The Application of GEO Publication No. 1/2023 to a Deep Excavation in Hong Kong

Gavin S.H. Toh, S.S. To, T.S. Ho, Y.L. Yeung & M.C. Fok
Lambeth Associates Limited, Hong Kong

doi: https://doi.org/10.21467/proceedings.7.7.2

ABSTRACT

This paper offers an overview of the implementation of the GEO Publication No. 1/2023 revamped monitoring scheme at an excavation and lateral support project (ELS) in Kwai Chung, New Territories. Introduced by the Geotechnical Engineering Office (GEO) in late 2023, this publication features significant differences from the monitoring practices commonly used across Hong Kong today, particularly regarding ground settlement. Adoption of design assumptions and guidelines from this publication in ELS submissions of the Project were made to the Buildings Department by the end of 2024 to replace the previous 3A monitoring with the new 5A trigger level, which received approval from government authorities as well as agreement from utilities companies. This paper will explore the distinctions between the new 5A levels and the traditionally used 3A levels outlined in the Practice Note for Authorized Person (PNAP) APP-137, while also considering the design water levels suggested and comparing with the common approach in Hong Kong. By examining these differences, the study aims to provide insights into the implications and benefits of adopting this newly released monitoring scheme for large-scale excavation and infrastructure projects in the region.

1 INTRODUCTION

Before the release of GEO Publication No. 1/2023, the most recent reference document for ELS design in Hong Kong was GCO Publication No. 1/90, published in March 1990. Over the past thirty years, advancements in technology and modelling methods, along with industry experience, professional feedback, and trends from international practices regarding partial factors, led to the publication of GEO Publication No. 1/2023 in December 2023. This update aims to achieve more economically efficient designs for ELS works, reduce construction time, and enhance ground deformation monitoring and control.

Considering the Project's location in a relatively suburban area with fewer sensitive receivers, the project team submitted the ELS package with the application of the GEO Publication No. 1/2023. Following further discussions and meetings with government and private stakeholders, the ELS design was approved in 2024, making this project one of the first in Hong Kong to implement GEO Publication No. 1/2023. This paper will primarily focus on ground settlement monitoring and updates to design groundwater levels in the Project, facilitated by GEO Publication No. 1/2023 (referred as the Publication in this paper).

Lastly, measured data from inclinometers and strain gauges installed on site will be reviewed and discussed.

2 PROJECT BACKGROUND

The project involves extensive deep excavation work with a depth of approximately 14m with an area of approximately 260 meters by 95 meters. This excavation features sheet pile and clutched pipe pile walls, supported

Proceedings DOI: 10.21467/proceedings.7.7; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-989164-3-3

by four layers of struts. Located on flat, reclaimed land in Kwai Chung, the site was developed as part of the container terminal expansion in the early 1990s.

The geological profile of the site comprises a sequence of fill, alluvial clay, alluvial sand/silt, completely to highly decomposed granite, and moderately to slightly decomposed granite. Refer to Figure 1 for soil profile. The fill from the reclamation is found to be between 22 meters and 34.5 meters thick, meaning that most of the excavated material consists of the sandy, compacted fill used for reclamation. Located just over 200 meters from the seaside, the site is surrounded by container yards and a car park, covering an area of about 55,245 square meters.

Adjacent to the site are existing utilities from various service providers, including the Water Services Department (WSD), Drainage Services Department (DSD), China Light and Power Limited, The Hong Kong and China Gas Limited, Hong Kong Telecommunications Limited. The diameter of the underground utilities range between 0.1meters and 1.65meters.

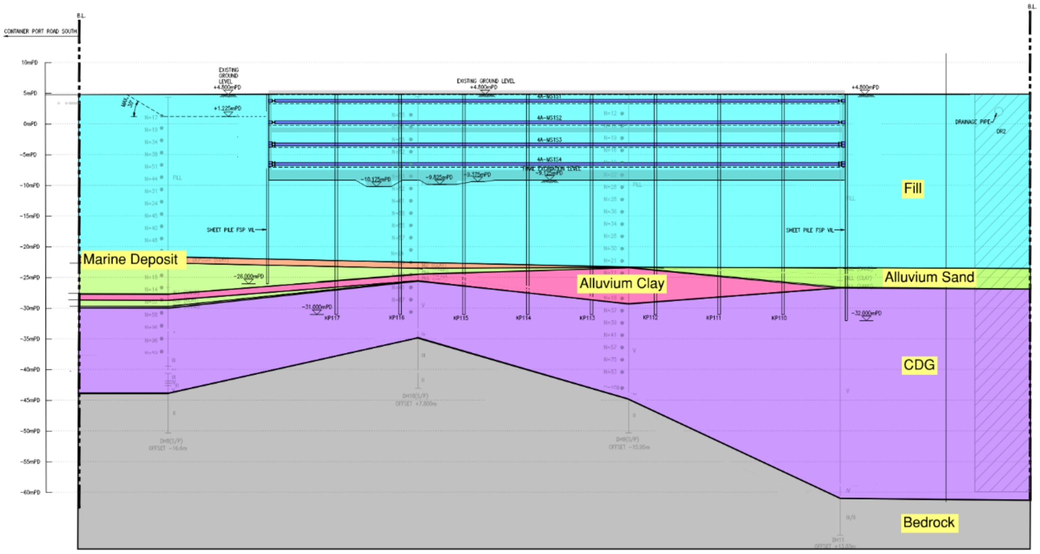


Figure 1: Section drawing of soil profile

3 GROUND SETTLEMENT

3.1 Original monitoring scheme

Prior to the introduction of the new publication, the ground settlement limit at the Site was set at 25mm, a standard commonly used across Hong Kong, primarily based on PNAP APP-137. The alert, alarm and action (AAA) level of ground settlement are detailed in Table 1.

Table 1: Alert, alarm and action (AAA) level of ground settlement suggested in PNAP APP-137 (October 2018 revision)

Instrument	Criterion	Alert (mm)	Alarm (mm)	Action (mm)
Ground settlement marker	Total settlement	12	18	25

According to PNAP APP-137 (October 2018 revision), titled "Ground-borne Vibration and Ground Settlement Arising from Pile Driving and Similar Operations," a 25mm empirical ground settlement action limit is recommended and widely adopted throughout Hong Kong. The alert, alarm and action levels were set at 50%, 70% and 100% of the 25mm value. PNAP APP-137 addresses vibrations and settlements that may occur due to foundation and excavation activities, maintaining the same limit regardless of excavation depth or the type of construction work performed.

3.2 Ground settlement trigger level in GEO Publication No. 1/2023

With the introduction of the Publication, the 5A trigger values have been recommended, with the highest-level set at 0.5% of the retained height (He) as shown in Table 2 below.

Table 2: Recommended trigger values for ground settlement monitoring in 5A Approach by GEO

Instrument	Criterion	Alert (mm)	Alarm (mm)	Action (mm)		
				Level 1	Level 2	Level 3
Ground monitoring marker	Total settlement	10	15	20	0.3%He* subject to a range of 25mm to 60mm	0.5%He* subject to a range of 30mm to 100mm

*He = the maximum excavation depth

Unlike the previously adopted PNAP APP-137 guidelines, the maximum values in the 5A trigger levels now vary based on the excavation depth. For this project, 0.5%He equates to a settlement limit of 69mm, given the retained height of 13.925m—significantly larger than the previous 25mm settlement limit. This increase in allowable settlement enables a substantial reduction in the preloading force required on site. Consequently, a submission incorporating the 5A trigger levels and the reduced preloading value was made to the Buildings Department (BD).

3.3 Ground settlement comparison between 3A and 5A trigger levels

Although the largest allowable ground settlement has been increased from 25mm to 0.5%He, the updated 5A trigger level encourages a quicker response from the project team to any measured ground settlement. A comparison between the 3A and 5A trigger levels, for this Project, is detailed in Table 3.

From this table, it is evident that the alert, alarm, and action level 1 in the Publication have lower settlement values compared to PNAP APP-137. Additionally, the Publication recommends earlier inspections and necessary measures when the first action level is reached. Consequently, the new ground settlement allowance ensures that potential issues are addressed promptly, minimising risks associated with settlement.

Table 3: Trigger values comparison in 3A and 5A approaches in monitoring ground settlement in Kwai Chung

Instrument	Criterion	Approach of Setting Trigger Values	Alert (mm)	Alarm (mm)	Action (mm)		
					Level 1	Level 2	Level 3
Ground monitoring marker	Total settlement	3A Approach (PNAP APP-137)	12	18	25		
		5A Approach (GEO Publication No. 1/2023)	10	15	20	41*	69*

*= the calculated trigger value is rounded to nearest integer

In the most recent update to PNAP APP-137, which was revised and published in November 2024, the monitoring control table has been expanded to include 5As instead of the previous 3As. However, the highest action level, Level 3, remains an empirical value of 25mm, consistent with the suggested value in the previous version, as shown in Table 4.

Table 4: Recommended 5A values for ground settlement monitoring in PNAP APP-137 (November 2024 revision)

Instrument	Criterion	Alert (mm)	Alarm (mm)	Action (mm)		
				Level 1	Level 2	Level 3
Ground monitoring marker	Total settlement	12	18	20	22	25

PNAP APP-137 also mentions that the engineering approach for assessing ground settlement is an alternative to the empirical 25mm limit. Site-specific limits can be established by referring to Appendix C of PNAP APP-24, which primarily addresses works related to railway structures and facilities. However, Appendix C of PNAP APP-24 indicates that the suggested monitoring control mechanism is still based on the 3A system, which is different to the updated 5A monitoring control mechanism detailed in GEO Publication No. 1/2023.

4 SERVICE/ BUILDING MONITORING LIMIT

In addition to ground settlement, GEO Publication No. 1/2023 also addresses service/building monitoring limits. However, the limits for alerts, alarms, and actions remain unchanged. Table 5 provides a comparison of the AAA/trigger levels between PNAP APP-137 and the Publication.

Section 9.2.2.4 of the Publication highlights that the suggested action level 1 to 3 suggested have been set in alignment with recent WSD guidelines. For water mains made of different materials, deformation should be controlled within a range of 1:400 to 1:200. As a result, the updated action limits for Levels 1, 2, and 3 are set at 1:400, 1:350, and 1:300, respectively.

These updated action levels promote a quicker response from the contractor and mandate more frequent reviews once action level 1 is reached. This proactive approach aims to ensure that any potential issues are addressed swiftly, enhancing the project's safety and efficiency.

Table 5: Trigger values comparison in 3A and 5A approaches in monitoring services

Instrument	Criterion	Approach of Setting Trigger Values	Alert	Alarm	Action		
					Level 1	Level 2	Level 3
Services monitoring marker	Angular distortion	3A Approach (PNAP APP-137, Oct 2018)	1:600	1:450	1:300		
		5A Approach (GEO Publication No. 1/2023)	1:600	1:500	1:400	1:350	1:300
Building monitoring marker		3A Approach (PNAP APP-137, Oct 2018)	1:1000	1:750	1:500		
		5A Approach (GEO Publication No. 1/2023)	1:1000	1:750	1:600	1:550	1:500

5 DESIGN GROUNDWATER LEVEL

5.1 Original design water levels

Before the release of the Publication, the common approach for determining design groundwater levels (DGWL) was as follows:

For the design groundwater level, the usual practice was to use the greater of either the highest measured groundwater level plus 2 meters or one-third of the retained height. GCO Publication No.1/90 did not provide specific guidance on DGWL, which led some Engineers to refer to Geoguide 1 for suggestions. According to Section 8.2.1 of Geoguide 1, the design for retaining walls should consider the worst credible groundwater conditions that might occur during extreme events such as heavy rainfall, flooding, or water main bursts. However, Geoguide 1 primarily addresses permanent works, with DGWL intended for a much longer design life than that of ELS design.

In this Project, before implementing GEO Publication No. 1/2023, the Serviceability Limit State (SLS) water level and Ultimate Limit State (ULS) water levels were set at +3.03mPD and +3.66mPD, respectively. The SLS water level was used for assessing deflection, while the ULS water level was applied for structural and stability checking. The +3.03mPD level represents the extreme sea level at Victoria Harbour with a five-year return period, measured at the Quarry Bay/North Point station. Meanwhile, the +3.66mPD level corresponds to the extreme sea level with a fifty-year return period at the same location. The ULS water level is also approximately 2meters above the measured highest groundwater level +1.87mPD. These levels were agreed upon in discussions with the GEO, considering the site's proximity to the sea.

The predicted tidal levels at Kwai Chung in 2024 indicate that the highest tide level, reaching +2.8mPD, was expected to occur in November.

5.2 Design groundwater levels in GEO Publication No. 1/2023

In the Publication, three design groundwater levels are recommended, as shown in Figure 2 below: the DGWL for ULS and two DGWL for SLS. The two SLS levels are the design high groundwater level (DHGWL) and the design low groundwater level (DLGWL).

The DHGWL should be based on a realistic estimation of the highest groundwater level and is used for assessing wall deflection and settlement caused by excavation. The DLGWL is utilised to determine acceptable ground settlement resulting from groundwater level drawdown outside of the excavation area.

As outlined in section 6.5 of the Publication, the DGWL should reflect possible scenarios that may occur during the temporary nature of ELS works. It is not necessary to account for effects from long-term and extreme events, such as those due to climate change. The Publication also advises against setting the SLS level too high for projects that involve preloading of struts to control wall deflection. This caution is due to the potential for adverse effects at higher-level struts when lower-level struts are preloaded excessively high. Furthermore, section 4.4.1 notes that excessive preloading can be counterproductive, as it may damage grout curtains, nearby utilities, and underground structures.

Additionally, the Publication notes that in reclaimed land, groundwater levels can be significantly influenced by tidal variations, with attenuation and lag depending on the permeability of the fill material, storage capacity, and horizontal distance from the shoreline.

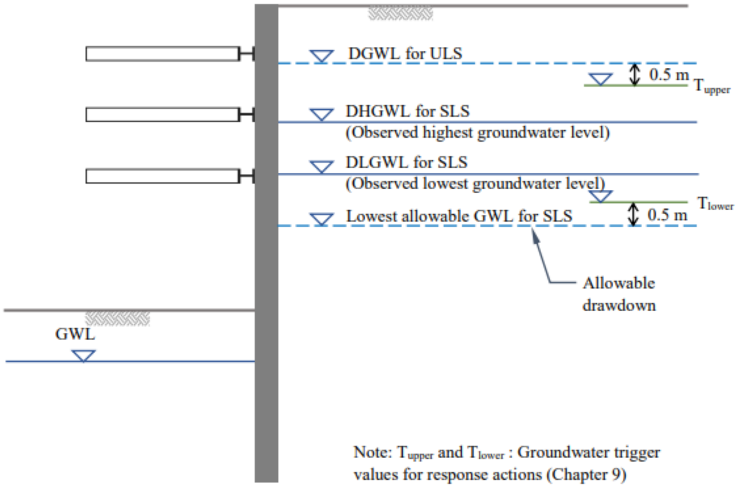


Figure 2: Recommended designed groundwater level by GEO for impact assessment. Extract of Figure 6.7 of GEO Publication No. 1/2023

During the site investigation period of the Project, standpipes were installed, and monitoring was conducted over a seven-day period. Additionally, before the contractor Gammon Construction Limited (GCL) was awarded, a comprehensive groundwater monitoring program was conducted over a nine-month period from January 2023 to October 2023, capturing data during typhoon and black rain storm event in early September 2023.

Once GCL commenced construction, daily groundwater monitoring was performed using standpipes installed on site. Overall, intensive monitoring was carried out over a 12-month period from August 2023 to August 2024 following contract award. Figure 3 provides a sample overview of the groundwater measurements.

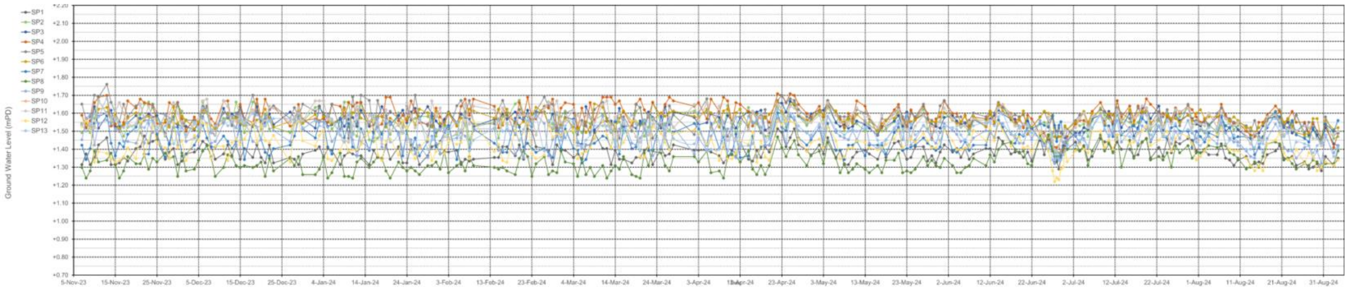


Figure 3: Sample overview of groundwater measurement on site

The measured groundwater levels on site generally ranged between +1.2mPD and +1.8mPD. Thus, by the time GEO Publication No. 1/2023 was applied and submitted to government authorities, a 21-month monitoring period had been completed, from January 2023 to September 2024, covering two wet seasons with typhoons and heavy rains.

With the highest recorded groundwater level being +1.87mPD throughout this long 21-month period, including during wet seasons with typhoons and heavy rain, the submission proposed a DHGWL for SLS of +1.9mPD, which received approval.

With sufficient data obtained from the 21-month groundwater monitoring period, the SLS water level was successfully reduced from +3.03mPD to +1.9mPD. This demonstrates the advantages of maintaining comprehensive groundwater monitoring records prior to the project's commencement. The reduction in DGWL and the increase in the settlement limit allowed for a considerable decrease in the preloading value (up to 80-90% at lower level) of the struts, as well as a reduction in the size of the struts required, if materials have not been purchased. Additionally, it provided greater flexibility in the sequence of strut removal, facilitating safer and easier construction of the permanent slabs. For instance, it became possible to remove more than 1 layer of struts before the construction of permanent slabs above them.

6 APPROVAL PROCESS

During the submission of the ELS packages, which included a proposal for a higher settlement limit and an updated DGWL, stakeholders across the project area had varied responses. Since GEO Publication No. 1/2023 is relatively new to approval bodies, public and private stakeholders, the design team had to put in extra effort to explain the changes and guidelines outlined in the document. Despite receiving governmental approval from BD, GEO, WSD, DSD and Highways Department, the project team still needed to engage with all utilities stakeholders to secure their approval or ensure no adverse comments regarding the higher settlement limit.

As the project team reached out to various utility providers, they received acceptance of the higher settlement limit from all public entities. Among the three private or semi-private stakeholders surrounding the sites, two accepted or conditionally accepted the proposal without significant issues. However, one stakeholder expressed concerns about their services and would not agree to increase the settlement limit beyond 25mm. Consequently, additional settlement points were established for the concerned party, ensuring that the settlement limit for their installed services remained at 25mm, while other utilities can be monitored under the new 5A scheme.

7 MEASURED DATA AND PREDICTION

In this project, the horizontal support system consists of flying struts, corner struts, and trusses. The design team has reviewed monitoring data, including ground settlement, utility measurements, inclinometer readings, and strain gauge recordings. This section briefly discusses the ground settlement data before focusing on the analysis and interpretation of inclinometer data near the flying struts, as well as strain gauge measurements installed on these struts. The findings from these instruments offer insights into the support system's performance, allowing for comparison between predicted and observed behaviour during preloading and excavation. Figure 4 presents the layout of the ground settlement markers, inclinometers, and strain gauges discussed in the subsequent sections.

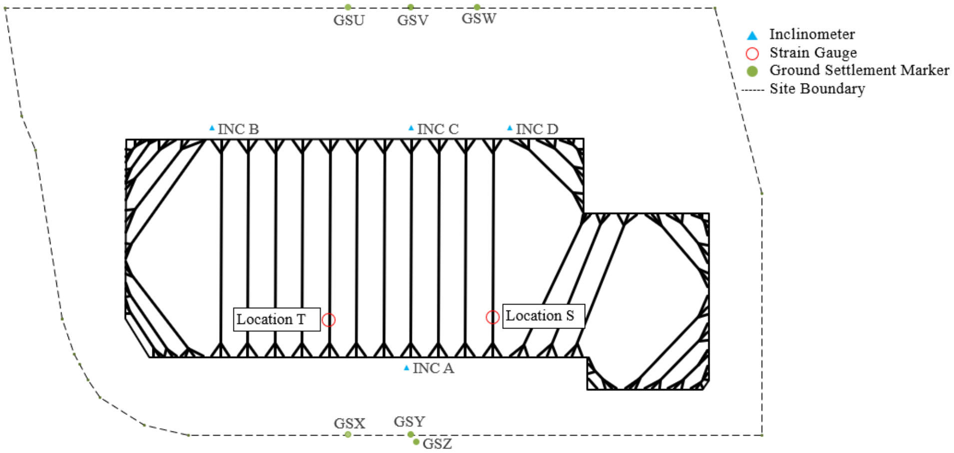


Figure 4: Schematic layout plan of ground settlement markers, inclinometers and strain gauge. Tie/Bracing has been omitted for clarity

7.1 *Ground Settlement*

Although the approved 5As settlement criteria permit settlements of up to 69mm, the predicted settlement exceeded 40mm in only a few isolated locations. As illustrated in Figure 4, the ground settlement markers on this site were installed at a considerable distance from the piled wall, primarily near the site boundary, which is at least 30 m away from the excavation. The predicted settlement at the final excavation stage was approximately 15 mm and the measured settlement at those markers was around 5 to 6 mm.

7.2 *Inclinometers*

Nine inclinometers have been installed around the excavation area, with approximately half positioned near flying struts. Figure 5 below illustrates the normalised predicted wall movement (to maximum value) at Inclinometer INC-A alongside the actual inclinometer measurements' normalised shape at each stage of excavation from Layer 2, until the final excavation level (FEL) is reached. The predicted wall movements were derived from a Plaxis 2D model, providing a comparative basis for assessing the accuracy of the design assumptions and the actual behaviour of the excavation support system.

The comparison in Figure 5 reveals that the measured displacements at the top of the wall consistently exceed the predicted values, likely due to additional surcharge loads at ground level, such as those induced by traffic or construction plant activity. In contrast, the recorded displacements at the base of the inclinometer are notably smaller than those predicted by the Plaxis model. This discrepancy may result from the presence of stiffer material at the wall toe, leading to less mobilisation of the lower wall section compared to the model's predictions.

Although not illustrated in Figure 5 for clarity, the data indicates that the wall experienced a measurable but not significant reduction of wall's deflection compared to the values predicted by the numerical model. This discrepancy suggests that while the preloading process restrained wall deflection, the actual behaviour of the wall deviates slightly from the modelled assumptions, potentially due to factors such as soil-structure interaction or variations in ground conditions.

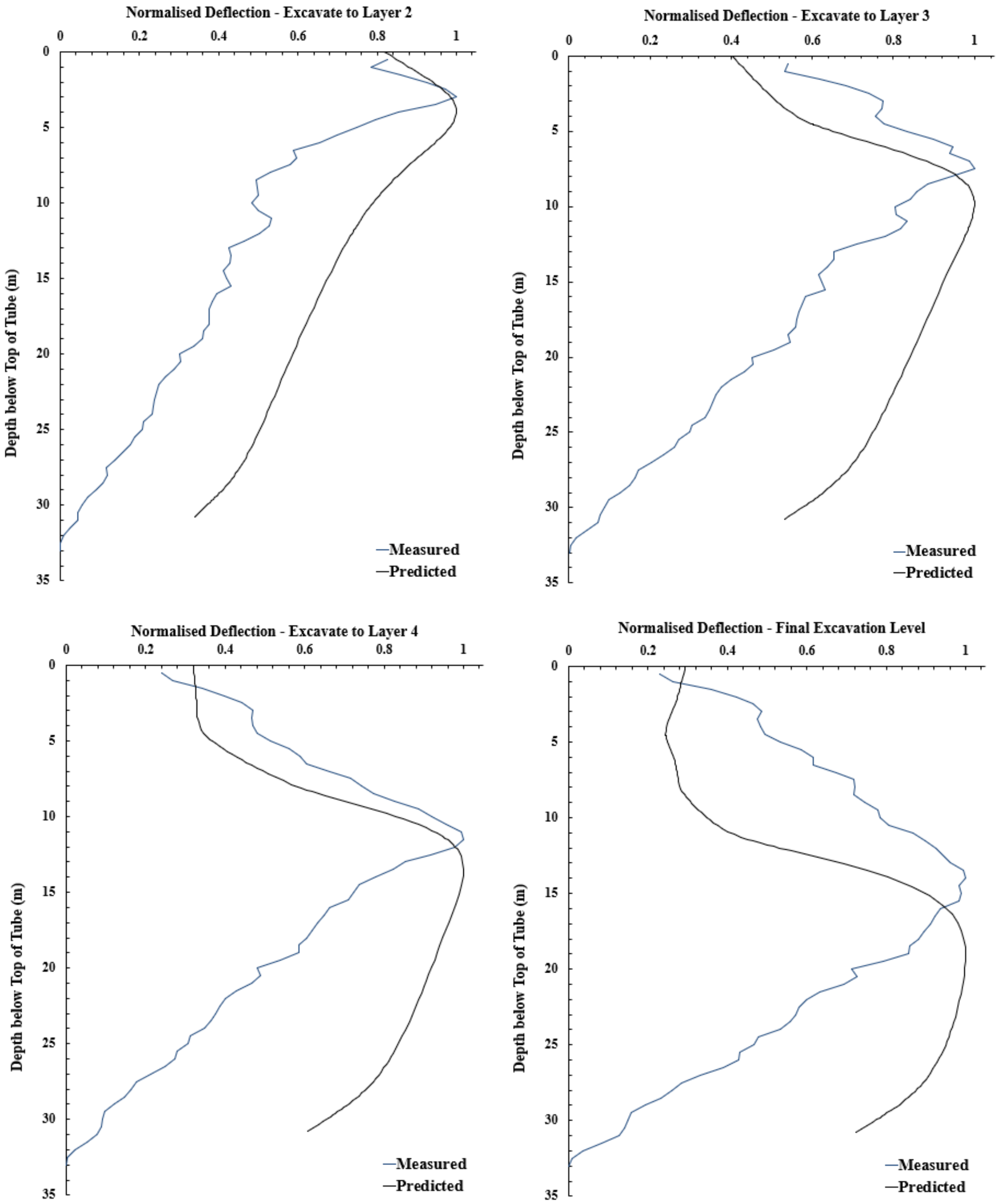


Figure 5: Inclinometer A’s predicted shape and measurements at excavation to Layer 2, Layer 3, Layer 4 and FEL

Following the final excavation stage, the inclinometer readings from four inclinometers (INC A to INC D) adjacent to the flying struts are presented below in Figure 6. For majority of the inclinometers, the top of the wall exhibits larger deflections than predicted. In contrast, the bottom of the inclinometers remains relatively stable, showing minimal displacement, contrary to the expected behaviour, as mentioned previously.

All struts exhibited the largest deflection around the Layer 4 excavation level, although the observed behaviour differs slightly from the Plaxis model predictions, which indicated peak deflection at or below final excavation level. The soil below the excavation level may be stiffer than predicted, enhancing wall stabilisation, effectively limiting substantial outward displacement beneath the excavated zone, a finding consistent with INC A’s earlier observation.

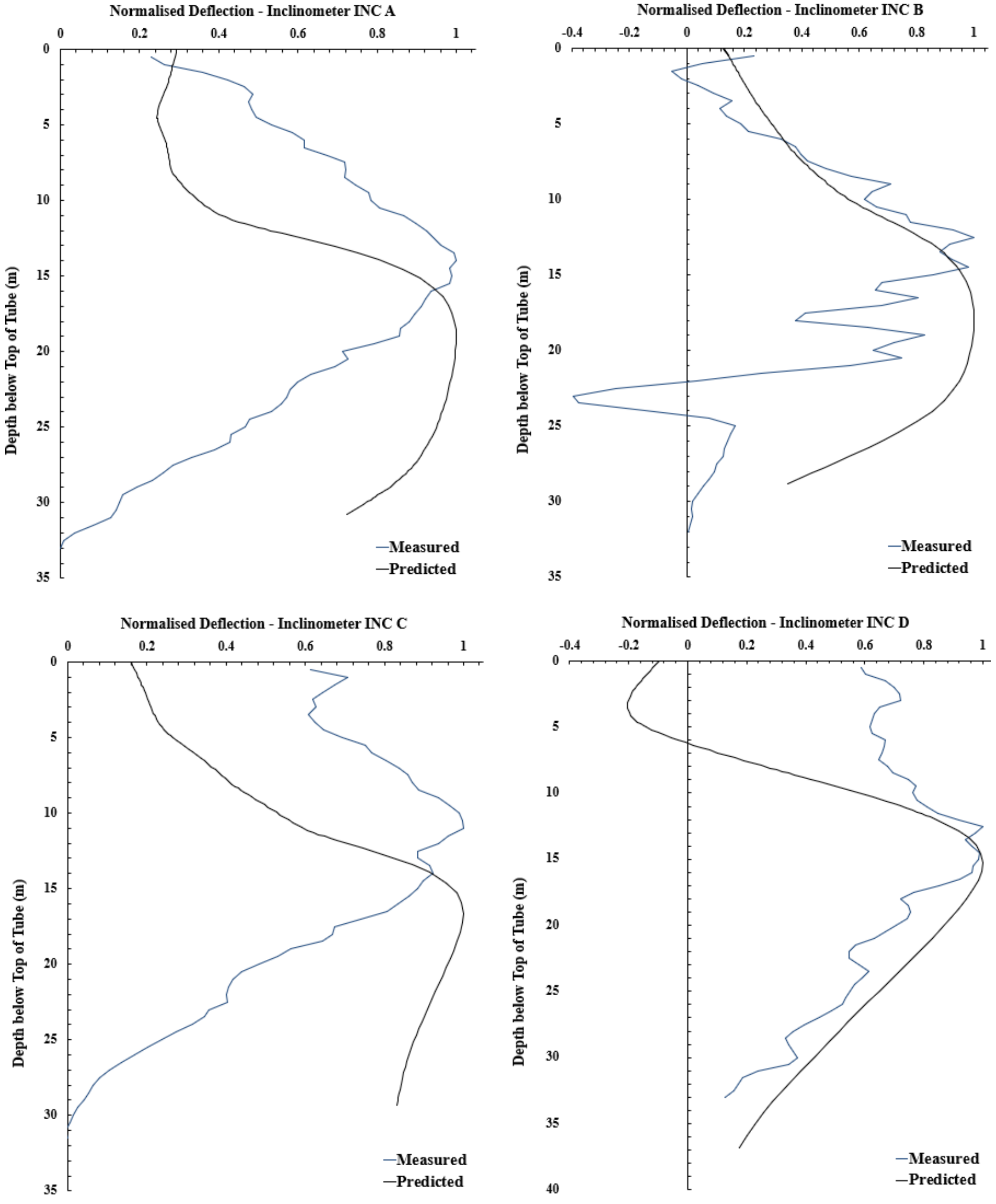


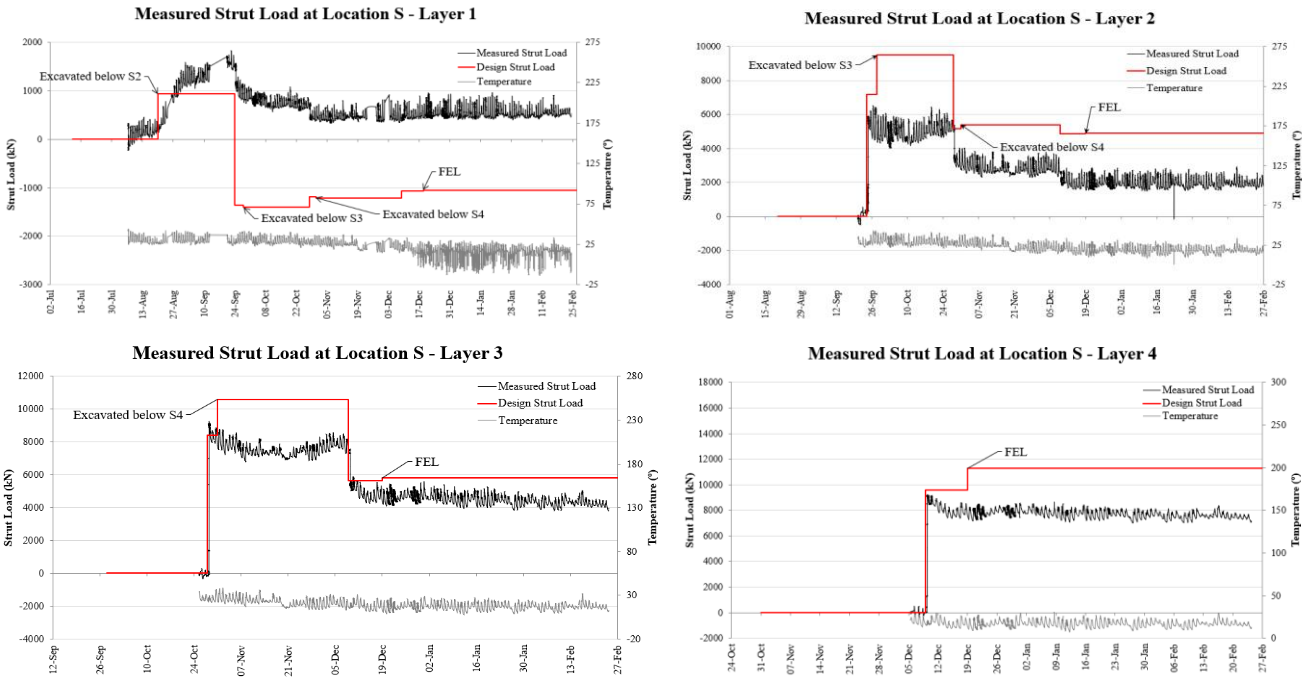
Figure 6: Inclinometer predicted shape and measurements at final excavation stage for INC A, INC B, INC C and INC D

In the case of inclinometer INC B, which recorded displacement in the opposite direction, the unusual readings are likely due to instrument damage or malfunction, as they deviate significantly from the expected trends and the behaviour observed in other inclinometers. These findings highlight the importance of cross-verifying instrument data and considering potential anomalies when interpreting results.

7.3 Strain gauges

Strain gauges have been installed on selected struts across the cofferdam, with data from those placed on the flying struts presented below. By analysing the strain gauge data, it is possible to determine whether the preloading value is maintained within the strut and whether the actual strut load deviates from the anticipated values.

The plots in Figure 7 present strain gauge measurements converted to strut load for the first to fourth layers, comparing them against the predicted SLS design loads at Location S. The plots reveal that strut loads fluctuate with daily temperature variations. Frequent strain gauge readings are especially valuable for verifying preloading values during preloading stage. Table 6 summarises the comparison between measured and predicted strut loads, especially during the FEL stage, along with key observations on strut load behaviour.


Measured Strut Load at Location S - Layer 1

Measured Strut Load at Location S - Layer 2

Measured Strut Load at Location S - Layer 3

Measured Strut Load at Location S - Layer 4

Figure 7: Strain gauge reading at Location S

Table 6: Comparison between measured and predicted strut load at Location S

Layer	Preload	Measured Load vs Predicted Load at FEL	Observation
1	No	Measured: 750kN Predicted: -1050kN	- Predicted tension not achieved - Possible due to additional surcharge on ground
2	Yes	Measured: 2000kN Predicted: 4900kN	- Lower load maybe due to higher than anticipated load in Layer 1 - Measured load at FEL is 41% of predicted value
3	Yes	Measured: 4200kN Predicted: 5810kN	- Strut load remained relatively stable for further excavation - Measured load at FEL is 72% of predicted value
4	Yes	Measured: 7600kN Predicted: 11270kN	- Strut load remained relatively stable for further excavation - Measured load at FEL is 67% of predicted value

Figure 8 illustrate the measured strut loads for the first to fourth layers at Location T compared to their SLS design loads. The load pattern at this location differs slightly from that observed at Location S.

Table 7 provides a summary of the comparison between measured and predicted strut loads at FEL, along with key observations on their behaviour.

Overall, the strain gauge measurements from both Location S and Location T closely align with the design predictions. Majority of the measured strut loads are consistent with the anticipated values and the measured strut loads did not exceed their ultimate structural capacity at any stage. Notably, both strain gauges recorded higher-than-predicted strut loads immediately following the installation of the Layer 1 strut. However, as excavation levels progressed, the strut load in Layer 1 gradually decreased.

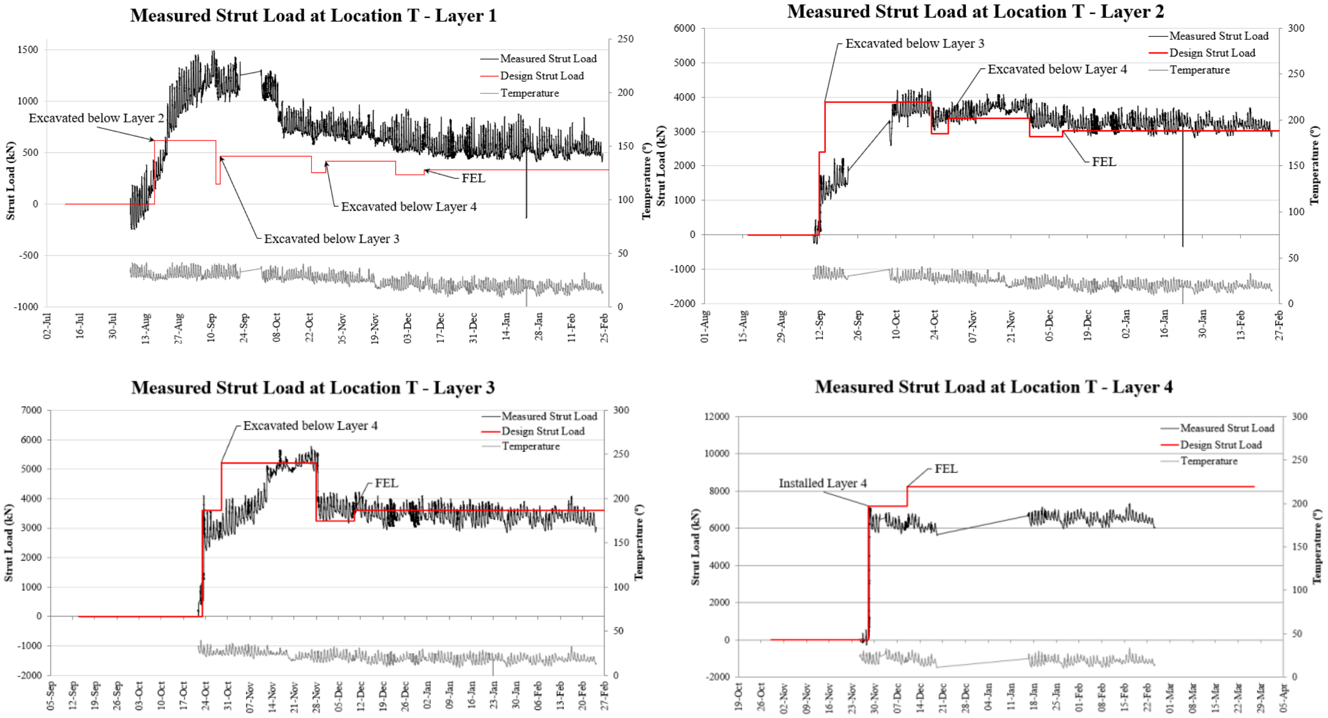


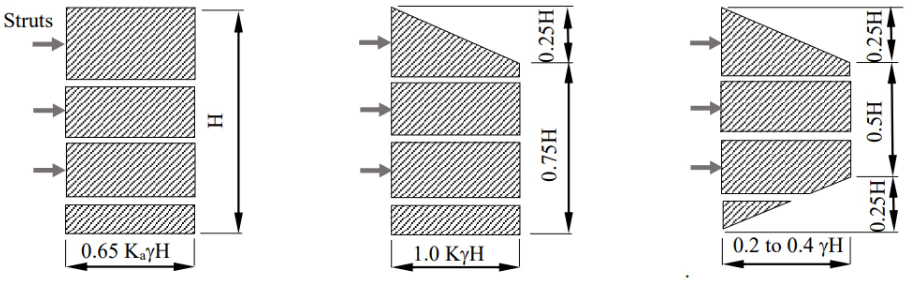
Figure 8: Strain gauge reading at Location T

Table 7: Comparison between measured and predicted strut load at Location T

Layer	Preload	Measured Load vs Predicted Load at FEL	Observation
1	No	Measured: 550kN Predicted: 330kN	- Measured values remained within structural capacity - Measured load at FEL is 60% of predicted value
2	Yes	Measured: 3200kN Predicted: 3010kN	- Temporary loss of connection - Measured load at FEL is 94% of predicted value
3	Yes	Measured: 3200kN Predicted: 3600kN	- Measured load at FEL is 89% of predicted value
4	Yes	Measured: 6300kN Predicted: 8230kN	- Measured load at FEL is 77% of predicted value

Regarding the higher-than-anticipated Layer 1 strut loads, comparison with results from a conventional empirical formula (as specified in the Publication Section 7.6.3 for multi-level strutted wall and illustrated in Figure 9) reveals close agreement between calculated and measured values. The observed discrepancy between the measured loads and the numerical model predictions, yet similarity with the values derived from the formula, can likely be attributed to lack of soil interaction with the piled wall in actual condition. In this early stage of excavation, a greater portion of the lateral load is transferred to the strut compared to the distribution along the piled wall predicted by the numerical model.

Despite this, the strain gauge results from both locations, aside from the higher-than-expected Layer 1 measured load, demonstrate a strong correlation with the design assumptions. Additionally, each strut experienced its peak load during the excavation phase, prior to the installation of the subsequent strut layer. This pattern underscores the importance of timely installation and the redistribution of loads as excavation advances. The observed behaviour further validates the design approach and provides confidence in the structural performance of the system.



$K_a = \tan^2 (45 - \frac{\phi'}{2})$

$K = 1 - m\frac{4s_u}{\gamma H}$

m = 1.0 except where the excavation is under-lain by deep soft normally consolidated clay, then m = 0.4

(a) Sand (b) Soft to Medium Clay (c) Stiff-fissuerd Clay

where γ = Bulk unit weight of soil

Figure 9: Apparent pressure diagram for computing strut loads in strutted excavations. Extract of Figure 7.20 of GEO Publication No. 1/2023

8 CONCLUSION

The recently published GEO Publication No. 1/2023 aims to promote more economical designs for ELS works, reduce construction time, and enhance ground settlement monitoring and control. At the Project, ELS submissions incorporating the new publication were successfully approved, resulting in more efficient designs. Monitoring data from inclinometers and strain gauges adjacent to flying struts generally align well with design assumptions, though minor discrepancies were observed in some instances. As more projects in Hong Kong adopt the guidelines from GEO Publication No. 1/2023 and contribute performance data and insights, the industry can further refine these guidelines to develop more sustainable solutions for ELS construction.

ACKNOWLEDGEMENTS

The authors would like to thank the whole project team for the support, contribution and participation on the project.

REFERENCES

Buildings Department (BD). 2022. *PNAP APP-24 – Railway Protection under Railways Ordinance, Mass Transit Railway (Land Resumption and Related Provisions) Ordinance and Area Number 3 of the Scheduled Areas in Schedule 5 to the Buildings Ordinance*. Buildings Department, Hong Kong Special Administrative Region Government.

Buildings Department (BD). 2018. *PNAP APP-137 – Ground-borne Vibrations and Ground Settlements Arising from Pile Driving and Similar Operations*. Buildings Department, Hong Kong Special Administrative Region Government.

Buildings Department (BD). 2024. *PNAP APP-137 – Ground-borne Vibrations and Ground Settlements Arising from Pile Foundation and Excavation and Lateral Supports Work*. Buildings Department, Hong Kong Special Administrative Region Government.

Geotechnical Control Office (GCO). (1990). GCO Publication No. 1/90, *Review of Design Methods for Excavations*. Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong Special Administrative Region Government.

Geotechnical Engineering Office (GEO). (2020) Geoguide 1 *Guide to Retaining Wall Design* (2020 Version). Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong Special Administrative Region Government.

Geotechnical Engineering Office (GEO). (2023) GEO Publication No. 1/2023, *Deep Excavation Design and Construction*. Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong Special Administrative Region Government.