An Innovative ELS System on Recently Reclaimed Land – Design and Analysis

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doi: https://doi.org/10.21467/proceedings.171.31

ABSTRACT

The Third Runway at Hong Kong International Airport sits on a newly reclaimed land formed by non-dredged method where soft muds remain in place under the reclamation fill. Ground improvement works mainly in the form of Deep Cement Mixing (DCM) were installed within the soft marine clays with embedment into a competent stratum. The APM and BHS tunnels were proposed along the new artificial shoreline. To enable the construction of the cut-and-cover tunnels, it is viable to have an open-cut excavation at landside because of the abundant space. At seaside where space constraints are present, a double-wall system was introduced to retain the earth. The beauty of this system is a strut-free zone can be created, which minimizes the construction constraints and shortens the construction programme significantly. A double-wall system is composed of continuous front wall and discrete back wall connected by steel ties. The front wall relies on the back wall which is anchored into DCM panels. The spacing between the front wall and the back wall varies from 9m to 15m depending on site constraints. The design approach and failure mechanisms are discussed.

1 INTRODUCTION

Excavation and later support system is indispensable to enable the construction of basements and underground structures in Hong Kong, in which steel struts are commonly adopted as the lateral support. It can be attributed to some reasons such as availability and re-usability of high yield steel, better elastic modulus of steel, local construction techniques and practice and compliance with local codes. Although the strutted ELS provides limited space for construction inside the excavation pit, it is a reliable solution in most of the basement and underground construction projects in urban districts where strength and stiffness in the ELS system are usually prioritised.

However, it becomes prominent that an unconventional ELS system is required for the construction of a mega-scale infrastructure in an open area such as a long underground tunnel where the vertical alignment varies along the chainage. Strutted excavations are not an economical or effective solution in case a large open-cut excavation is involved because of the reduced construction efficiency coming from strut installation and removal. Given the temporary nature of the excavation system, large wall deformation may be acceptable as long as the ultimate limit state is designed for. (Lee et al. 2013)

The unconventional and innovative ELS system shall have fewer elements which are prone to changes during construction stage. At the same time, it shall provide abundant construction space to facilitate construction, heavy machinery mobilization and reproducible construction logistics. Therefore, a double wall ELS system without struts is well suited in the aforementioned site setting.

This paper summarises the design and analysis experience of an innovative double wall excavation and lateral support system on a recently reclaimed land at the Hong Kong International Airport between Ove Arup & Partners Hong Kong Limited, Lambeth Associates Limited, and Gammon Engineering and Construction Company Limited.

Published by AIJR Publisher in "Proceedings of The HKIE Geotechnical Division 44th Annual Seminar - Elevating Geotechnical Excellence: Novel Practices & Innovative Solutions" (GDAS2024). Organized by the Geotechnical Division, The Hong Kong Institution of Engineers, Hong Kong on May 31, 2024.

Proceedings DOI: 10.21467/proceedings.171; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-970666-7-2

2 PROJECT BACKGROUND

2.1 Three Runway System (3RS)

Hong Kong International Airport has undergone a transformation into a three-runway system. The Three Runway System (3RS) aims to strengthen Hong Kong’s status as an international aviation hub, and to cater for the city’s long term air traffic demand.

2.2 Automated People Mover (APM) System and Baggage Handling System (BHS)

The construction of APM and the construction BHS are two of the seven core projects which the 3RS project consists of. The APM and BHS will connect Terminal 2 with the T2 Concourse. The new APM system will operate at a top speed of 80km/h and transport up to 10800 passengers per hour. The new BHS will be capable of handling 9600 bags per hour. Innovative double wall ELS system was adopted in the construction of the new APM and BHS.

Figure 1: Three-runway system layout (Airport Authority Hong Kong 2021)

3 GROUND CONDITIONS

3.1 Site geology

The site is located offshore of the original Chek Lap Kok Island as well as the existing reclaimed land of the airport area. Marine muds underlain by alluvium layers of different characteristics are present, followed by saprolite and solid rock. The solid geology is predominantly granite – Chek Lap Kok and Lantau Granite of Lamma Suite.

The site was newly reclaimed by non-dredged method that left soft marine deposits in place beneath the reclamation fill. Sand blanket was placed on the seabed followed by ground improvement involving the installation of Deep Cement Mixing (DCM) elements along the tunnel alignment. The area replacement ratio (ARR) of DCM varies with the locations.

3.2 Hydrogeology

The site is on a newly reclaimed land extending from existing reclaimed land. The groundwater regime is expected to be dominated by the seawater level with tidal fluctuation.

4 Site Challenges

4.1 Considerations of Existing DCM Columns

The third runway reclamation adopted the non-dredged “Deep Cement Mixing” (DCM) method, which reduced impact on water quality and marine ecology nearby. DCM method involved the injection of cement slurry from works vessels into the marine mud on the seabed by “mixing” them together. In a DCM treatment zone, DCMs were in the forms of conjoint and non-conjoint columns of different patterns. The seabed was treated in a way that the ground conditions were only improved for the support of future vertical loads such as seawall structures and fill materials to be deposited. When it came to excavation where significant lateral earth pressure was to be supported, considerations of existing DCM were required to be taken into account. For example, the lateral movements and bending of DCM columns had to be assessed to avoid impairing the load-carrying ability of DCMs.

4.2 Under-consolidated Marine Deposit

According to site-specific ground investigation and the interpretation of the cone penetration test (CPT) results, the marine deposit was under-consolidated and only had an undrained shear strength of as low as single digit kilopascal. The weak marine deposit would not only imply that the horizontal elements of the ELS had to be strong and stiff, but it would also require the vertical elements had to be sunk into deeper soil strata such as alluvium and completely decomposed granite from which larger soil strength could be derived.

4.3 As-built seawall and swale in the vicinity

The alignment of the APM and BHS tunnels was close to the seawalls of the third runway reclamation on one side. Due to limited construction space, a more economical conventional open-cut construction method could not be adopted. On the opposite side in the inland area, open-cut construction was possible. However, along the tunnel chainage, the construction space was getting narrower because of the presence of an existing swale between the existing Chap Lap Kok airport island and third runaway reclamation.

5 PROPOSED DOUBLE WALL ELS SYSTEM – DESIGN

5.1 Design Aim

To enable a fast-track construction cycle of APM and BHS tunnel segments, the ELS design was required to accommodate a construction system called travelling formwork. It enabled the repeated construction of structural elements and so was ideally suited to long stretches repetitive concrete forming.

5.2 Choice of Excavation and Lateral Support System

A strutted lateral support system in a conventional ELS would obstruct the deployment of the travelling formwork. On the other hand, a tied-back retaining wall without struts would not be suitable for the ground conditions of the project site. At last, an ELS system with the combination of an open-cut slope on the landside and a double wall system on the seaside was proposed.

Excavation system with double wall set up is not uncommon in neighbouring regions such as mainland China and Taiwan. In China, double row steel sheet pile cofferdam structure was adopted in projects such as Shenzhen-Zhongshan cross-river channel and Shanghai wharf projects. It was particularly favoured in soft soil areas due to its strong resistance to seepage and adaptability according to Jiang et al. (2023). Several excavation projects in Taiwan also involved a double-rail system where two rows of regularly spaced rails were penetrated into the ground as a retaining wall. The front and back rows of rails were usually separated at 600-1200mm. As suggested by Hsieh et al. (2003), this system was applicable to excavation in gravels or sands for single floor basement construction and widening the row spacing of rails can reduce the overall deformation of the retaining system. The design of the double wall ELS system adopted in the APM and BHS tunnel constructions borrowed the successful cases in Taiwan and was further developed to suit the project site.

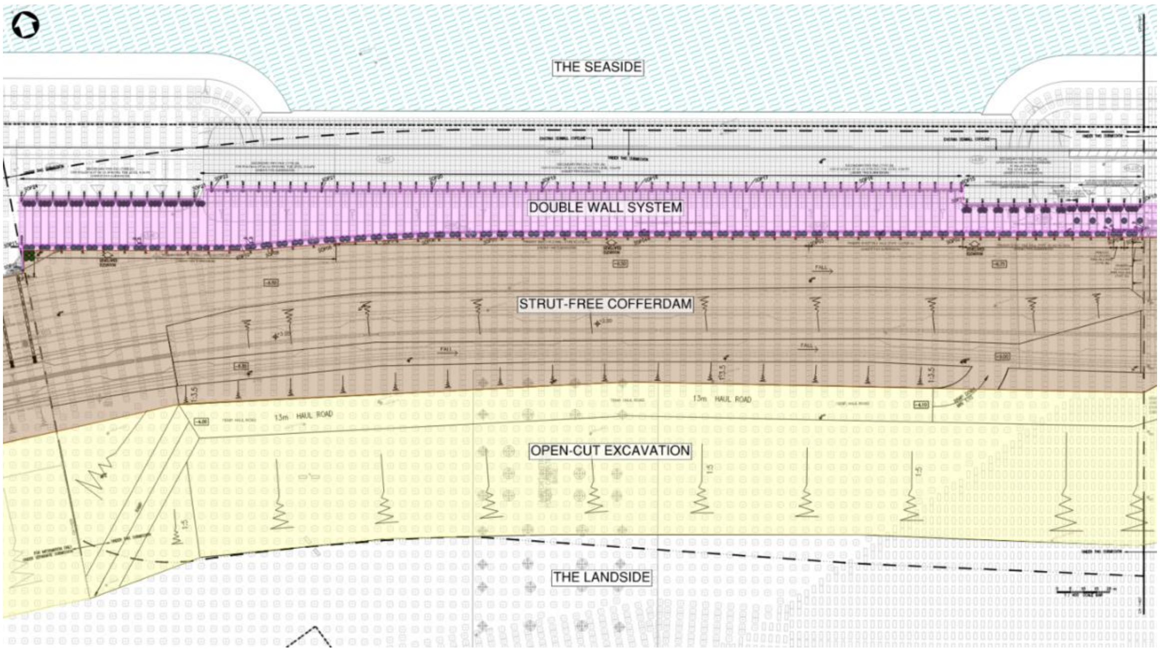

Figure 2: ELS layout plan

5.3 *Design Development of Double Wall ELS System*

The innovative double wall system was composed of three major elements, the front wall, the tie and the back wall. The idea was borrowed from a deadman anchored retaining wall where a single sheet of wall, referred as "front wall", is held back by deadman anchors installed at the back. Rankine's Theory of Active and Passive Earth Pressure forms the basics of the system. The active earth pressure acts on the "front wall" and the passive earth pressure acts on the "back wall". To maximise the resistance provided by the deadman anchor, the overlapping between the "active zone" and the "passive zone" should be avoided as much as possible. In other words, the angle of internal friction should be fully mobilised in the planes of soil wedges.

The design approach assumed an independent behaviour of the double wall and the soil in between, which was not applicable to the challenges encountered on the site. Such structure should be analysed as a composite structure where the physical interactions between each element were taken into account (Sawaguchi 1974).

In designing the double wall ELS system for the APM and BHS tunnels, PLAXIS 2D and 3D were utilised to study the soil-structure interactions of the double wall ELS system.

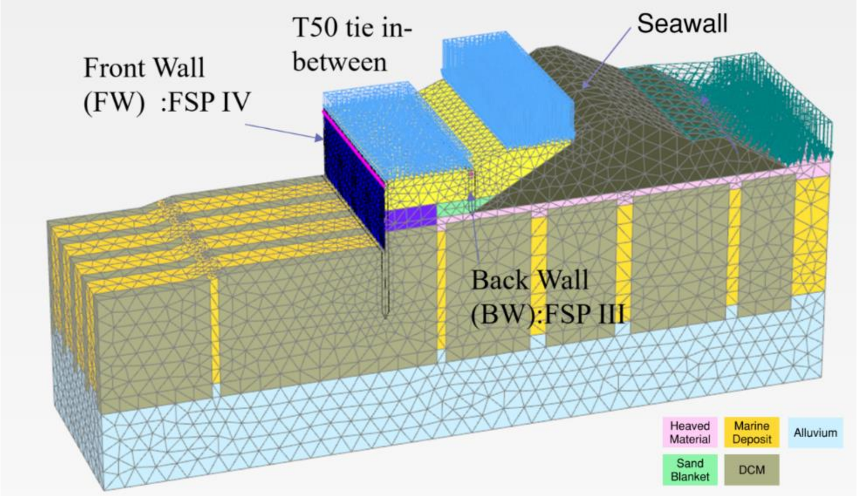

Figure 3: Back wall modelled as deadman anchor in PLAXIS 3D (original approach)

In the APM and BHS tunnel, the deadman anchor was originally designed to be in a form of sheet pile wall, referred to as "back wall". Due to the close vicinity of the as-built seawall, the separation of the front wall and the back wall was limited. The separation between the front wall and the back wall was 12m in general but it could be as narrow as 9m, which was smaller than the required length of 16-17m to prevent the overlapping between the "active zone" and the "passive zone".

From PLAXIS safety analysis, there was no distinct difference in soil movement at failure between the double wall, indicating that there might be overlapping and thus the effectiveness of the deadman anchor was reduced. In conventional strutted ELS design, it is typical to enhance the robustness and the ground movement control by using stronger and stiffer vertical and horizontal steel elements and increasing the wall embedment depth, etc. However, these typical methods cannot fully address the overlapping problem which can only be effectively resolved by increasing the separation between the front wall and the back wall.

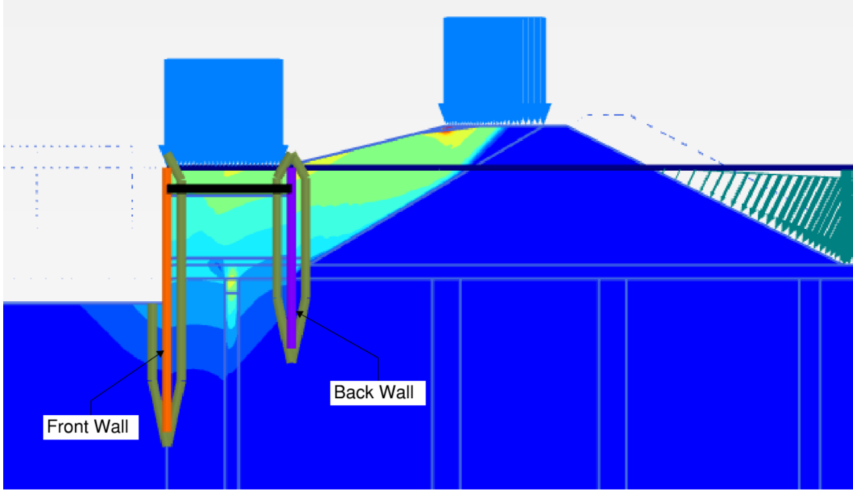

Figure 4: Safety analysis in PLAXIS 2D

After considering the potential failure mode, the double wall design was modified to be less dependent on the passive soil resistance in front the of back wall. Therefore, the modified system changed the back wall from sheet pile to pipe pile. The back wall was rather individual piles than a continuous wall. The pipe piles were designed and positioned to be sunk into the top portion of the DCM columns, which took advantage of the as-built DCM columns in marine deposit. The DCM benefited the modified double wall ELS system in two ways.

Firstly, it treated the marine deposit soil stratum as a whole and improved the strength of the weak and under-consolidated marine deposit. It provided adequate passive soil resistance to the front wall embedded into DCM-treated marine deposit and thus enhanced the toe-kick stability.

Secondly, the individual DCM columns had a uniaxial compressive strength ranging from 800kPa to 1200kPa. It provided strong anchorage for those pipe piles embedded into it. The back wall behaved as laterally loaded piles which did not rely on the passive soil resistance. The potential failure mode of the modified double wall system was changed. The behaviour of the laterally loaded piles was analysed by Oasys Alp and the result was compared with that of PLAXIS 2D to verify the intended working mechanism of the discrete pipe piles.

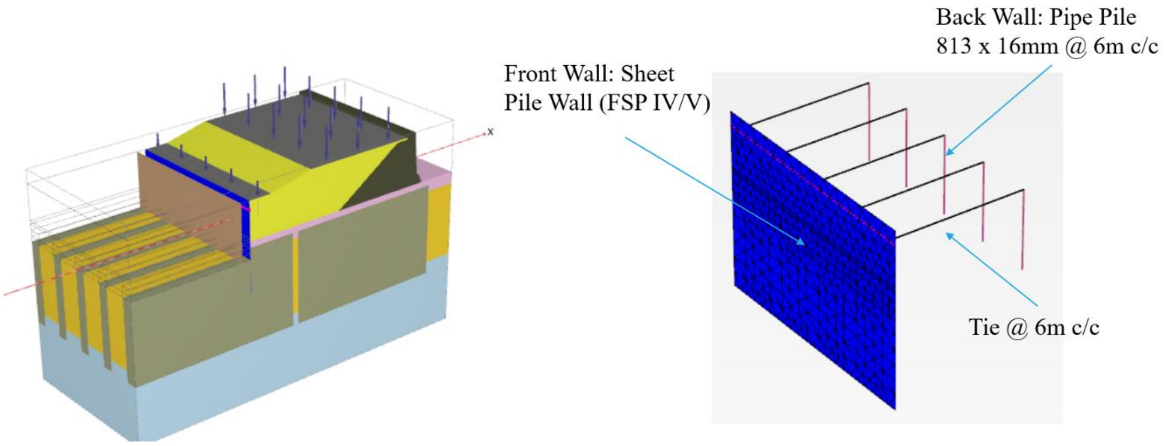

Figure 5: Back wall modelled as individual piles in PLAXIS 3D (modified approach)

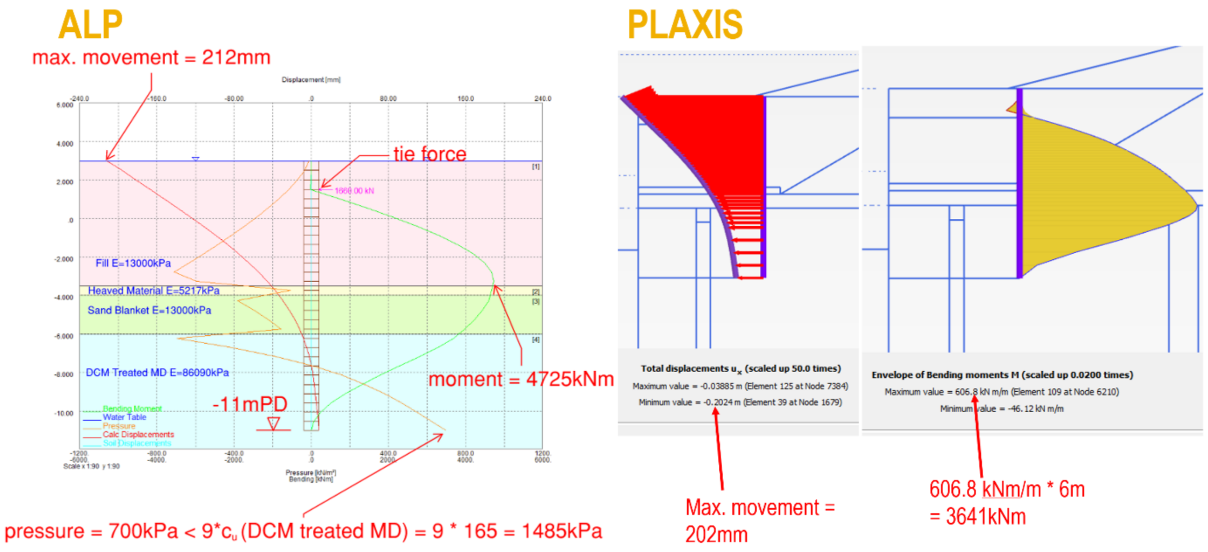

Figure 6: Comparison of results from Oasys Alp and PLAXIS 2D

5.4 Mechanism of the Modified Double Wall ELS System

The front wall was held back by the spaced anchored piles at the back through the connecting tie-backs and acted like a simply supported beam with supports on both ends. It was propped by the tie-backs at the top and the strong DCM-treated marine deposit at the bottom. For ultimate limit state, this ELS system behaved like a singly strutted ELS and the toe stability was checked. For structural check, the front wall, the back piles and the tie-backs were checked against factored forces.

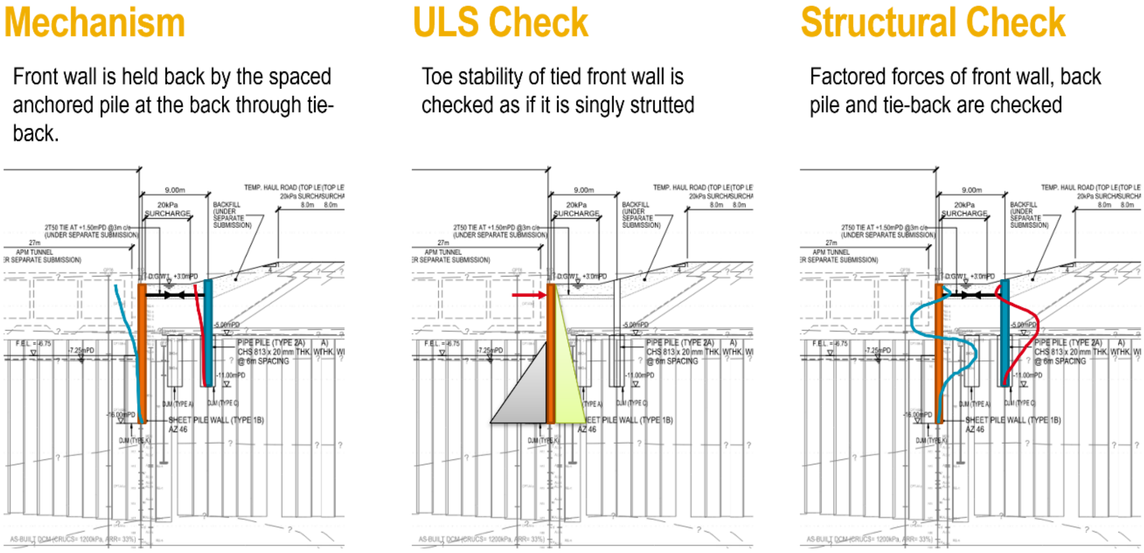

Figure 7: Failure mechanism of double-wall retaining system

6 PROPOSED DOUBLE WALL ELS SYSTEM – NUMERICAL ANALYSIS

The section focuses on the numerical analysis and modelling of the modified double wall ELS systems where different modelling techniques were adopted to validate of design assumptions and verify of the failure mechanism. Improvements on the double wall system have been done with considerations of different potential failure modes.

6.1 Key Design Parameters

The choice and design of ELS system was based on the aforementioned. The design parameters were determined from the site-specific ground investigations that involved extensive in-situ vane shear tests and cone penetration tests. One of the key design parameters that had considerable impact on the design was the undrained shear strength of the marine deposit. It was much weaker than that of the consolidated marine deposits usually encountered in other Hong Kong districts.

6.2 Analysis approach

As DCM columns are surrounded by very weak marine deposits, the ARR of DCM needs to be considered to determine the smeared strength and stiffness for application in PLAXIS 2D with a plane strain assumption. It is a good approximation of behaviour inside a thick composite material loaded in one plane.

Apart from the traditional toe stability check, the overall stability of the system was computed by phi-c reduction in PLAXIS. DCM panels were assumed to have a tensile strength which was directly proportional to their uniaxial compressive strengths (UCS). If the tensile stress exceeded the limit over the course of excavation, the corresponding fractions were replaced with frictional material to mimic the cracked behaviour of DCM. Several iterations were carried out as the stress points might propagate to the surroundings upon the replacement with frictional material. Consequently, safety check was carried out by successively reducing the tensile strength of DCM and shear strength of soils until failure of the structure occurred. It helped identify the critical failure mechanism of the system as well as ensuring the overall stability was up to design requirement.

6.2 Assumptions of back wall

If a continuous back wall was to be adopted, the active wedge of the front wall overlapped greatly with the passive wedge of the back wall, which resulted in a large overall movement of the system. The overall movement was inversely proportional to the distance between the walls. Due to the space constraints of the site, the back wall was changed from the continuous deadman anchor to laterally-loaded piles anchoring into DCM panels to limit the movement. The laterally-loaded discrete back wall was modelled as embedded beam row in PLAXIS.

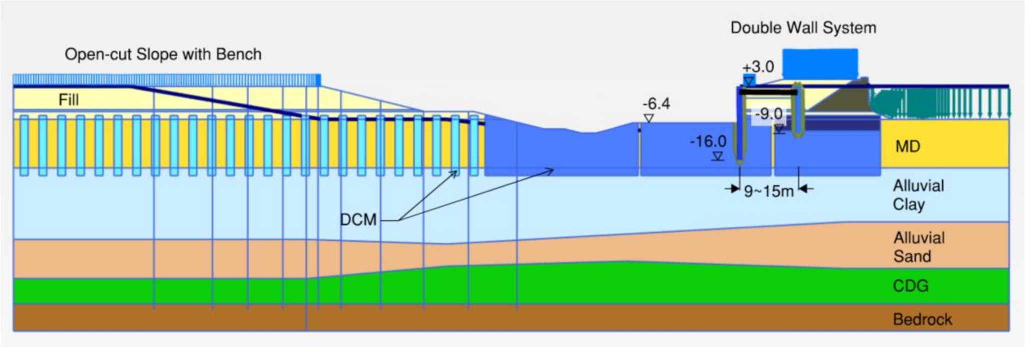

Figure 8: Typical double-wall system setup in PLAXIS 2D

6.3 *Interactions with DCM*

It was uncertain whether analyses in 2D space were insufficiently conservative in predicting the behaviour of the system as DCM panels are present in rows with compartmentalized marine deposit. The smeared properties might not be representative enough to appraise the local variation in movements and forces of the system. In addition, the back wall was essentially considered discrete because the spacing of the back wall was more than 3 times of the pipe pile diameter. To further verify the accuracy of the 2D model, finite element analysis was conducted in 3 dimensional spaces using PLAXIS 3D at critical and representative locations.

Stress concentration and excessive differential movement was revealed from PLAXIS 3D at the interface of DCM and soft marine clays, which were attributed to the enormous stiffness difference across the different materials. Bending moment of the front wall was found peaking at DCMs along the wall alignment. Additional ground improvement by Dry Jet Mixing (DJM) were proposed at certain soft spots to enhance the robustness of the design. With the addition of DJM columns, the spikes in wall forces were evened out to avoid high local stress concentration which reduced the wall size to yield a cost-effective design and boost the robustness of the system.

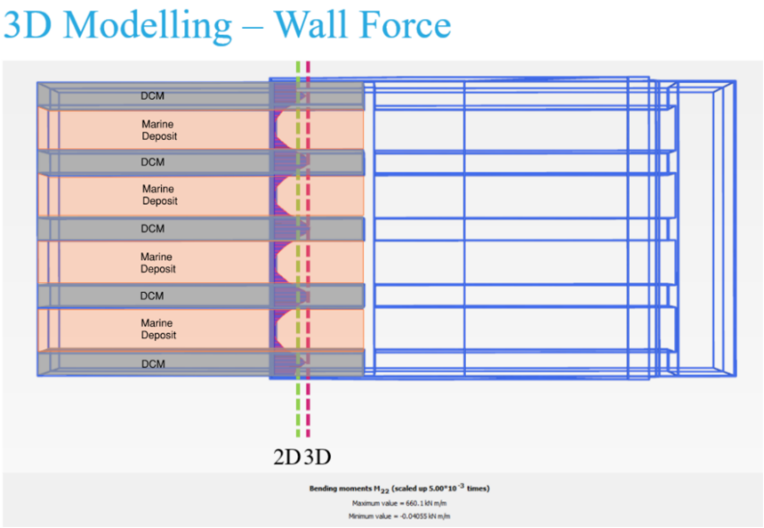

Figure 9: Bending moment of front wall in PLAXIS 3D along wall alignment in absence of additional DJM

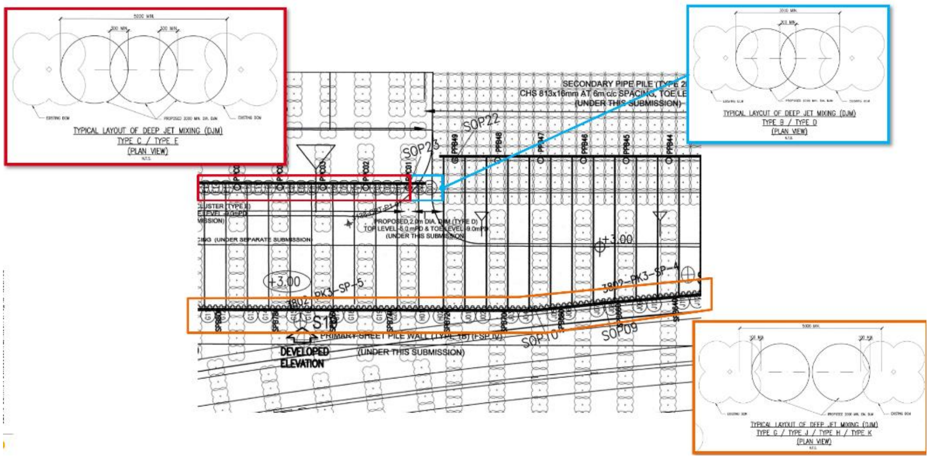

Figure 10: Arrangement of additional DCM/DJM

An approximately 10% increase in wall moment and shear stress was revealed from PLAXIS 3D which confirmed the hypothesis. Hence, modelling in 2D space was considered acceptable by applying a bulk factor to the obtained results. At critical locations, 3D analyses were carried out to countercheck and verify the results in the 2D analysis.

6.4 Transition to strutted cofferdam

The double wall system had great compatibility when it came to interfacing with the conventional strutted excavation. The transition was effortless. However, attention was required to be drawn to the differential movements between the non-strutted wall and the strutted wall during the course of excavation. Grout curtain was recommended to be deployed to the location where transition occurred as precautionary measures to ensure water tightness and to increase robustness at the interface.

7 PERFORMANCE REVIEW DURING CONSTRUCTION STAGE

Different types of monitoring and instrumentation were proposed to monitor the performance of the double-wall system, including ground settlement markers and inclinometers. However, inclinometers were considered key performance indicators as they were less susceptible to disturbance. They were installed in both the front wall and back wall along the wall alignment.

Excavation was carried out progressively by bays along the longitudinal direction of tunnels, with each bay approximately 20m long. At the location where final excavation level was first reached (Day 0), both inclinometers in the front wall and the back wall captured a substantially smaller deflection than the design predicted value. However, the deflection went up significantly as revealed by the next measurement (Day 3). By the time of reporting, the adjacent two bays were proceeding to their FELs. Both the front wall and the back wall deflected by around 50mm more, breaching the alert level. This undue movement had drawn the project team’s attention despite the movements were within the predicted value, which eventually led to a performance review. The actual wall deflection profile was checked and compared against the envisaged deflection profile. The depth where largest deflection took place was comparable and it matched with the design expectation. The wall portion socketed into DCM panels had undergone a significantly smaller movement than the predicted value which the integrity of DCM panels was implied. The elongations of tie bars were also found consistent with the prediction. Therefore, it could be concluded that the overall stability and structural integrity were not compromised. The delayed movement might be attributed to the limitations of a staged plane strain analysis. The monitoring of the system movement continued throughout the construction stage and the maximum movement had been within the design limit.

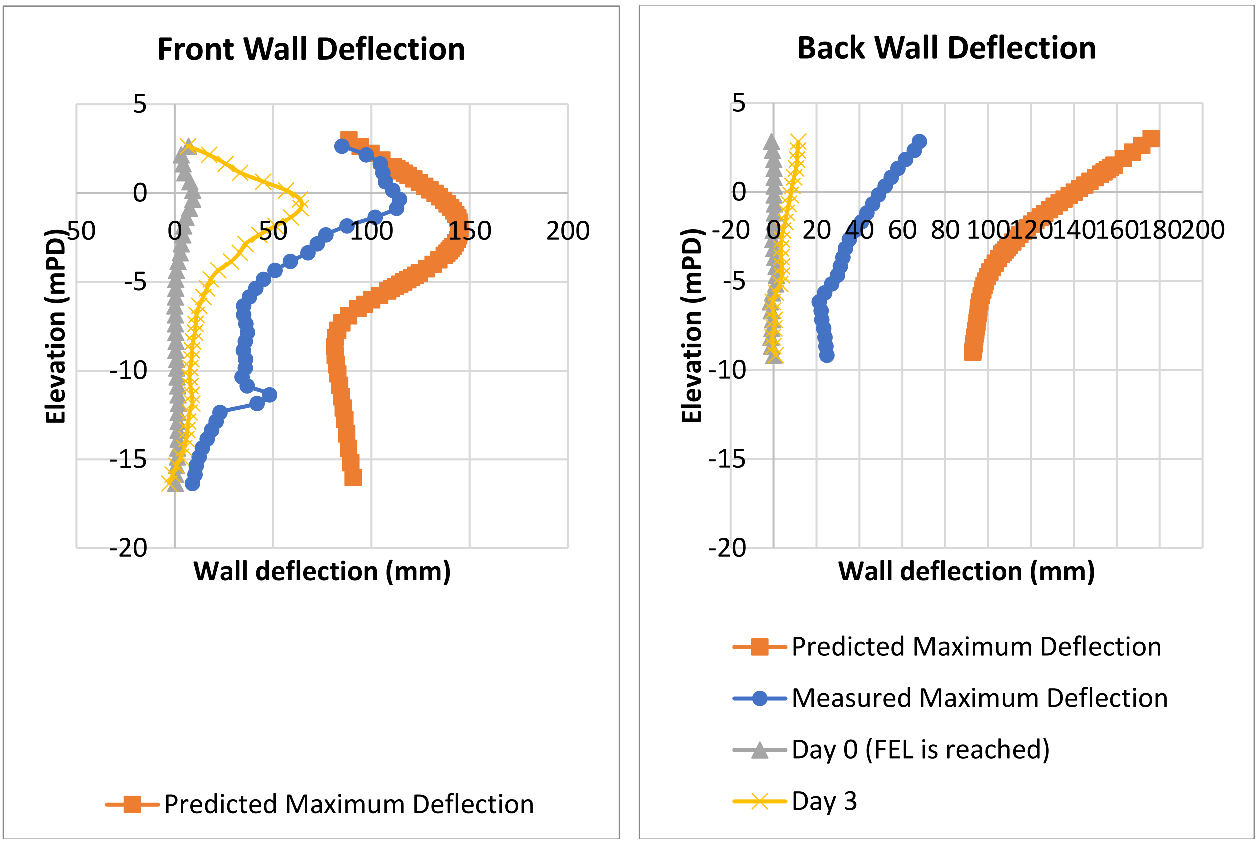

Figure 11: Comparison of predicted and measured wall movement

8 CONCLUSIONS

An innovative design of double-wall system featuring a strutless excavation zone has been carried out for APM/BHS tunnel construction of the Third Runway Project. The double-wall system is the first of its kind in Hong Kong in difficult soft ground conditions. The design principles and envisaged failure mechanisms were discussed in this paper. Careful selection of the analysis methods is required to cater for project specific risks and constraints. The designer shall consider additional measures to ensure the risks are properly mitigated during the design stage as well as the construction stage. Comprehensive instrumentation and monitoring plan for the monitoring and validation of the performance of the double wall ELS system are necessary during construction.

ACKNOWLEDGEMENT

The authors thank the Airport Authority Hong Kong for the permission and kind support to publish this paper. The efforts and participation of the project teams and supervision teams are highly appreciated.

PUBLISHER’S NOTE

HOW TO CITE

Yiu *et al.* (2024). An Innovative ELS System on Recently Reclaimed Land – Design and Analysis. *AIJR Proceedings*, 348-357. https://doi.org/10.21467/proceedings.171.31

REFERENCES

Lee, C.J., Chen, H.T., Wei, Y.C., Lin, Y.C., Huang, W.S. and Chiang, K.H. 2007. Centrifuge modeling of a self-supported double soldier-piled wall in sandy soil. *J. GeoEng*, 2(3), pp.97-109.

Jiang, Y., Guo, F., Wang, W., Yang, G., Yue, J. and Huang, Y. 2023. Stability Study of a Double-Row Steel Sheet Pile Cofferdam Structure on Soft Ground. *Water*, 15(14), p.2643.

Hsieh, H.S., Shih, C. and Lin, T.M. 2003. A note on the behavior of double-rail earth retaining system. *Sino-geotechnics*, 97, pp.5-14.

Sawaguchi, M. 1974. Lateral behavior of a double sheet pile wall structure. *Soils and foundations*, 14(1), pp.45-59.

Airport Authority Hong Kong 2021. *LC Paper No. CB(4)1696/20-21(01), Legislative Council Panel on Economic Development, Update on the Development of the Three-Runway System at Hong Kong International Airport, 27 October 2021.*