

# An Innovative ELS System on Recently Reclaimed Land – Construction and Performance

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## ABSTRACT

On the recently reclaimed land for the airport three-runway system, deep excavations have been carried out to construct tunnels connecting the terminals. A novel excavation and lateral support (ELS) design comprising a double wall system connected by ties was introduced in one portion to cater for the challenging geotechnical condition with improved constructability at the site adjacent to the shoreline. This paper will briefly discuss the development of the scheme, then focus on the construction and performance of the system. The design was developed through close collaboration between the designers and contractor, based on a thorough site investigation and analyses. It offered a cost-effective construction option allowing clear access to the cofferdam, flexibility for lifting and logistics, and efficient structure construction processes. The robustness of the system could also be enhanced by additional ground improvements across a limited extent. The performance of the system during construction has been reviewed by comparing the predicted deflection of the temporary vertical walls in design analyses with the monitoring data. It is observed with positive results giving confidence in the implementation of deep excavation with a double wall system. Site observations are also shared with recommendations of potential improvements for future implementation.

## 1 INTRODUCTION

### 1.1 Project Background

The Airport Authority Hong Kong Contract 3802 project is a part of the Three-Runway System (3RS) to construct tunnels and related works for an automatic people mover (APM) and baggage handling system (BHS) at Hong Kong International Airport connecting the third runway concourse (TRC) building and the system on the existing reclaimed land. The tunnels were mostly to be constructed on the recently reclaimed land by cut-and-cover method. The excavations involved varying depths, different ELS systems were therefore proposed for different portions. This paper will focus on discussing the construction and performance of a double wall ELS system for up to 9.5m deep excavations.

### 1.2 Ground Conditions

The site is located offshore of the original Chek Lap Kok Island as well as the existing reclaimed land of the airport area in the north. Marine muds underlain by alluvium layers of different characteristics are present, followed by saprolite and solid rock. No dredging had been carried out for the recent reclamation in this area and up to more than ten metres of soft marine clay remains beneath the reclaimed land. Around ten metres of fill materials were placed on top of the marine mud improved by deep cement mixing (DCM) elements. Sand blanket was placed on the seabed followed by ground improvement involving the installation of DCM elements before reclamation. There were different zones with DCM in different patterns, replacement ratio, required uniaxial compressive strength, installation methods, and embedment into competent stratum.



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## 2 EXCAVATION AND LATERAL SUPPORT (ELS) DESIGN

### 2.1 Constraints

The tunnel structures to be constructed were in various depths. Conventional multi-strutted cofferdam was used for deeper excavations more than 10m. For shallower excavations, more cost-effective design was pursued. Where space was abundant, open cut excavation could be carried out. While at the subject portion of tunnel, the seaside was close to the shoreline of the new reclamation, being only 10 to 20m away from the seawall. With the landside having enough space for open cut, struts were desired to be avoided not to introduce additional retaining wall on landside and obstructions across the tunnel construction footprint, with the help of a self-sustained retaining system on the seaside. With the limited distance of 10m shortest between the tunnel and the shoreline, it made effective typical tie-back wall into soil and deadman anchor system difficult. A double wall system was therefore introduced for retaining an up to 9.5m deep excavation on the seaside coupling with the open cut on the landside (Figure 1 and Plate 1).

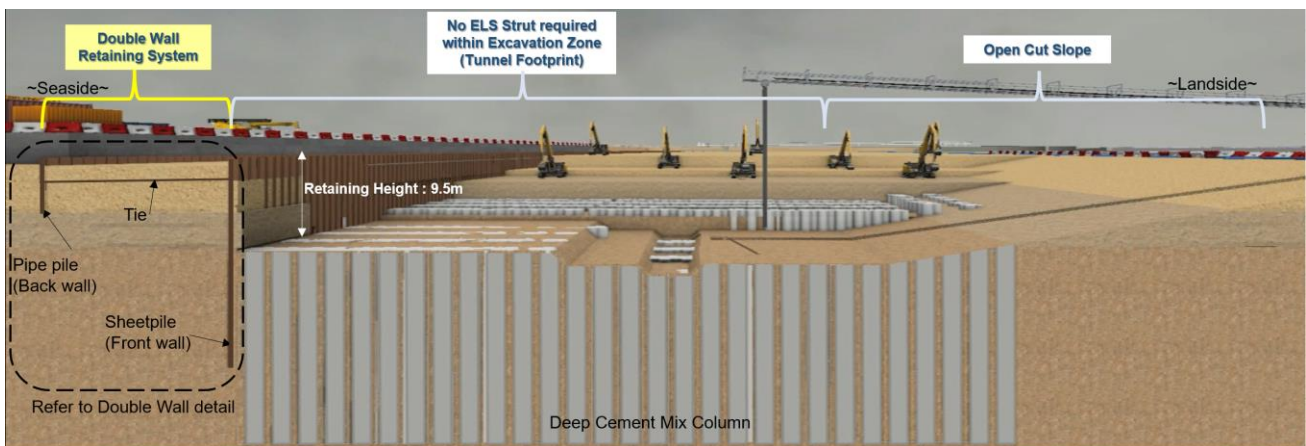


Figure 1: ELS design with double wall and open cut

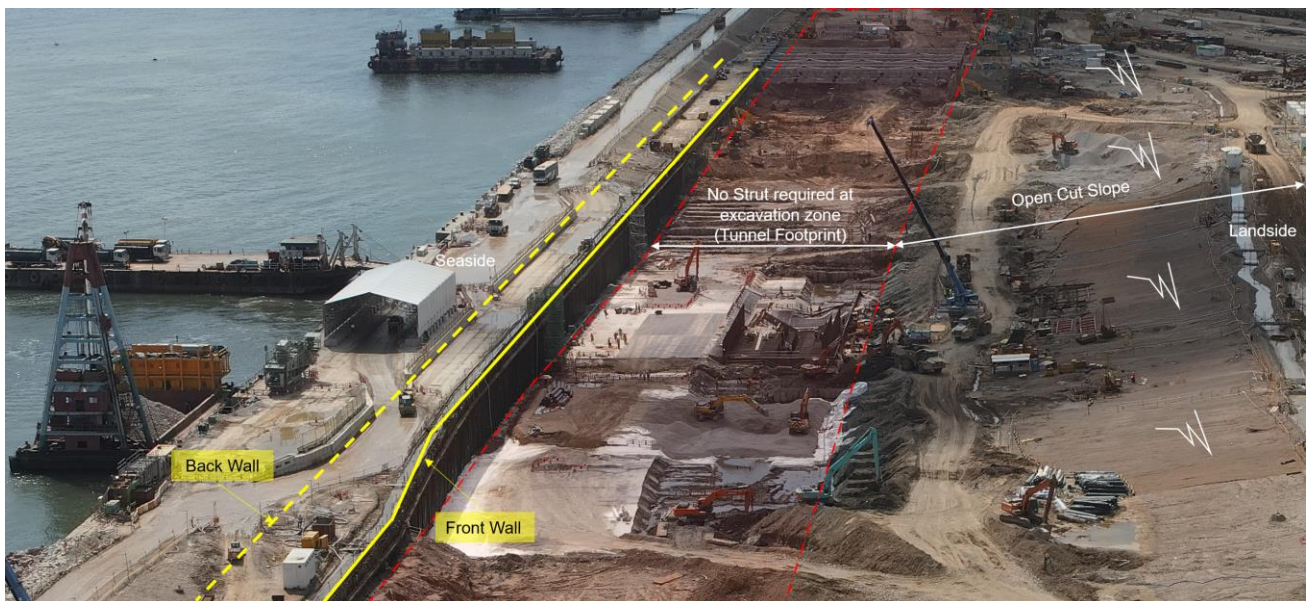


Plate 1: General view of the double wall and open cut ELS

## 2.2 The ELS system

With the abovementioned constraints, an extra element was designed for tie-back anchorage to form a double wall system. It was composed of a continuous front wall (sheet piles) and discrete back wall (pipe piles) connected by steel ties (Figure 2). The member sizes of sheet piles and pipe piles were various at different design sections, and UB sections were inserted into the pipe piles where necessary. The spacing between the front wall and back walls varied from 9m to 16m. The back wall was designed as a laterally loaded pile row, with enhanced resistance from the existing DCM panels. Additional ground improvement by Deep Jet Mixing (DJM) was also constructed at certain spots to enhance the robustness of the design (Figure 3).

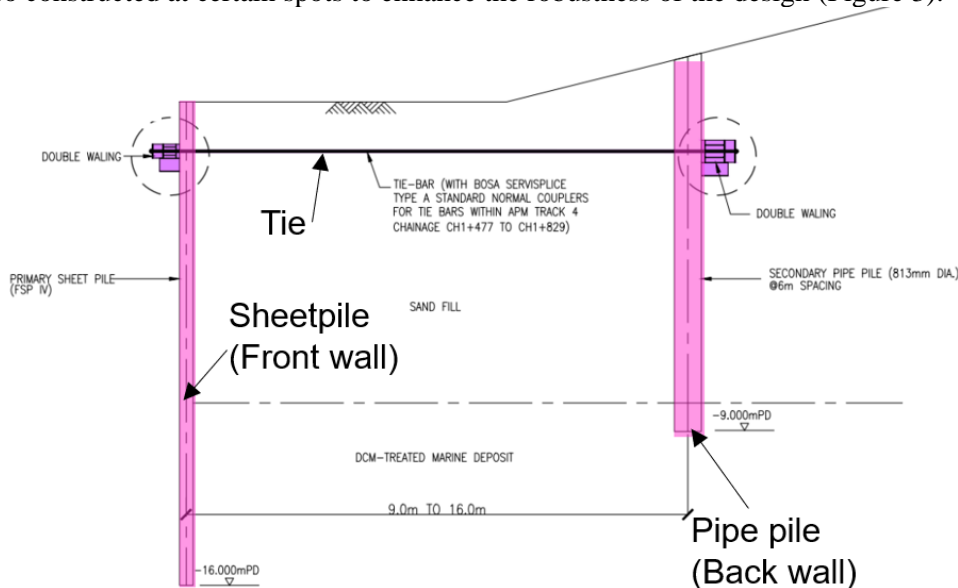


Figure 2: Double wall detail

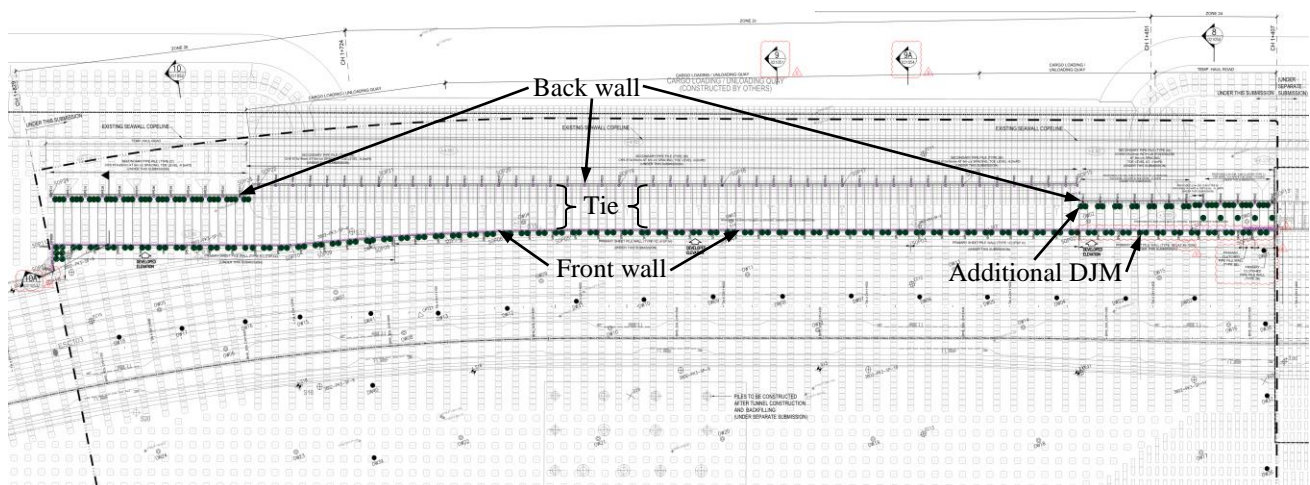


Figure 3: Double wall layout plan

The double wall system is the result of the interaction between the front and back wall as well as the soil in between. Early in 1974, Sawaguchi recommended that a double sheet pile wall structure should be analyzed as a composite structure consisting of both sheet pile walls and the filling so that the interaction between the components could be taken into account. While it was a problem to establish soil constants for more accurate computation by the theory of elasticity, the current design is well facilitated with the help of finite element modelling. Lee et al. (2007) suggests a double piled wall system could be effective in reducing by more than half the surface settlement, horizontal displacement, tilting angle, and the maximum bending moment on the

pile compared to the single pile wall. These made the double wall design feasible as a desired self-sustained retaining system.

The ELS system was a result of the close collaboration between the designers and contractor. The communication of the site constraints and design considerations made the scheme satisfy both the site and design requirements. The client also welcomed innovative ideas and was supportive to motivate the development of the solutions and eventually the real construction of the system. When modifications were needed during construction, the team could address the safety concerns and constructability problems upon site conditions effectively.

### 3 ELS CONSTRUCTION

#### 3.1 Construction Sequence

At this site with complicated ground conditions, thorough ground investigation played an important role to facilitate the geotechnical interpretations including delineation of design ground profile and selection of design parameters. Only after the design had been verified with a detailed geotechnical interpretative report based on the ground investigation, the installation of ELS elements on site was carried out. The major steps (Figure 4) of the construction included:

1. Install front wall and back wall
2. Install DJM in front of wall toe where applicable
3. Shallow excavation for tie installation (Plate 2)
4. Backfill with compaction on top of tie (Plate 3)
5. Bulk excavation to final excavation level (FEL) for tunnel construction

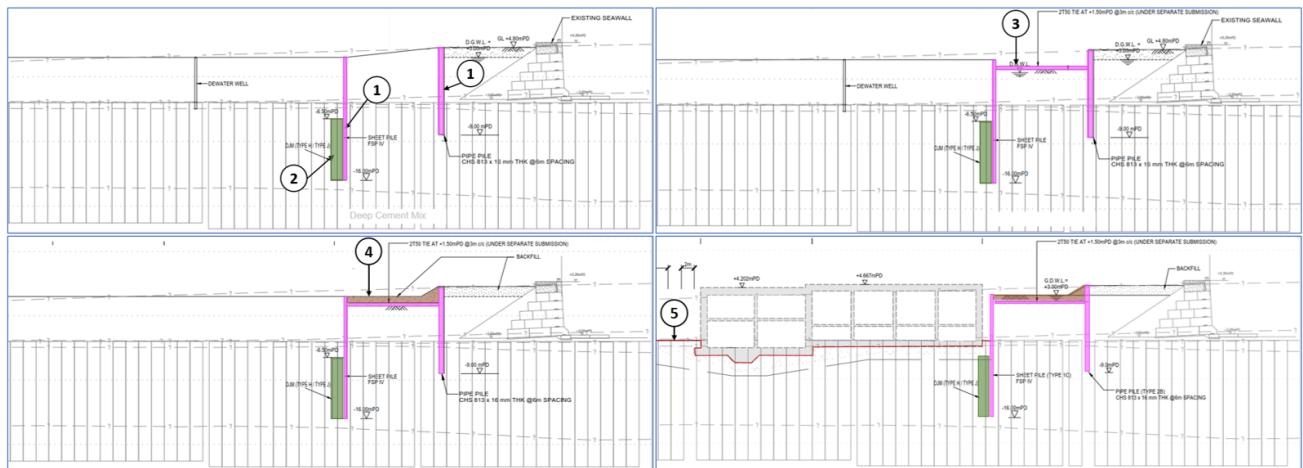


Figure 4: Construction steps



Plate 2: Shallow excavation for tie installation

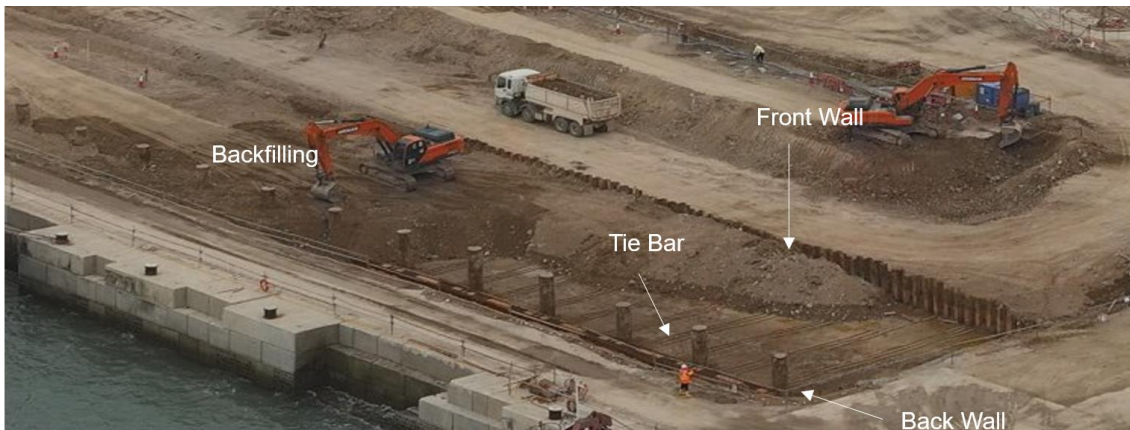


Plate 3: Backfill with compaction on top of tie

During the construction, there were different considerations in each step of the sequence. For installation of the front wall and back wall, on top of the common problem of potential obstructions to sheet piles which would require pre-boring, the embedment locations of the walls were of importance dependent on the design assumptions. Where the front or back wall was assumed to be embedded in DCM ground improvements, engineering control procedures were implemented to ensure the wall was properly installed at the right positions. The as-built information of the ground improvements would be reviewed, and the site responsible personnel would confirm the pile wall to be located at the centre of the DCM clusters or panels on site. Geotechnical engineers or geologists would inspect the materials when the drilling is sunk to the designated depths, both at the top of the ground improvements and at design wall toe levels, to confirm the materials reached. Installation records would be taken and properly filed. Additional DJM works had to be carefully executed not to damage the adjacent installed walls.

The shallow excavation for tie installation was next to the shoreline. While the back wall was individual pipe piles at spacing without full cutoff, the excavation works had to be planned with consideration of the tidal conditions and proper water management. Special connection details were developed facilitating both the load transfer design and fabrication considerations, and it was also made for easy installation on site (Plate 4). During backfill with compaction on top of tie, attention was paid not to damage the installed tie bars.



Plate 4: Tie connection installation

The bulk excavation seemed to be straight forward without the level limitation for strut installation or headroom restriction from struts, yet problems could be encountered in the process and close supervision could not be relaxed. For example, where imperfection of wall installation was encountered, water leakage could occur. Well planned bay by bay excavations with sequential level difference were still carried out to ensure problems could be spotted at an early stage and timely remedial measures could be carried out.

### 3.2 Features

With the double wall system adopted, several obvious benefits were observed. First, heavy lifting works were saved, as no shoring installation layer by layer was required. Plants could be delivered from the open cut side here in one piece. Works at height were also minimized without the shoring segments installation and dismantling. The ties here could be installed or trimmed at the corresponding formation level. The use of mobile elevating work platforms (MEWP) and elevated mucking out were therefore not required. Next, hot works including welding and flame cutting could be minimized with no shoring installation and dismantling. The ties could be designed to allow mainly mechanical installation. Moreover, the site logistics were improved by the open working space (Plate 5), eliminating the congestion and headroom restriction caused by the shoring. Lifting works could be carried out more smoothly, plants could transport across the site freely, and man access to within the excavation could be safer. This also allowed the smooth use of travelling formwork facilitating the tunnel structure construction. All these made the system preferred with enhanced productivity and safety.

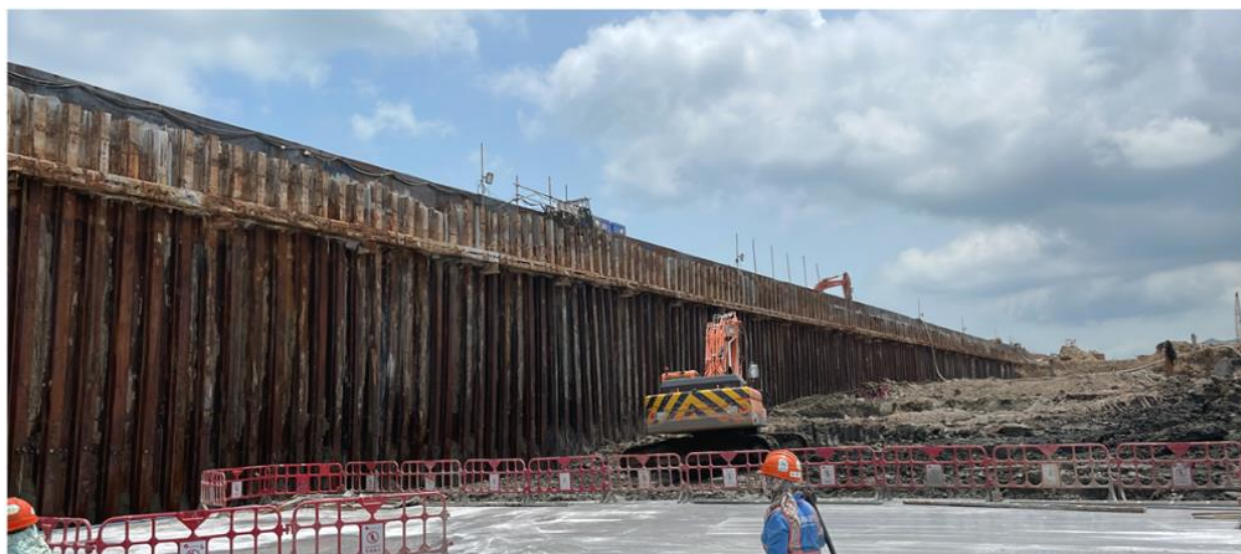


Plate 5: Open working space in excavation

The double wall system was also flexible for variations of design. Different wall types could be used according to different conditions and constraints, for example, different sizes of sheet piles and pipe piles as well as interlocking pipe piles. Transition to adjacent strutted cofferdam was also feasible, where struts could be installed against the front wall.

## 4 PERFORMANCE OF THE SYSTEM

### 4.1 Instrumentation and monitoring

The geotechnical instrumentation and monitoring programme had been developed in accordance with the project requirements and predicted zone of influence and included both geotechnical and structure monitoring as a precautionary measure to closely monitor the construction works. The proposed monitoring points were generally within a distance of 1.5 times excavation depth of the subject cofferdam. The instrumentation types used to monitor the ground movements, structure movements and changes in groundwater levels during the

relevant ELS stages included ground settlement markers, building settlement markers (for seawall), tilt plates, standpipes/piezometers, inclinometers (in soil, pipe pile and DCM), and vibrating monitoring points. A monitoring programme with Alert, Alarm and Action (AAA) triggering system was implemented on site to provide a safeguard against any abnormal or rapid change of movement of the adjacent ground and ELS structures during the construction works.

#### 4.2 Comparison between design prediction and monitoring

The inclinometers were particularly useful for comparison with the design analyses to verify the performance. Compared to ground settlement markers, they were less vulnerable to site works disturbance and more continuous readings could be retrieved. They also provided more than a single value for each reading, where both the magnitude and shape of deflections could be investigated. A number of inclinometers were used to compare with the analysis predictions in four design sections (Figure 5).

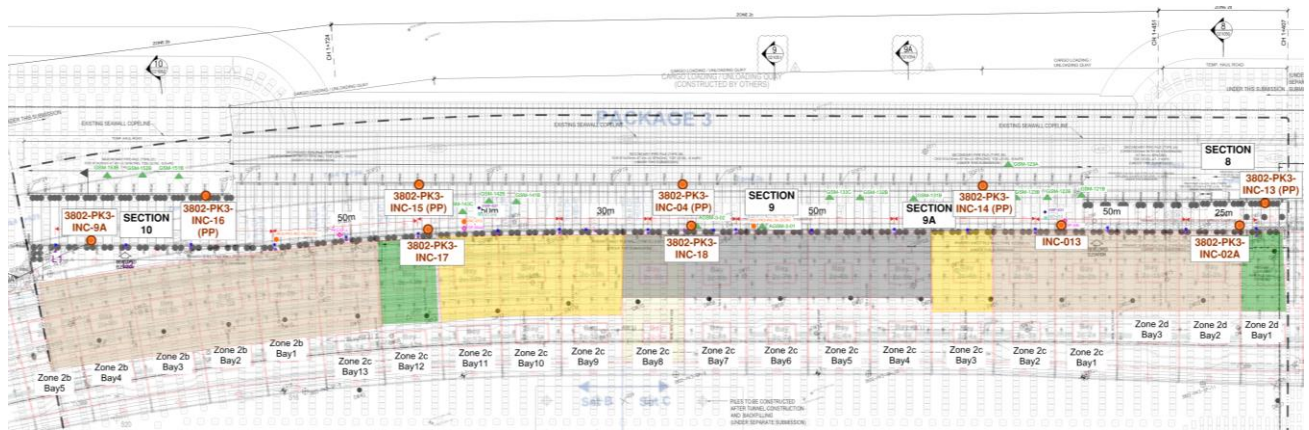


Figure 5: Monitoring layout plan – inclinometers for comparison

The data on the date with maximum magnitude of deflection for each target inclinometer was extracted, and the readings from top level to wall toe level were plotted against the predicted maximum wall displacement profile in the corresponding 2D finite element analysis model under normal loading (Figure 6 and Figure 7). First, most of the deflection shapes from inclinometers were comparable to the predicted ones, verifying the design failure mechanism where the back wall was laterally loaded at the top tie level having maximum deflection, and the front wall was held by the tie and embedment having maximum deflection in between. Second, most of the monitored magnitudes of deflection were well within the predictions except at the front wall of one location. It could have implied that the moderately conservative design approach was justified, where the actual stiffness of soil or ground improvements was higher than that adopted in design. The adoption of reduction factors on the stiffness of sheet pile could also contribute.

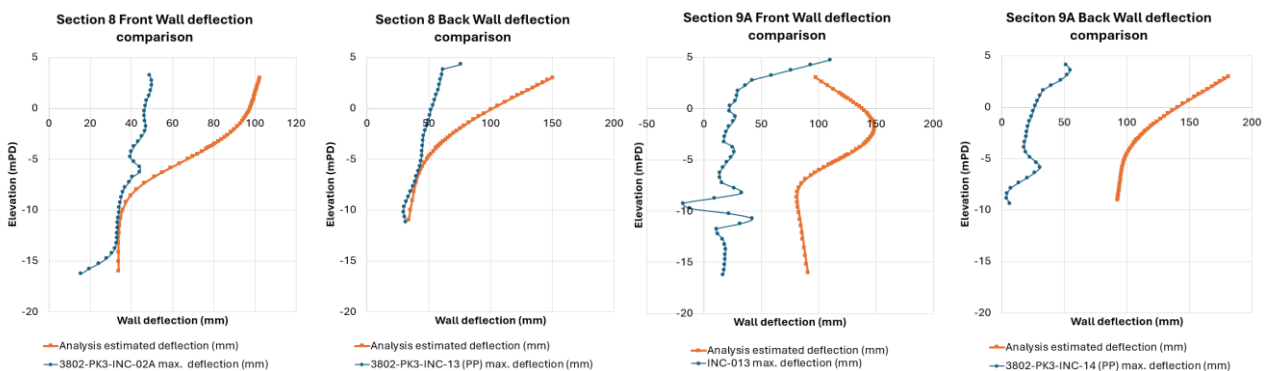


Figure 6: Comparison between prediction and monitoring – part 1

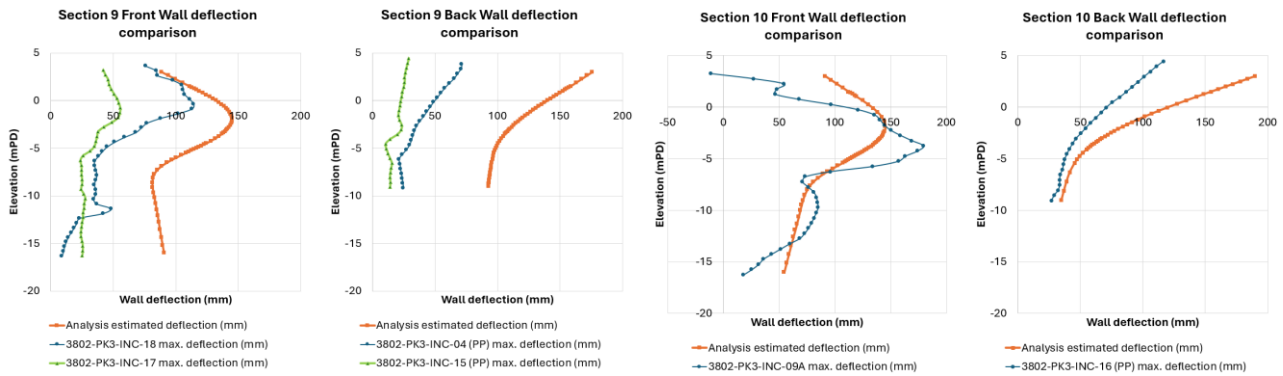


Figure 7: Comparison between prediction and monitoring – part 2

Looking into individual comparisons, variations were observed and the potential contributing factors will be discussed. At Section 8, the deflection shapes of both walls between inclinometer readings and predictions matched well. The magnitudes of deflection were also close from wall toe to around top of existing ground improvement levels, while further towards top level the monitored deflection became smaller and smaller compared to the predicted values. This could imply the wall embedment was working hard as in design while the fill and ELS walls on site could be stiffer than in design. At Section 9A, inclinometers showed much smaller deflection from top to bottom of both walls. The back wall looked mildly loaded while the front wall did not show an obviously larger deflection between the tie and embedment, the mobilizing pressure could be much smaller than as predicted. At Section 9, there was a similar trend to what was observed at Section 9A except the front wall showed a more obvious bulge below tie level. The area was with a temporary bus stop and close to a traversing haul road, which may be subject to a higher surcharge loading condition causing the difference. At Section 10, the shapes of deflection matched well. The maximum deflection reading of the front wall exceeded what was predicted in the analysis with normal loading as shown but still within the prediction with additional loading, and that of the back wall was still within prediction. Other than in a period there was a working barge unloading materials onshore around the area, this could be attributed to a water leakage incident at the location near the subject inclinometer which caused minor soil washout at the front wall sheet pile. Provided the back wall still performed well and the exceedance was local and within the prediction with loading variation, the system was considered still functioning well as designed.

Overall, the monitored deflections were with considerable safety margin from the predictions for Section 9A and 9 where the distance between front and back walls was larger, while those at Section 8 and 10 with closer front and back walls were approaching the corresponding predictions, especially near the wall toe level. It was inferred that the double wall system could work better with larger front and back wall separation distance, benefiting from the resistance of soil in between. As moderately conservative design parameters were adopted in design predictions, a further gap from reality may be observed. When the two walls were closer to each other, more structural capacity of the back wall could have been mobilized and the laterally loaded pile behaviour became more obvious. With the more certain structural stiffness assumption in the design, the predictions could have been more realistic and approached by the monitoring readings.

### 4.3 Other Observations

Other than the movement readings of the ELS system, there were also some site observations worth noting which may give insights into the understanding of the system. While the wall deflection profile could be inferred from inclinometer monitoring readings, the potential variations along the wall alignment direction were not captured. Upon reaching the final excavation level, an obvious varying wall deflection along wall alignment direction was noted (Plate 6). This suggested that solely 2D analysis may not be thorough for representing the behaviour of the ELS system, especially at this site where DCM ground improvements were present at a spacing with untreated in-situ soft marine clay in between. This, in addition to the tie supports at a spacing, could lead to a complicated behaviour variation in 3 dimensions. Hence, a more representative 3D analysis may help the further understanding of the potential impact on the system performance including the bending along the wall alignment direction.



Plate 6: Varying wall deflection along the wall alignment direction

The water tightness of the ELS was not perfect but manageable. Local leakage occurred for a few different reasons. Some minor water inflow came in from the lifting eyes of the sheet piles, this was improved when awareness was raised and covers were welded after lifting. There was also local declutching resulted from the wall installation process, and it cost some efforts for remedial measures when excavation had reached relatively low level. It would be better if any water leakage problems could be spotted at an early stage with timely remedial measures carried out.

## 5 RECOMMENDATION

With the successful experience of adopting the double wall system for a 9.5m deep excavation (Plate 7), it is recommended the system shall be considered for future projects. It is shown to be well applicable for a site requiring space within the cofferdam, far from sensitive structures while having limited space next to the excavation. Upon reaching the final excavation level, the open working space could facilitate productive structure construction without obstructions (Plate 8).

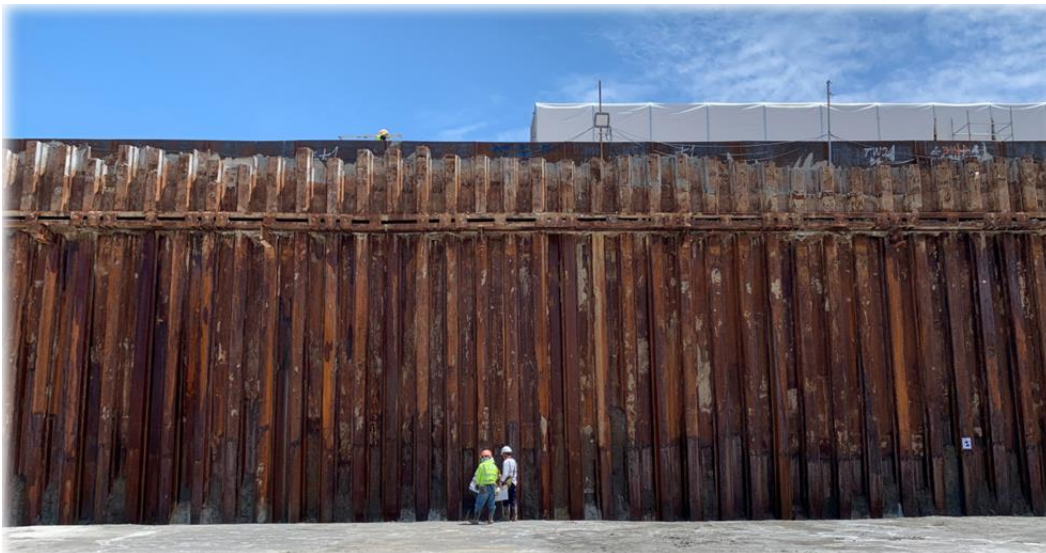


Plate 7: Maximum 9.5m excavation without strut



Plate 8: Construction of tunnel structure in spacious area

As suggested by Jiang et al. (2023), the excellent structural stability, strong resistance to deformation and seepage, and adaptability to engineering challenges of double-row steel sheet pile cofferdam is favoured in soft soil areas, with numerous studies having analyzed the structural stability of cofferdams and the safety of the construction process. The system has been shown here suitable for the complicated soft ground conditions with the aid of DCM/DJM ground improvements. The existing ground improvements as well as additional ones were made use of. While non-dredged reclamation with ground improvements has become more common, it may help if their planning such as DCM patterns and strength involves considerations of facilitating future development such as the potential ELS systems for excavations.

It shall however be noted that the design and construction of a double wall system may not always be successful. As recorded by Hsieh et al. (2003), the underestimate of the influence from groundwater, overestimate of soil strength and optimistic design without proper supervision could have led to an excessive displacement and collapse after rainstorm in a case study. Here, incidents were also encountered but thanks to the robust monitoring system, close supervision, good responsive action planning and continuous design review, a safe construction was secured. In the future, improvements to the double wall system are feasible with its flexibility. The choice of wall types, use of additional ground improvements and combinations with other systems could all be worked on according to the specific site conditions. For example, the use of interlocking pipe piles could maintain the water tightness feature while offering stiffer option of pile members, the use of interlocking wall system for both front and back walls may further improve water cutoff performance.

It is also hoped that the successful experience here would give confidence for checkers to be more open for innovative solutions, not only the presented system but also any uncommon systems in Hong Kong supported by theories, overseas experience, and robust monitoring and review processes. With a close collaboration between the designers, contractors and clients, a safe and efficient design and construction can be produced.

## 6 CONCLUSION

The subject construction and performance review of the application of double wall ELS system hopes to provide a case study for future reference. The site conditions, constraints and the elements of the system have been presented. The construction sequence and benefits of the system to construction process are then investigated. The performance is reviewed by inspecting the inclinometer monitoring results, which are compared with the design analysis predictions and found generally satisfactory. Discussion is provided for

variations at a few different locations. There have also been some site observations and recommendations on the future application of such a double wall ELS system. Facing more and more engineering challenges in a world looking for higher productivity and cost efficiency, the self-sustained strut-free double wall ELS system would provide an option for consideration.

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