application of this new ground treatment technique. In this paper, some background and geotechnical considerations for the adoption of DCM method and design approach in TCE reclamation will firstly be discussed. To date, majority of the DCM works have been completed and the reclamation works have been proceeding well. With the experience acquired and construction data collected at the site specific DCM trial embankment as well as during the construction stage, the merits and benefits of DCM method, in terms of both stability and settlement control, will be highlighted. More importantly, there has been a lot of precious experience upon construction and the project team has ironed out all these hurdles through adaptation of this technology on site. There is no doubt that the documentation of all the experience in TCE reclamation could become a great reference for the development of a local guidance for practitioners in Hong Kong and upcoming mega development projects.

Keywords: Deep cement mixing, Non-Dredged Reclamation, Fast-Track Ground Treatment

1 Introduction

1.1 Reclamation in Hong Kong

In the last century, there was a rapid and continuous growth in population in Hong Kong, from less than 2 million in the 1950s to over 7.4 million in 2020. The stable growth of population at the same time drove a substantial economic growth and transformed Hong Kong from a re-export port with GDP per capita of less than HK$2,400 in 1961 to an international metropolitan with GDP per capita of over HK$340,000 in 2020. The unremitting growth of economy in Hong Kong would not have been possible without the provision of sufficient land to meet the development needs. Out of the numerous land supply options, land reclamation has been the most tenable supply in the interest of the public. Today, around 27% of Hong Kong people live on reclaimed land formed in the past decades.

In the 20th century, there were different land reclamation projects, for example Kai Tak Airport Extension (1957 - 1974) and new town developments. Formation of land by reclamation for new town development in Hong Kong was initiated in the 1970s, including Tsuen Wan, Shatin, Tai Po, Ma On Shan, Tseung Kwan O and Tung Chung etc. (1973 – 2003). Other notable reclamation projects include the Disneyland development at Penny's Bay, Hong Kong International Airport at Chek Lap Kok, and

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artificial island for Hong Kong Port of Hong Kong-Zhuhai-Macao Bridge. Currently, reclamations for the Three Runway System (3RS) at the Hong Kong International Airport (commenced in 2016), TCE and Integrated Waste Management Facilities (IWMF) (both commenced in 2017) projects, with a total reclaimed area of about 796 ha, are in progress.

1.2 Tung Chung East (TCE) Reclamation

The planning and engineering study for Tung Chung New Town Extension commenced in 2012 and the reclamation works, Contract No. NL/2017/03 for the reclamation of about 130 hectares at TCE (Figure 1), started in end 2017 seizing a record of less than 6 years from planning to commencement of works for projects of similar scale. Land formation is completed by phases and and is scheduled for completion in 2023. The first phase involving around 7 hectares of land was completed and handed over for housing development in Q1/2020, that was 27 months from the commencement.

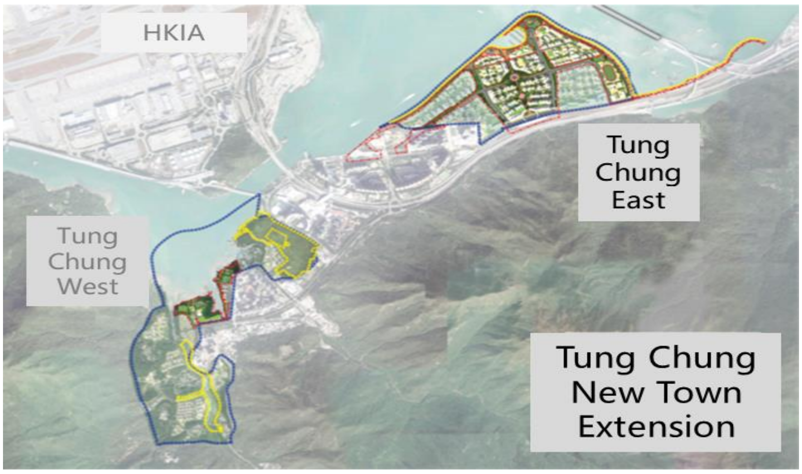


Figure 1: Tung Chung New Town Extension

Concerns over impact of land reclamation on its surrounding environment and ecology are appreciated. While with proper investigation, planning and mitigation measures, it is possible to work out some environmentally friendly solutions to strive for a balance between development and conservation. Over the past few decades, reclamation methods and ground treatment techniques have advanced considerably to meet the technical requirements and social acceptance. In the TCE reclamation project, a new sustainable ground treatment method. i.e., the deep cement mixing (DCM) method has been adopted in non-dredged reclamation.

2 Geology of Tung Chung East

The marine environment in TCE is generally covered by very soft to soft marine deposit of silty to clayey material. The marine deposit is classified as Holocene Hang Hau Formation and the thickness of the marine deposit is generally in the range of 10m to 16m. It is locally about 17m to 18m thick near western flank of the reclamation area. Underlying which is an alluvial layer of Chek Lap Kok Formation, and it is typically between 15m and 20m thick.

Based on results from vane shear tests and unconsolidated undrained triaxial tests, the undrained shear strength (Su) of marine deposit is found to be from 3kPa to 25kPa (Figure 2) and it exhibits an increasing trend with depth as revealed from cone penetration tests. The trend can be expressed as $S_u/\sigma_i = 0.11 + 0.0037\, I_p$ with reference to the empirical relationship between undrained shear strength, effective overburden pressure and plasticity index as given by Skempton (1957). Oedometer tests have been carried out to determine the compressibility of marine deposit and the compression index (Cc) of marine deposits is around 1.0. The over-consolidation ratio (OCR) is generally close to 1.0, whereas OCR is slightly higher, up to 1.5, close to the original seabed level.

The underlying unit is Chek Lap Kok Formation (Strange & Shaw, 1986) which comprises a 10 to 20m thick highly heterogeneous mix of sands, gravels, silts and clays interbedded with each other. The thickness of the formation is typically between 10m and 20m. Cohesive alluvial layers are generally described as firm to stiff, light grey or dark red with orange or red mottling slightly sandy clayey silts, and these softer layers normally have a high moisture content. The plasticity index of cohesive alluvial silts/clays is around 30% with a corresponding liquid limit of around 50%. The undrained shear strength of cohesive alluvial silts/clays is estimated to range from 20kPa to over 80kPa. Stiffer layers generally lie at a deeper depth. Based on laboratory test data, the compression index is from 0.2 to 0.5 that is markedly less compressible as compared with marine deposit. According to previous local experiences such as Endicott (1992) and Koutsoftas et al. (1987), OCR of alluvium can be in the range from 2 to 3. Granular lenses of silty sand with occasional fine to coarse gravels are interbedded with alluvial clays/silts layers. In some areas, dense cobble sized granular layers are present overlying cohesive alluvial layers.

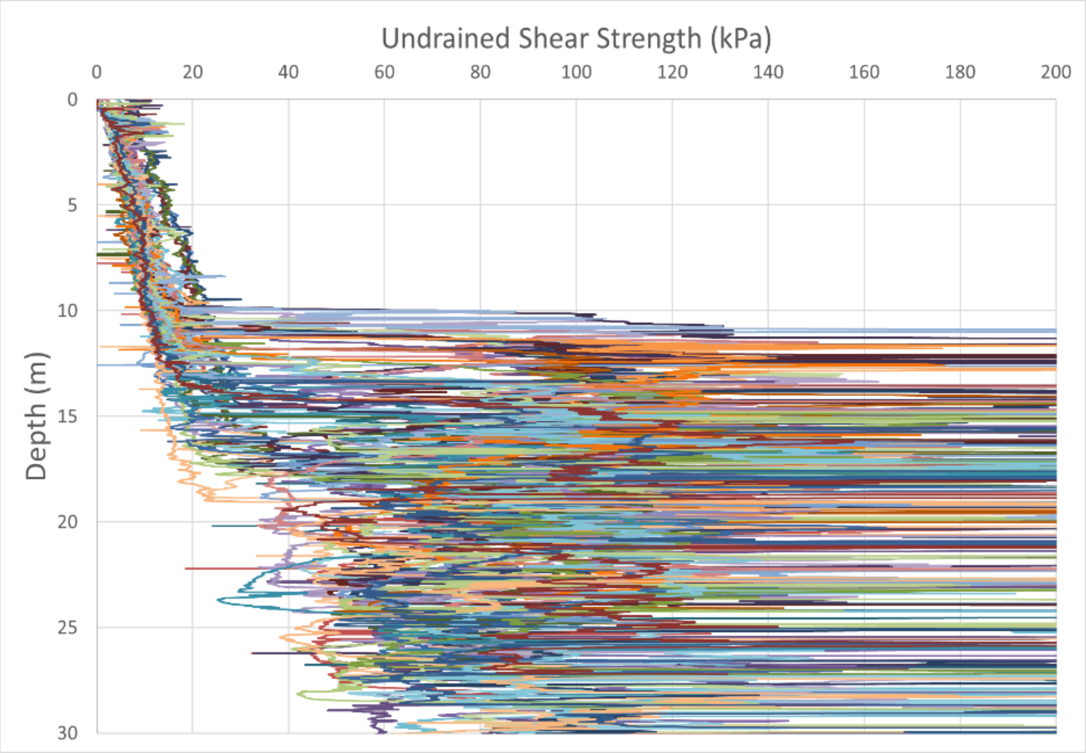


Figure 2: Variation of Undrained Shear Strength

3 Considerations Of Ground Treatment Method

The low shear strength and high compressibility of soft marine deposit and alluvial layers renders reclamation and construction of revetment structures difficult. The major challenges involve stability and settlement control in the course of seawall construction and filling. The soft marine sediment is highly compressible and would exhibit large settlement or even shear failure under the weight of the reclamation fill, if suitable ground treatment is not carried out. In evaluating ground treatment options, a basket of factors including cost, time, robustness, safety and environmental etc. are considered. For soft clay, it is the major challenge to develop a suitable solution to safeguard stability and avoid excessive deformation affecting the functional performance of the structures/utilities etc. during and/or after construction. Three approaches namely, (a) fully dredged method to replace soft sediment with granular soil; (b) conventional drained method to improve soil properties through consolidation, and (c) deep cement mixing method to reinforce soft soil to form a composite material, have been considered.

3.1 Fully Dredged Method

In the old days, soft marine deposit was completely dredged and subsequently filled with sand fill or general fill. While dredging eliminates the engineering problems arising from these soft strata, there is a substantial implication to the environment and society. Disposal of dredged sediment may use up the capacity of disposal sites. In addition, it would generate substantial marine vessel trips for transportation of dredged sediment to disposal pits and import of fill material for backfilling that results in significant carbon footprint. Coupled with the increasing social awareness on environment, it is preferable to adopt non-dredged methods and treat the soft marine sediment in-situ.

3.2 Conventional Drained Method

Conventional drained method has been adopted for decades. Instead of fully removal of the marine sediment, prefabricated vertical drains (PVDs) are installed through the soft compressible soil stratum to facilitate drainage and consolidation. Together with surcharge loading on top, the soft marine sediment layer is compressed to eliminate primary consolidation within design timeframe. Based on the experience in TCE, the estimated consolidation period is normally in the range of 9 months to 12 months that results in a relatively longer construction period. Apart from a longer construction time, previous experience revealed that the performance of PVDs is relatively uncertain in some circumstances, e.g. under substantial ground settlement. Construction time and quality control pose critical factors to the option assessment.

3.3 Deep Cement Mixing

Amongst the approaches considered, in-situ deep cement mixing has the advantage of which it can quickly solidify soft sediment as compared with conventional drained method, whilst removal of sediment is not required. The merits and considerations are further presented in the following paragraphs.

4 Deep Cement Mixing Method

DCM method involves in-situ solidification of marine sediment by mixing with stabilization agent or binder such as lime, cement, or a combination of different binders. Research and development of modern mixing technique commenced in late 1960’s using lime as the principle binder. DCM method was put into practice in Nordic countries and Japan in mid-1970’s. The technique has been recognized worldwide as an effective ground treatment method of soft marine sediment. Major infrastructure project like Haneda Airport at Tokyo in Japan has adopted DCM method as part of its runway extension.

4.1 Design Considerations

The deep mixing technique has been well-established. Factors governing the performance of DCM method can be categorised into 4 key groups (Kitazume & Terashi, 2013) (i) characteristics of in-situ soil, which include physical and chemical properties, organic content, pH value and moisture content; (ii) characteristics of binder, which include binder type, binder dosage and water to binder ratio; (iii) mixing conditions, which include blade rotation number and type of mixing tool; and (iv) curing conditions, which include curing time, temperature and confining pressure along a DCM element. All the above factors can affect the performance of DCM works, which is usually assessed in term of Uniaxial Compressive Strength (UCS) in laboratory. The design UCS is the principle parameter in the determination of the treatment pattern, or the replacement ratio in the design.

4.2 Ground Investigation

Like other geotechnical engineering projects, thorough understanding of geological setting and ground conditions is essential for reclamation. Ground investigation for detailed design of reclamation and ground treatment works was carried out in 2017. Geophysical survey was first conducted to reveal the general conditions of the ground and identify anomalous features on the seabed that might pose potential obstructions to the ground treatment works. Apart from geological units, site history and anthropogenic features are also of interest for the design and construction ground treatment works. Granular soils of cobble / boulder-sized with thickness exceeding 1m embedded within sediment / deposits could pose significant difficulties to the penetration of ground treatment equipment and mixing shaft. The persistence of such obstructions is warranted to be identified during ground investigation as far as practicable, so that the subsequent ground treatment design could cater for such hard crust.

In addition to marine boreholes, in-situ field tests such as cone penetration tests (CPT) and vane shear tests were particularly important for acquiring in-situ engineering properties of the sediment. CPT provided continuous data for evaluating soil profile and properties, which were essential for the design and construction of DCM works. To prepare for reference data for DCM design, a series of laboratory trials were conducted in addition to conventional laboratory tests.

Water content is a prime factor for the chemical reaction of cement-based binder. As revealed from site-specific ground investigation, moisture content of marine deposit is generally from 60% to 108% with an average of around 86% and a higher moisture content near the seabed as shown in Figure 3. For alluvium, moisture content is generally from 16% to 50%, with some outliers up to 84% as shown in Figure 4.

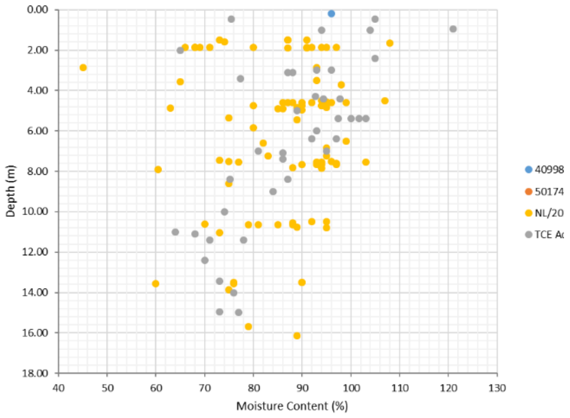


Figure 3: Moisture Content of Marine Deposit

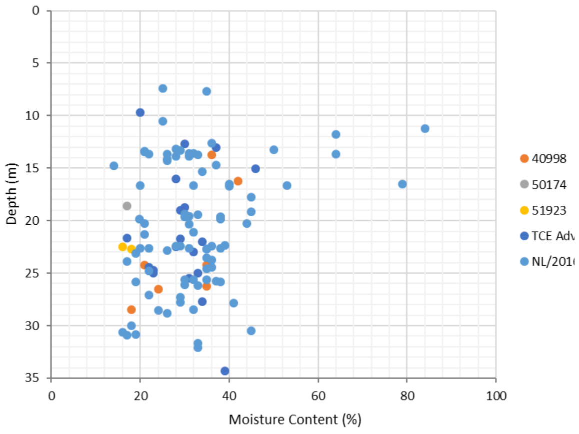


Figure 4: Moisture Content of Alluvium

In terms of chemical properties, the key parameters of interest are the pH value and the organic content of the in-situ soil. The effects of pH value and organic content of in-situ soil have on cement stabilisation are well documented in various literatures (Babasaki et al., 1996). For optimal results, the pH value of the in-situ soil should not be lower than 5, and the ignition loss should not be greater than 15%. Based on laboratory testing results, marine deposit at Tung Chung East are slightly basic with an average pH value of around 8.0 and the ignition loss is around 6%. The chemical properties reveal that treatment with cement-based binder should be effective.

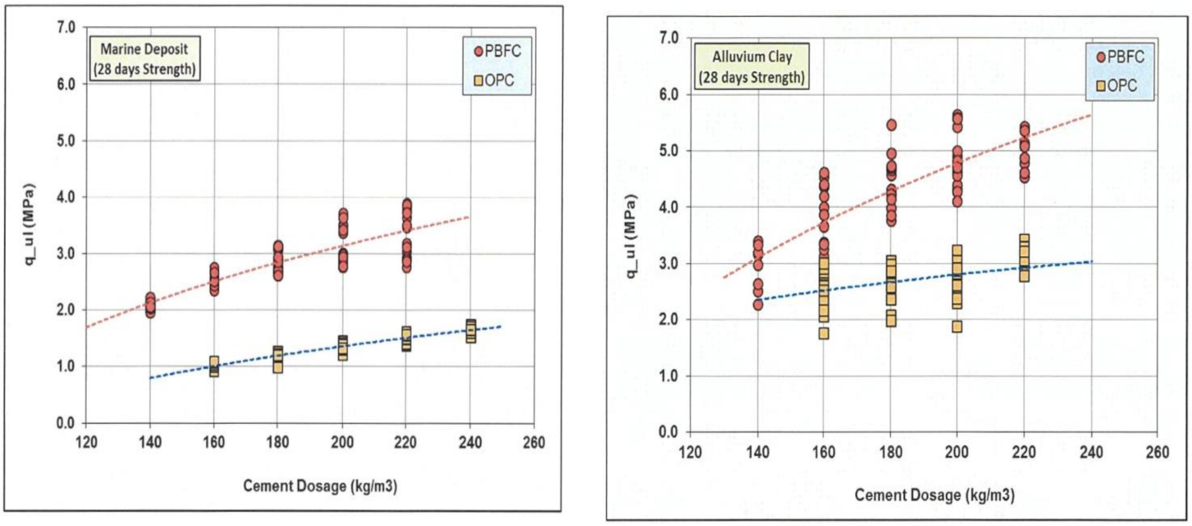
4.3 DCM Laboratory Mixing and Field Trials

The performance of DCM treatment attributes to soil properties, binder dosage and workmanship despite a robust quality assurance and quality control framework. All these mixing parameters shall be developed based on laboratory testing which provides an indication of required dosage and mixability. With the results of laboratory testing, field trial shall be carried out to verify the mixing parameters including the required dosage and cycle diagram etc.

A series of laboratory mixing tests were carried out using the undisturbed soil samples of marine deposits and alluvial clay to develop the mixing parameters. The testing procedures followed the recommendations in Practice for Making and Curing Stabilized Soil Specimens without Compaction (JGS 0821-2009), by Japanese Geotechnical Society.

Ordinary Portland Cement (OPC) is commonly adopted as the binder for modern DCM works but it has an intrinsic drawback for its high carbon footprint. Ground Granulated Blast Furnace Slag (GGBS) is a by-product of steel industry and thus it is not only environmentally friendly for beneficial reuse of this by-product, but also improves overall durability that upholds the end-product resistance to alkali-silica, sulphate and chloride reactions. As an alternative, Portland Blast Furnace Cement (PBFC) has been adopted as the binder for DCM works in TCE reclamation. Specimens were prepared for these two different cement-based binders. The PBFC comprised 40% OPC and 60% GGBS. The reduction in greenhouse gas emission, in terms of carbon-dioxide (CO_2), is remarkable. The carbon emission in the course of production for GGBS is only 6~7% of that for OPC (Higgins, D. 2007).

Over 1400 in-situ soil samples of marine deposits and alluvial clays were mixed in laboratory with OPC and PBFC. Five different binder dosages were tested: 140, 160, 180, 200 and 220kg/m^3 for PBFC, and 160, 180, 200, 220 and 240kg/m^3 for OPC respectively. To evaluate the strength variation of the mixed specimens with respect to binder type and binder dosage, moisture contents of the marine deposit and alluvial clay specimens have been controlled and adjusted to the average value of the respective soil (by addition of water to the in-situ soil). The unconfined compressive strength (UCS) of these laboratory mixed specimens were tested on the 28th day. The results are presented in Figures 5 and 6. It is revealed that for a required strength, the required cement content and thus, embodied carbon, could be reduced considerably using PBFC. For the application at TCE reclamation, using PBFC as the binder for DCM works in this project reduced around 600,000 tonne CO_2 equivalent greenhouse gas emission.



Figures 5 & 6: Relationship between 28th day UCS and Binder Type for Marine Deposit and Alluvium

4.4 Binder Dosage and Water Content

Binder dosage is another important parameter as well as cost component to ground treatment works. Considering the particular shallow water depth site constraint at TCE, it is desirable to adopt a suitable binder and optimise the dosage that can minimise heaving of seabed, whilst the required quality and cost effectiveness can be maintained.

Figure 7 compares the UCS results of marine deposits and alluvial clays mixed with PBFC. The testing moisture contents of marine deposits and alluvial clays were 85% and 40% respectively. The specimens mixed with alluvial clay exhibited higher UCS than those mixed with marine deposit at the same binder dosage. The results attribute to a higher total water-to-binder ratio in marine deposit than alluvium. These results suggest that it is desirable to control binder dosage across different soil stratigraphy to enhance cost effectiveness of the design.

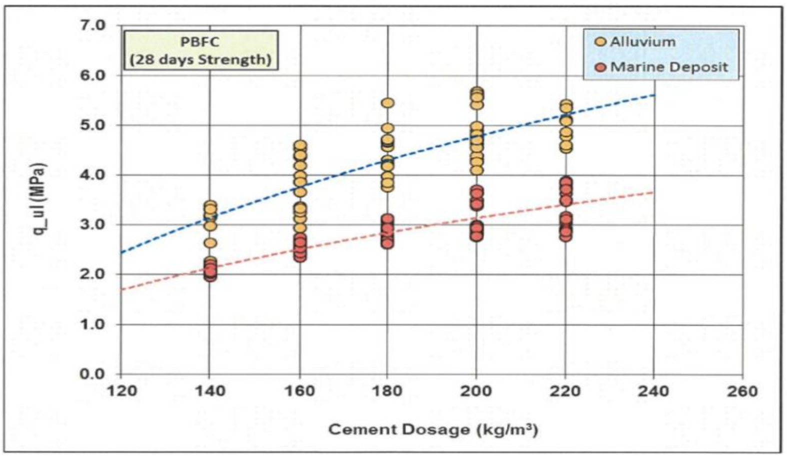


Figure 7: Relationship between 28th day UCS and In-situ Soil mixed with PBF

5 Design Approach

5.1 Design Concept and Approaches

DCM method is an in-situ ground treatment technique to mix soil and binder using mechanical tools to form DCM clusters. For seawall and revetment structures, DCM clusters are commonly overlapped to form wall, grid or block to enhance shear resistance, Figure 8 (Kitazume & Terashi, 2013). In between the DCM wall, cross walls may be constructed to provide lateral restraint and to prevent extrusion failure of soft soil in between two DCM walls. Where stress concentration is identified, short DCM clusters may be constructed as block type locally to enhance the resistance.

The current design practice of DCM treatment in Hong Kong have made reference to both US and Japanese standards (FHWA, 2013 and Kitazume & Terashi, 2013) which follow the limit state approach. Taking into account the uncertainties, partial factors are applied to material strength properties. For the ultimate limit state, both external and internal stability have to be considered. Potential failure modes including sliding, overturning, bearing capacity and shearing along other potential slip surfaces underneath the DCM treatment have to be studied, whereas crushing of DCM clusters under vertical load, crushing of shear wall panels at the outer treatment toe, vertical shearing between overlapped columns within a shear wall panel, shearing along other potential slip surfaces within the DCM treatment and extrusion failure of untreated soil between shear wall panels are considered in the internal stability check. For serviceability limit state, ground settlement and deformation are assessed.

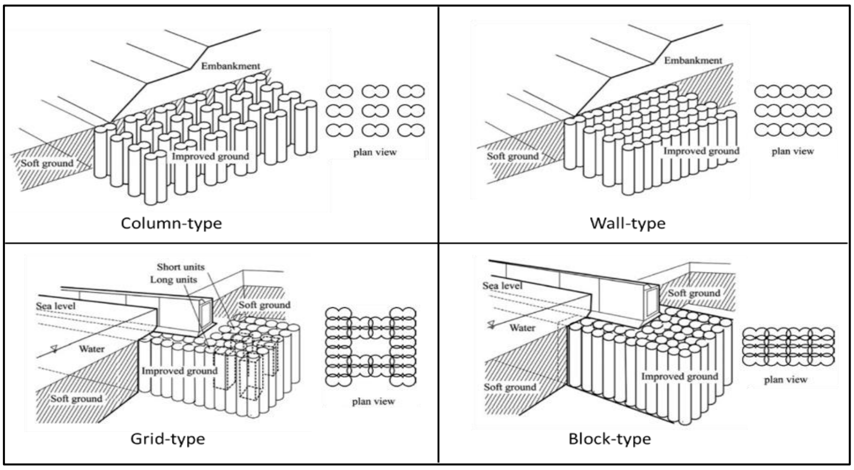


Figure 8: Typical DCM Treatment Pattern

5.2 Grid-type Treatment as Seawall Foundation

Grid-type DCM treatment has been adopted for seawall foundation (Figure 9) to improve lateral rigidity and robustness at TCE reclamation. In most of the design cases, overall stability in form of shear failure governs, especially during temporary loading stages of reclamation filling and surcharging, and the treatment extent shall be adjusted. The required treatment depths have strong correlation with the shear strength of the soil profile and is generally around 20m given the offshore stratigraphy in Tung Chung East.

In regions with high stress concentration, such as the base of a vertical seawall, localized higher replacement ratio has been adopted to facilitate the distribution of large stresses. Additionally, a DCM transfer slab consisting of short clusters is provided to prevent local failure of unimproved soft clays between DCM grids and to limit differential settlement. Evaluation of internal stability for vertical shearing between long and short clusters has been performed to assess the required thickness of the DCM slab.

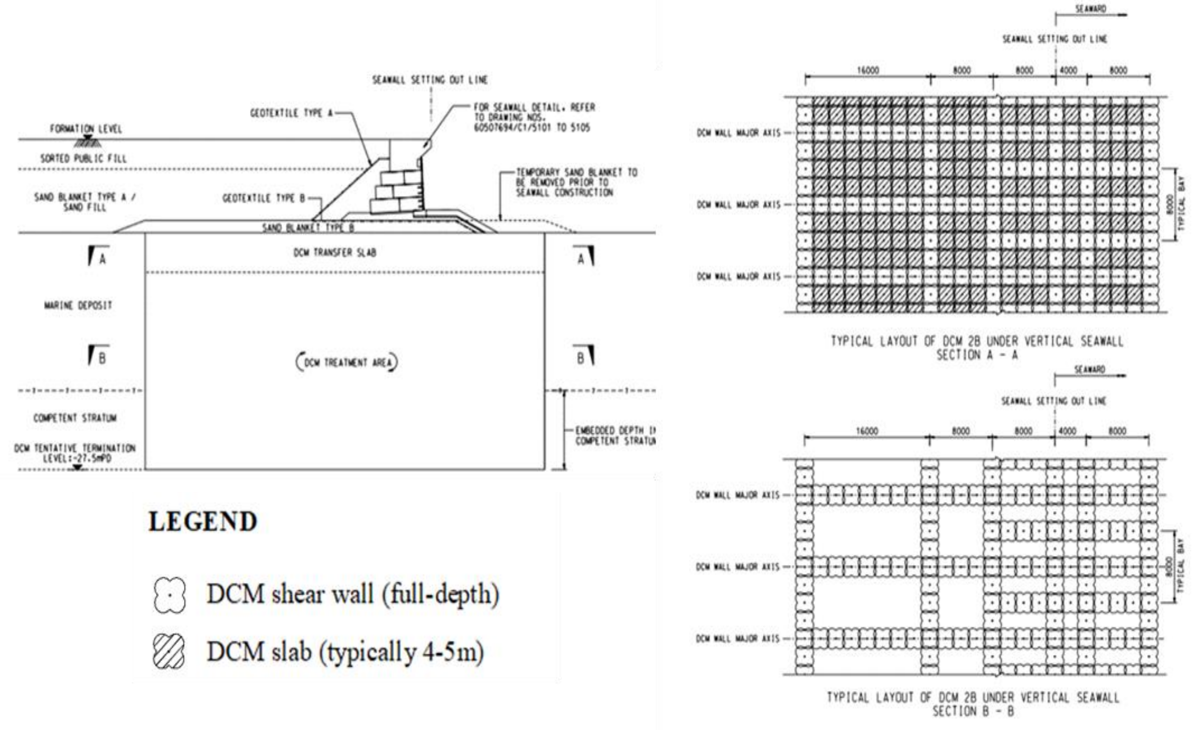


Figure 9: Typical Sections of DCM Treatment as Foundation of a Vertical Seawall

5.3 Finite Element Analysis

A more rigorous approach using finite element analysis with the input parameters properly evaluated is recommended throughout the design process to identify stress distribution and deformation, instead of solely relying on conventional limit equilibrium approach. The DCM treatment has been modelled with an undrained Mohr-Columb constitutive model. By assuming that the treated soil mass behaves as a composite material, parameters such as the undrained shear strength and Young's modulus have been derived using the concept of area replacement ratio. Figure 10 shows an example of a design case. It is noted that overall stability may be of concern when the surcharge height reaches 6m from the formation level. To prevent local failure behind the DCM treatment, reclamation filling is required to be carried out layer by layer to allow sufficient pause periods for consolidation at each loading stage. Additional sensitivity analysis has revealed that due to the relative stiffness between DCM treatment and in-situ soil, the design is governed by the extent of the DCM treatment and the properties of in-situ soils.

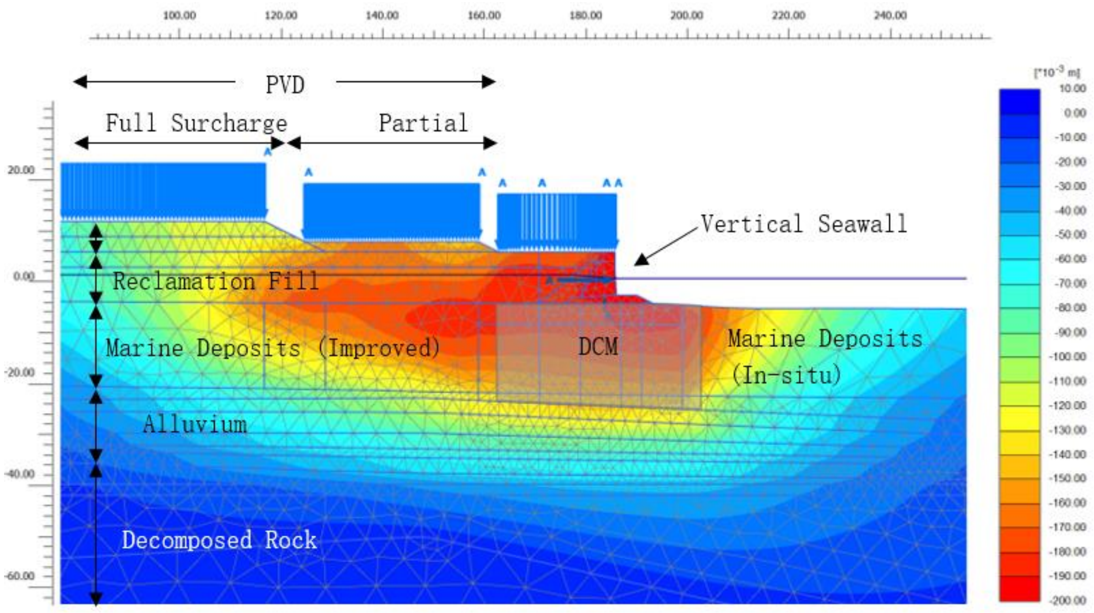


Figure 10: Finite Element Analysis – Lateral Deformation

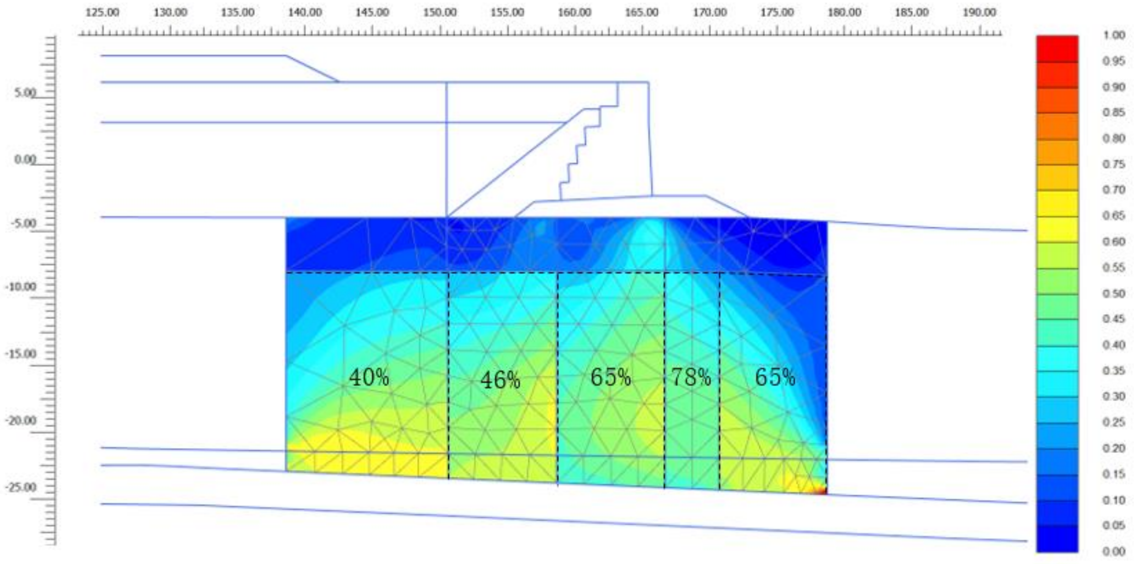


Figure 11: Finite Element Analysis Result – Ratio of Mobilised Shear Stress to Available Shear Strength of DCM

Finite element analysis has provided the insight for evaluating internal stability of DCM design. The analysis allows the designer to examine stress distribution of design model and optimise the treatment replacement ratio. The example as given in Figure 11 shows that there is a relatively high stress concentration directly underneath the vertical seawall and at the outer toe of the DCM treatment. Accordingly, a higher replacement ratio of DCM treatment is assigned near the regions of high stress concentration to evenly distribute the stress for a robust foundation. Although finite element analysis is versatile and power, it is of paramount importance to validate the input parameters and numerical model for better understanding of physical behaviour and meaningful results. One of the validation approaches is physical modelling in geotechnical centrifuge facilities (Ng, 2014). The recent collaboration project with HKUST has enabled the project team to acquire insightful knowledge of modelling parameters, and subsequently the reclamation design can be optimised for cost effectiveness (Figure 12).

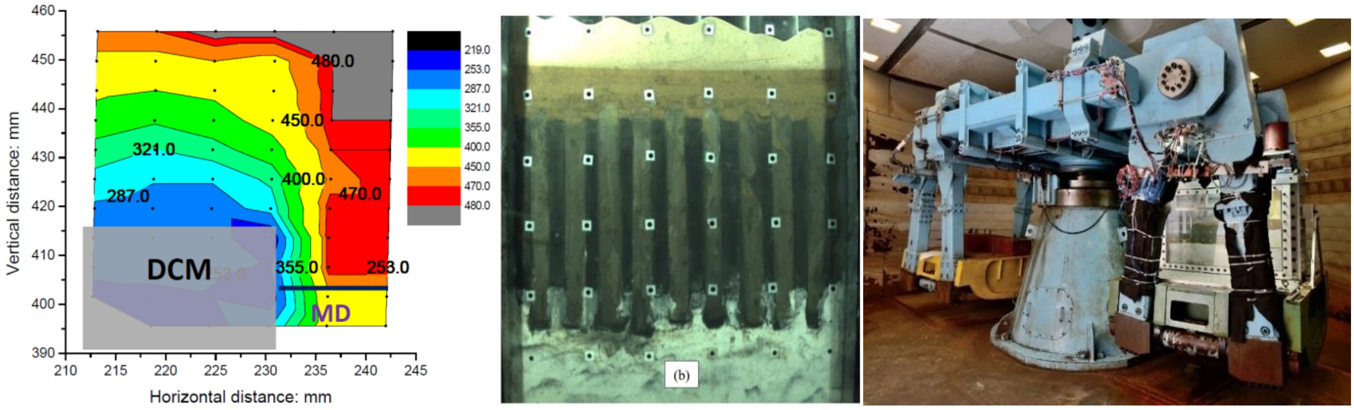


Figure 12. Physical Modelling of DCM Ground Treatment in the Geotechnical Centrifuge Facility at HKUST

6 Performance of DCM Method

6.1 Monitoring at Trial Embankment

At the time of drafting this paper, reclamation was in progress and monitoring stations were installed progressively. Notwithstanding, based on the monitoring data at the trial embankment and completed site areas, the performance of DCM ground treatment method has been found promising and the recorded ground settlement and deformation are within the design prediction.

The robustness of DCM method can be demonstrated from a fully instrumented trial embankment. At the early stage of reclamation works contract, a trial embankment was first constructed with a view to ascertaining the performance of DCM design and construction. The trial embankment consisted of a concrete blockwork seawall that was supported by DCM treated foundation. Earth filling was carried out behind the seawall to simulate permanent loading conditions in the future.

Intensive monitoring at the trial embankment was implemented. For the sake of clarity, only a selection of instruments will be discussed in this paper. The selected instruments were located in 3 different points namely Points A, B and C as shown in Figure 13. Point A was placed on top of the sand blanket situated within the PVD treatment at 25m from the edge of the DCM treatment zone. Points B and C were situated on the surface of the blockwork seawall, which in turn was founded on the DCM treatment. The monitoring data at these 3 locations are discussed in depth in the following sections.

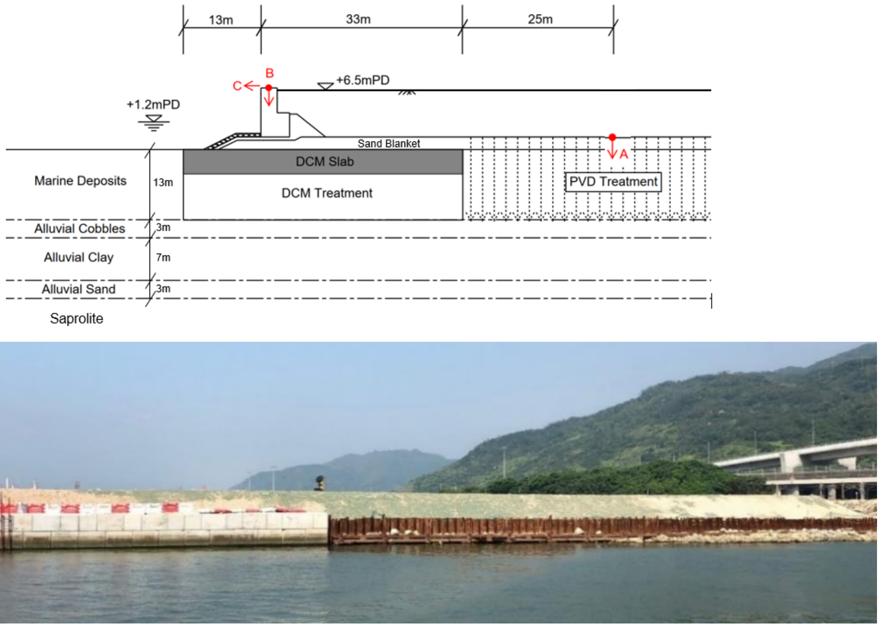


Figure 13: Section of the Trial Embankment

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6.2 Settlement Monitoring

Ground settlement recorded from settlement markers at Points A and B are plotted in Figure 14. At Point A, the ground settlement profile exhibits an exponential trend upon loaded with reclamation fill. The recorded settlement at Point A was roughly 2.3m after about 7 months.

At Point B, the ground settlement trend reached a steady state soon after loading. It should be noted that the settlement magnitude at Point B was a hundredfold smaller as compared with the settlement magnitude at Point A. The recorded settlement at Point B was roughly 25mm.

The settlement profile at Point B has been examined further with respect to depth by analysing data from magnetic extensometers. Settlement contributed by the fill layer could be obtained from the difference between settlement at the ground level and settlement at the top of DCM treatment zone. Settlement due to compression of DCM clusters could be obtained from the difference between settlement at the top and bottom levels of the DCM treatment zone. Based on the extensometer data (Figure 15), it could be concluded that the DCM treated marine clay layer was nearly incompressible at the trial embankment. Most ground settlement attributed to the overlying fill layer and the underlying alluvium.

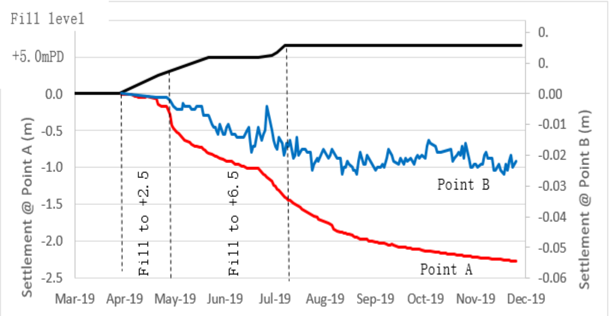

Figure 14: Ground Settlement measured from Settlement Markers at Points A and B

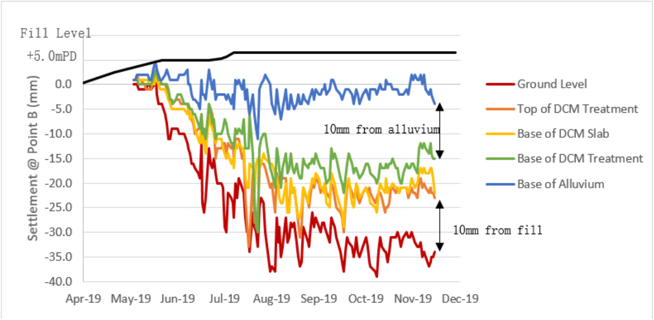

Figure 15: Ground Settlement measured from Magnetic Extensometer at Point B

6.3 Seawall Lateral Movement

Lateral seawall movement was measured by multiple surface movement markers installed along the seawall. Figure 16 shows the measurement from one of such markers. The general trend of the recorded lateral movement was consistent with filling activities, as spikes of lateral movements were observed when major filling works were taking place. Lateral movement stalled after filling reached the final formation level at +6.5mPD. After 7 months, the recorded seawall lateral movement was roughly 50mm. This lateral movement magnitude was within the predicted range of around 60mm. It could be concluded that the DCM treatment was very effective in controlling seawall lateral movement.

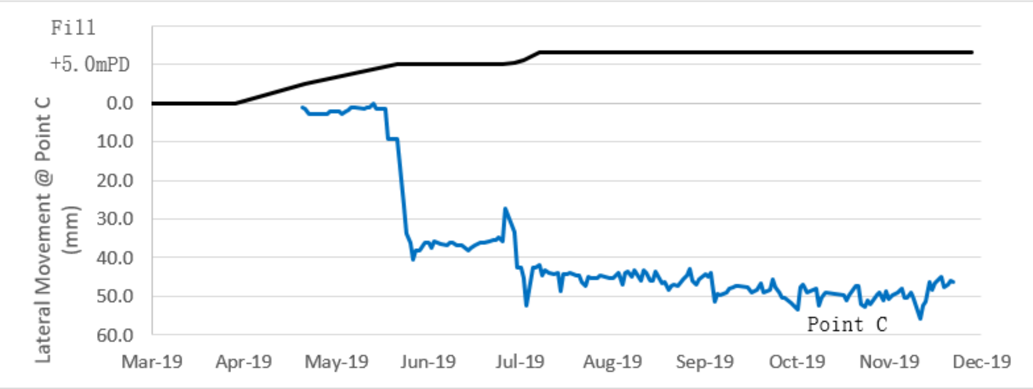

Figure 16: Seawall Lateral Movement measured from Surface Movement Marker at Points C

The above monitoring data demonstrates the effectiveness of settlement control. By reinforcing soft sediment to form a composite, ground settlement arising from the weight of reclamation fill can be effectively managed. As a result, the demand for fill material for replenishing settlement can be reduced significantly. In TCE reclamation, the saving of fill material was about 25%. This not only eased the demand of fill material but also reduced 3,000 vessel trips passing through the north Lantau water channel near Brothers Marine Park. The reduction in vessel trips would bring benefit in reducing the noise and air impacts and minimizing the disturbance of marine habitat. The reclamation works have been proceeding at a very promising pace with comparatively less impact on the environment. All these attributes to the adaptation of DCM method in the reclamation works.

7 Conclusions

A new technology – deep cement mixing (DCM) method, has been introduced in TCE reclamation materialising sustainable land reclamation. Through mechanical blending and mixing of binder slurry, soft marine sediment can be effectively reinforced and strengthened in-situ, and a composite material is formed quickly. This method fast-tracks the ground treatment process considerably as compared with conventional drained method and offers a robust solution for non-dredged reclamation.

Like many other geotechnical designs, a thorough understanding of ground conditions is vital for the DCM design and construction. A well-planned ground investigation and instrumentation monitoring programme and precise ground investigation data are the keys for the determination of mixing parameters, including binder type, dosage, and treatment pattern etc. In particular, the knowledge of in-situ water content and chemical composition within soft sediment are critical to the ultimately performance of DCM method, and cost effectiveness. The presence of obstructions, either natural or artificial, will affect the penetration of mixing shaft and constructability, that warrant to be attended during the planning and design stages.

Like other ground treatment methods, DCM method also involve certain embodied carbon, the choice of suitable binder augments the sustainability of DCM method, when applied in a large scale. The successful application of sustainable binder PBFC in TCE reclamation forms a model case for wider applications in future reclamation projects.

DCM is an effective and sustainable ground treatment method. The current design and construction contract specifications at TCE reclamation made reference to the FHWA design guidelines, (FHWA, 2013), but there is no doubt that the reference book is not fully applicable to local site conditions and practice in terms of design, construction and quality control. While the experience at TCE reclamation and ongoing site monitoring data are precious assets, the documentation of experience and collaboration amongst the industry, academies and the Government would definitely facilitate the technological advancement of the local construction industry to overcome the future challenges in upcoming reclamation projects.

8 Declarations

8.1 Acknowledgment

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8.2 Publisher's Note

References

Babasaki, R., Terashi, M., Suzuki, T., Maekawa, A., Kawamura, M. and Fukazawa, E. 1996. Japanese Geotechnical Society technical committee reports: factors influencing the strength of improved soil. Proceedings of the 2nd International Conference on Ground Improvement Geosystems, Vol. 2, 913-918

Endicott, L.J. 1992. Evidence from engineering properties. Proceedings of the Workshop on the Logging and Interpretation of Transported Soils in Offshore Boreholes, Hong Kong, pp. 39-48.

FHWA. 2013. "Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support." Report No. FHWA-HRT-13-046, October 2013.

Higgins, D. 2007. Briefing: GGBS and Sustainability. Proceedings of the Institution of Civil Engineers Construction Materials 160 August 2007. Issue CM3, pp 99-101.

JGS 0821-2009. Practice for Making and Curing Stabilised Soil Specimens without Compaction, Japanese Geotechnical Society.

Kitazume, M. and Terashi, M. 2013. The deep mixing method. CRC Press/Balkema, Leiden, 405 p.

Koutsoftas, D.C., Foott, R. and Handfelt, L. 1987. Geotechnical investigations offshore Hong Kong. Journal of Geotechnical Engineering, ASCE, 113(2), pp. 87-105

Ng, C.W.W. 2014. The state-of-the-art Centrifuge Modelling of Geotechnical Problems at HKUST. J. Zheijang Univ.-Sci. 15, 1-21.

Skemption, A.W. 1957. Discussion of the planning and design of new Hong Kong airport. Proceedings of the Institution of Civil Engineers, 7 (1957). pp. 305-307

Strange, P.J. and Shaw, R. 1986. Geology of Hong Kong Island and Kowloon. Hong Kong Geological Survey Memoir No. 2, Geotechnical Control Office, Hong Kong, 134 p.