Design of Protection Measures for Deep Excavation of A New Underground Station Closely Adjacent to Viaduct of MRT System in Operation

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Abstract

Due to limited land space in urban area, interchange MRT stations have to be constructed closely adjacent to existing system. Geotechnical design of new station has to ensure the safe operation of existing line. This paper presents a new underground MRT station located within 1 m of the foundation of viaduct of MRT line in operation with ridership more than 200,000 persons per day. Deformations inducted by deep excavation have to be controlled Deformations induced by deep excavation have to be controlled carefully to meet the rigorous limit values set up by Regulation of Building Restrictions along MRT Facilities. Sophisticated 2D/3D finite element (hereafter FEM) analyses have been performed to simulate the sequence of diaphragm wall constructions and Bottom-up deep excavation with pre-stress strut system. Deformation behaviors of adjacent viaduct foundation and pier are evaluated carefully. Various protection measures such as ground improvement of double packer grouting, buttress wall to enforced diaphragm wall and enlargement of existing pile caps are simulated and studied. The results demonstrate that combination of pile cap enlargement and grouting provide best protection of existing pile foundations.

Keywords: Deep excavation, Protective measures, Numerical modelling, Taipei MRT

1 Introduction

A new underground interchange station is located close to the viaducts of MRT line in operation to provide platform-to-platform transformation services. Excavation of the new station has to ensure the safe operation of the existing MRT line which provide more than 200,000 daily ridership.

Dimitrios Iliadelis (2006) indicated that in dense urban environments where land is scarce and buildings are closely spaced, cut-and-cover excavations are widely used for basement construction and development of underground transit facilities. Maruf and Darjanto (2015) indicated the excavation next to existing building or structure is one of the most problems in geotechnical practices. Research and investigation in this area had been conducted till recent time. Mandy Korff et al. (2016) indicated that underground construction supports the quality of life in cities by improving the availability and quality of the space above ground. Tunnels and deep excavations can, however, not be realized without affecting adjacent structures.

This paper presents the analysis and design of various protection measures for deep excavation around 24m adjacent to the foundations of viaducts in operation. This study conducted with 2D/3D FEM methods to simulate the ground condition, engineering properties of two systems, construction arrangements and processes.

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2 Geotechnical Properties

Information about the soil conditions along this area was interpreted from geotechnical investigation results at site and laboratory. Three geological bore holes with depths around 30 m have been conducted in this area. The geotechnical properties and design parameters are listed in Table 1. The ground formation in this area are divided into five layers, which includes backfill sand, silty clay, silty sand, boulders, and soft sand stone and shale interbedded, respectively. Ground water table is around 5m to 11m below ground surface.

Table 1. Geotechnical Parameters for Design

Layer	Soil type	Depth (m)	γ_t (t/m^3)	S_u (t/m^2)	C' (t/m^2)	ϕ' (degree)	E (kN/m^2)
1	SF	6	2	-	2	30	15385
2	CL	9	1.85	3	-	-	15000
3	SM	14	1.9	-	0	30	15385
4	GM	17	2	-	0	33	76923
5	SS/SH	40	2.47	-	5.6	35	104710

where γ_t: total unit weight of soil, S_u: undrained shear strength of soil, C': drained shear strength of soil, ϕ': drained friction angle, E: modulus of elasticity of soil.

3 Structural Information of Retaining Wall System and Existing Foundations of Viaduct

The depth of excavation of the new underground interchange station is 24 m. To minimize the impact of exist MRT line in operation, high stiffness and water tight diaphragm wall system is adopted. The thickness of diaphragm wall is 1.0 m to ensure the safety, constructability and economy of retaining wall system. Due to the rigorous rail deformation limits, displacement less than 15 mm, inclination less than 1/750, set by Regulation of Building Restrictions along MRT Facilities, additional protection measures are required to install around the adjacent foundation of viaducts.

The location of the new underground station and the existing viaduct foundations is shown in Figure 1. The foundations of viaducts (number 01, 02 and 03) located close to the new underground station. The distance between the existing foundations to the diaphragm wall is about 1 m. The foundation type is concrete bore piles with diameter of 1.2 m and length varied from 13.5 m to 16.0 m. The thickness of the concrete pile caps are 1.2 m and the overburden is about 2.0 m. The configuration profile of existing foundations of viaduct is shown in Figure 1.

4 Design of Protection Measures

Protecting the existing foundation adjacent to new underground station is studied with FEM method to simulate the construction arrangements and processes. Both two dimensional and three dimensional FEM modeling have been performed.

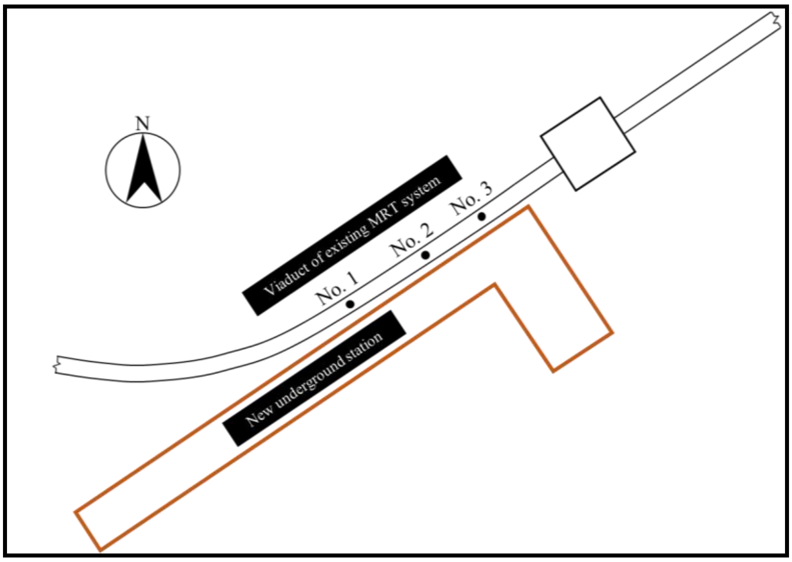

Figure 1: Relative position of the new station and existing viaduct foundations

4.1 Numerical Analysis in FEM for Simulating Various Methods to Protect Adjacent Foundations

4.1.1 Two Dimensional Model

The advantage of two dimensional analysis is time efficient and resources saving. Various construction schemes and alternatives can be studies quickly. Sensitive parameters and critical deformations can be identified through parametric studies. It is observed that ground improvement at greater depths, more than 6 m below ground surface provide better control of lateral deformation induced by excavation of underground station.

Figure 2 shows the sections of 2D FEM model and Table 2 shows the geometric characteristics of the numerical model. The fine element generation mesh as shown in Figure 3. Diaphragm walls were constructed to 26 m below the ground surface with six levels of bracing systems and 16 construction steps to simulate the actual construction processes. The ground water level was set at 8 m below the ground surface. Two schemes of double-packer low pressure grouting ground improvement protection measures have been studied as shown in Table 3. The grouting material properties show in Table 4. Due to the new station close to existing foundations, high grouting pressure would disturb the soil around the existing foundations. The grouting with high pressure is not feasible. Low pressure double packer grouting in silty sand and boulder formation (9 m below ground surface) is adopted as major grout improvement measures.

Scheme 1 is to study the performance of grouting to pile group from 9 m below ground surface to bottom of pile and Scheme 2 is to simulate the effects of grouting between the existing piles and new diaphragm wall as shown in Figure 4 (a) and (b), respectively. Results of numerical analysis of Scheme 1 show maximum horizontal displacement of existing pile is 10.7 mm and the inclination value is 1/614. Both deformation values are exceeding the limit values of 15 mm and 1/750 specified in the regulation. Results of numerical analysis of scheme 2 yield the maximum horizontal displacement of 12.2 mm and inclination value of 1/685. Obviously, the performance of scheme 2 is much better, but the inclination amount is exceeding the limit value of regulation.

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Both of the results of 2D FEM analysis cannot fulfill the limit values specified by the regulations. Part of the reasons is because the two dimensional analysis has simplified the three dimensional behavior into plan strain model which will yield too conservative results and costly solutions.

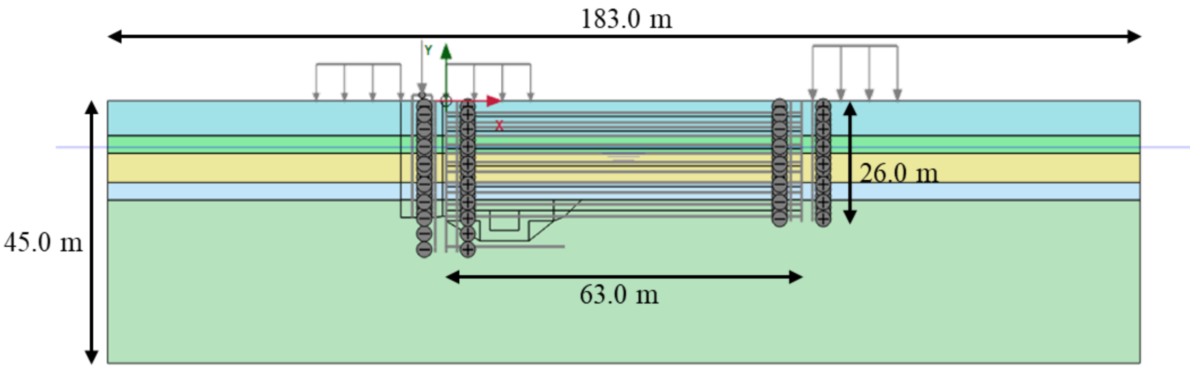


Figure 2: Model geometry in FEM 2D

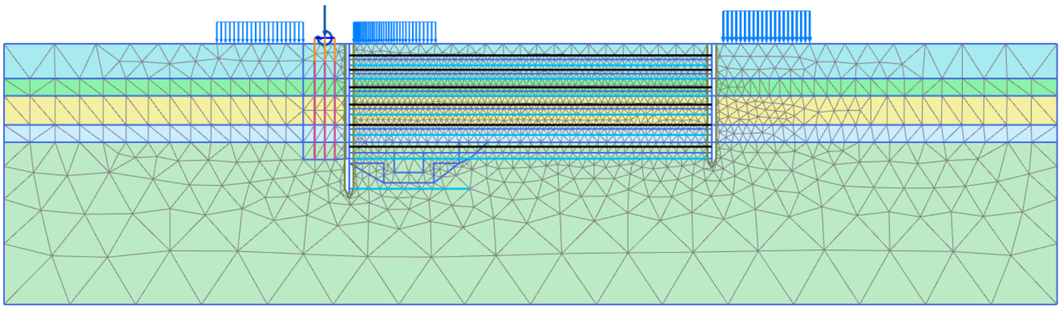


Figure 3: Fine element generation in FEM 2D

Table 2. Geometry characteristics of FEM 2D model.

Geometry characteristics	Values
Dimension of the model	183.0 x 45.0 m
Depth of excavation	24.0 m
Width of excavation	63.0 m
Thickness of diaphragm wall	1.0 m
Depth of diaphragm wall	26.0 m

Table 3. Schemes of ground improvement for 2D simulation

Scheme	Methods	Contents
1	Ground improvement below pile cap	Grouting from 9 m below ground surface to bottom of pile to strength the pile foundation
2	Ground improvement between pile foundation and diaphragm wall	Grouting between pile cap and diaphragm wall from 9 m below ground surface to bottom of pile

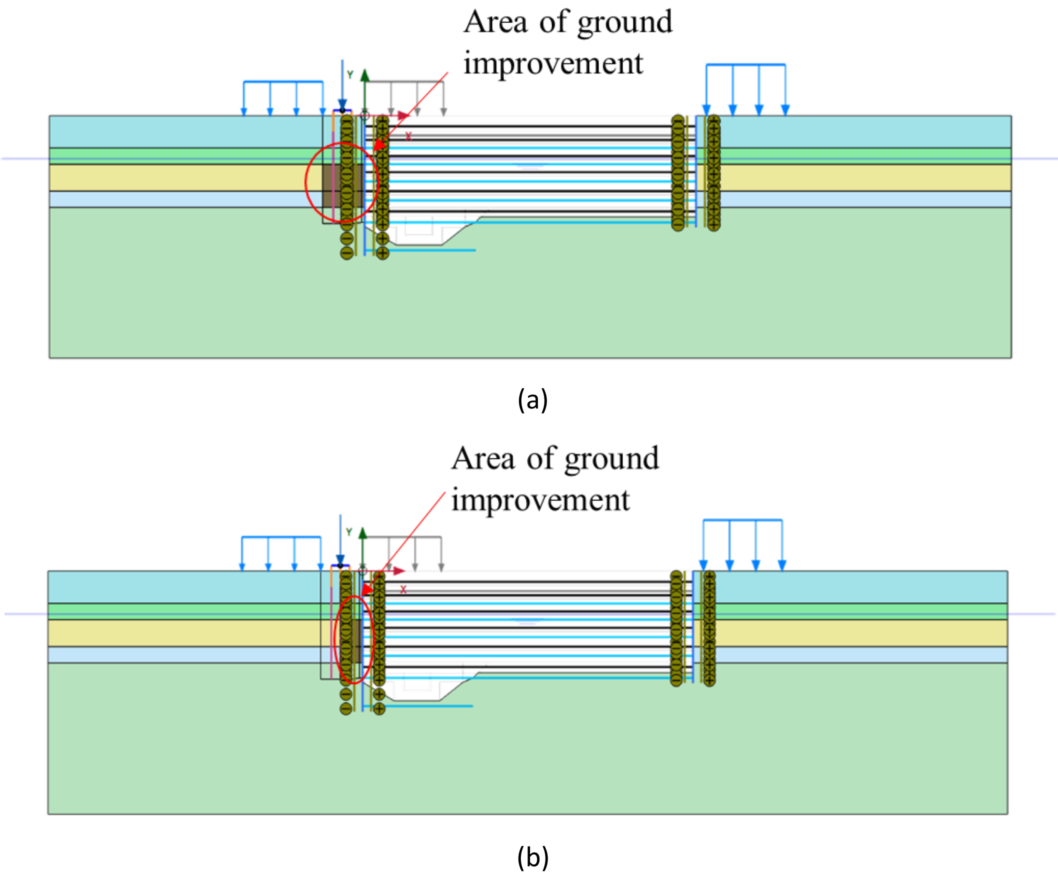


Figure 4: Foundation improvement with double packer low pressure grouting

Table 4. Grouting material properties

γ_t (t/m^3)	S_u (t/m^2)	C' (t/m^2)	ϕ' (degree)	E (kN/m^2)
22.0	50	-	-	20000

4.1.2 Three Dimensional Model

Based on the results of parametric studies of two dimension analysis, three protection schemes have been established to consider the effects of ground improvement and strengthening of existing pile foundation by three dimensional FEM analyses methods. The geometric characteristics of 3D model are shown in Table 5. The fine element generation mesh is shown in Figure 5. Ground improvement, cross walls installation and pile caps enlargements are simulated and evaluated as summarized in Table 6.

Scheme 1 utilize double packer grouting 9 m below ground surface to bottom of piles as shown in Figure 6(a). Scheme 2 provide buttress walls and cross walls to integrate with diaphragm wall of new underground station to minimize the deformation induced by excavation as shown in 6(b). Scheme 3 is to expand the existing pile caps and installed the pre-packed piles to confine the foundation as illustrated in Figure 6(c). Figure 7 illustrated the dimension of existing pile caps expanded. The diameter and length of each pre-packed pile bent installed around the pillars is 0.6 m and 15.8 m, respectively.

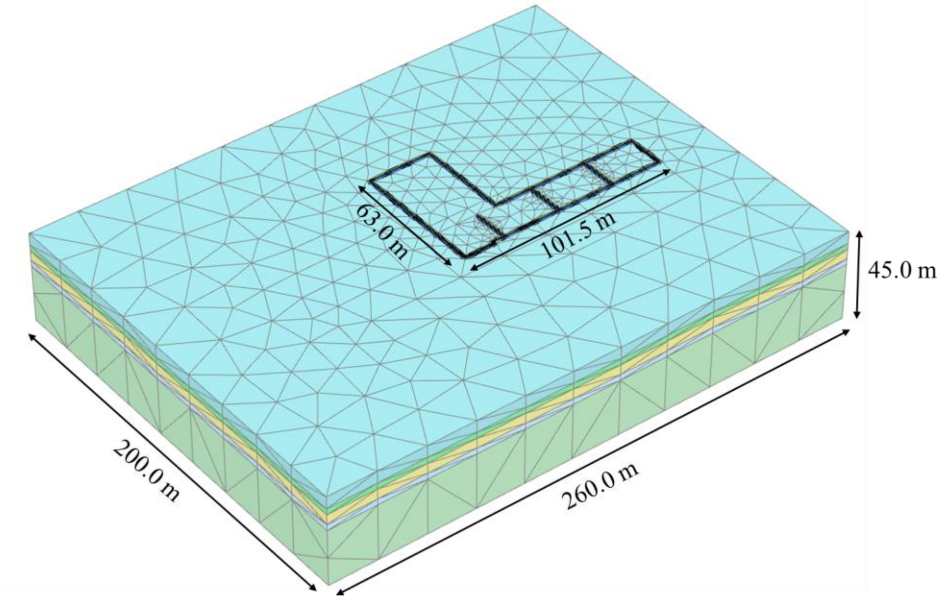


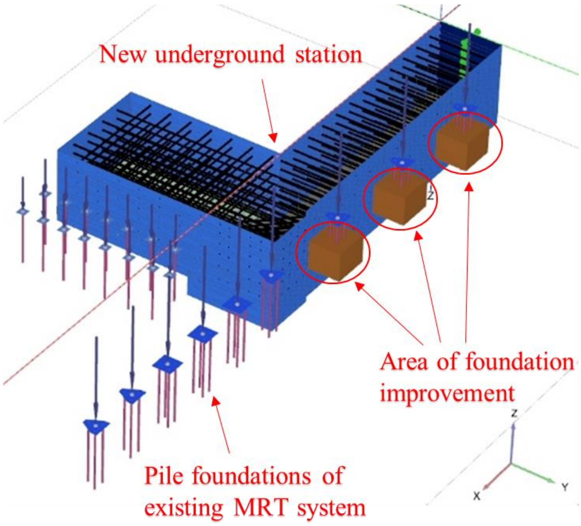
Figure 5: Fine element generation in FEM 3D

Table 5. Geometry characteristics of FEM 3D model.

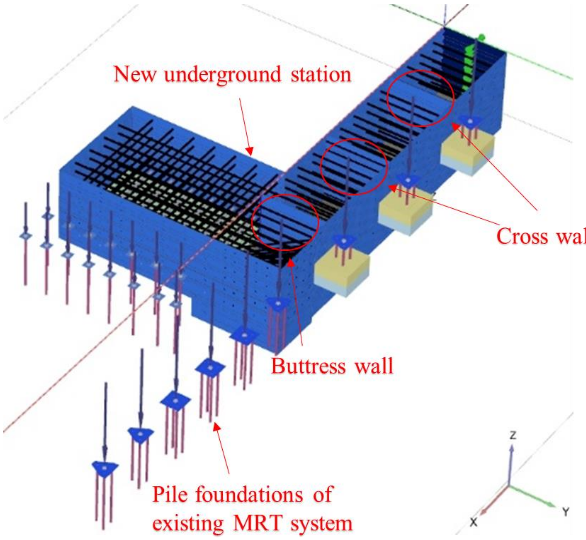
Geometry characteristics	Values
Dimension of the model	260.0 x 200.0 x 45.0 m
Depth of excavation	24.0 m
Width of excavation	63.0 m
Length of excavation	101.5 m
Thickness of diaphragm wall	1.0 m
Depth of diaphragm wall	26.0 m

Table 6. Schemes of Protection Measures for 3D Simulation

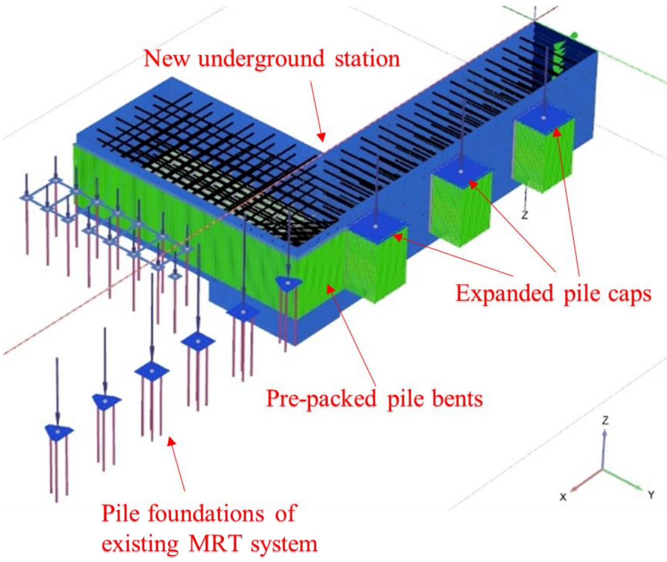
Scheme	Method	Content
1	Double packer grouting	Grouting from 9 m below ground surface to bottom of pile to strengthen the pile foundation
2	Buttress walls and cross walls	Installation of Buttress walls and cross walls adjacent to existing viaduct foundation
3	Pile caps enlargement and pre-packed piles	Enlargement of existing pile caps to 8.1* 8.1 m and installation of pre-packed piles to confine the pile foundation



(a) double packer grouting under the ground surface 9 m



(b) Install buttress walls and cross walls



(c) Expand the existing pile caps and install the pre-packed pile bents

Figure 6: Existing foundations protecting methods

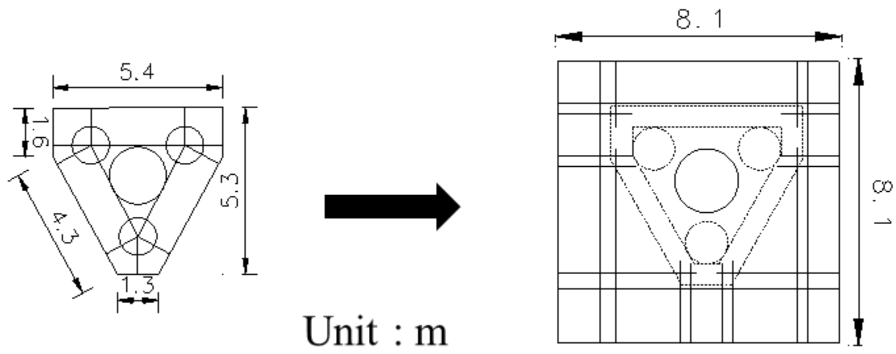


Figure 7: Existing pile caps enlargement

4.2 Results of 3D FEM Analysis

Scheme 1 utilize deep grouting to strengthen the ground around exist pile foundation. Due to three dimensional effects, both displacement and inclination values of pile foundation have been reduced significantly compared with the results of two dimensional analysis. However, it is concerned that the quality of deep grouting is difficult to control especially in mix-ground conditions.

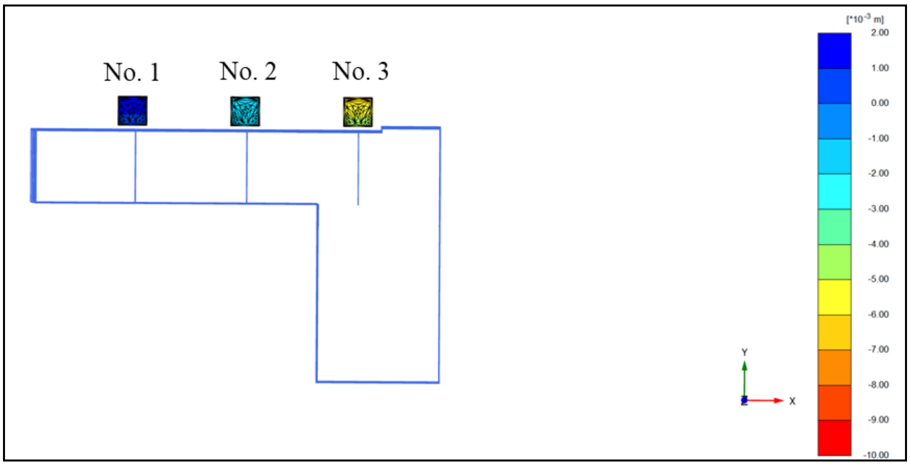
Scheme 2 adopted cross walls and buttress walls to connect with diaphragm wall adjacent to existing pile foundation. Displacements of existing pile foundation have been control effectively. However, the inclination value cannot fulfil the limit value required. Uncertainties due to densely allocated utilities below the road have increased the difficult and risk of this approach. Quality control of the interfaces between cross/buttress walls and diaphragm walls is another critical issue.

Scheme 3 focus on the structure strengthening of existing pile foundations with enlargement of pile cap and installation of pre-packed piles around the pile caps. Both displacements and inclination values are less than the limit values as shown in Figure 8 to 10. Performance of these strengthening works can be ensured with reasonable construction management and quality control.

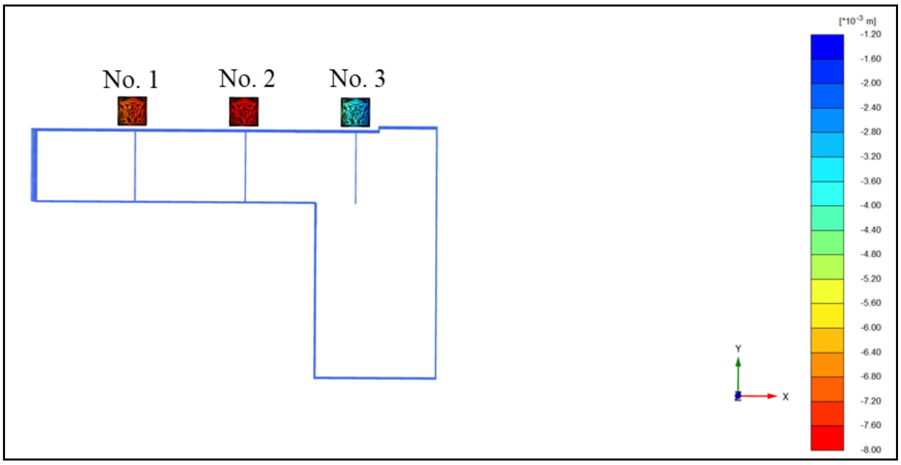
Based on the above evaluations, Scheme 3 has been adopted as final design option and the comparison of these three schemes have been summarized in Table 7.

Table 7. Comparisons of protection measures

Scheme	**Method**	**Max. horizontal displacement (mm)**	**Max. inclination value**	**Construability and quality control**	**Overall performance**
1	Double packer grouting	12.63	1/728, NG	Difficult to control the quality of grouting	Fair
2	Buttress walls and cross walls	7.61	1/494, NG	Significant conflicting with existing utilities, Need careful control of the interface b/w cross walls and diaphragm walls	Poor
3	Pile caps enlargement and pre-packed piles	8.02	1/793	Better control of the performance and quality of strengthening works	Best



(a) x-direction total displacement



(b) y-direction total displacement

Figure 8: Existing foundations horizontal displacement due to the new station deep excavation for scheme 3

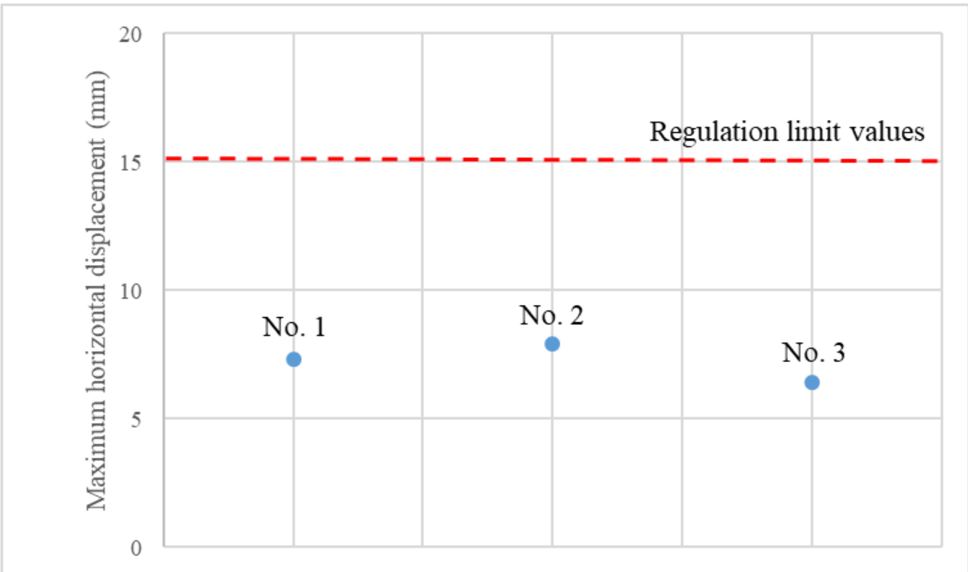


Figure 9: Existing foundations maximum horizontal displacement due to deep excavation for scheme 3

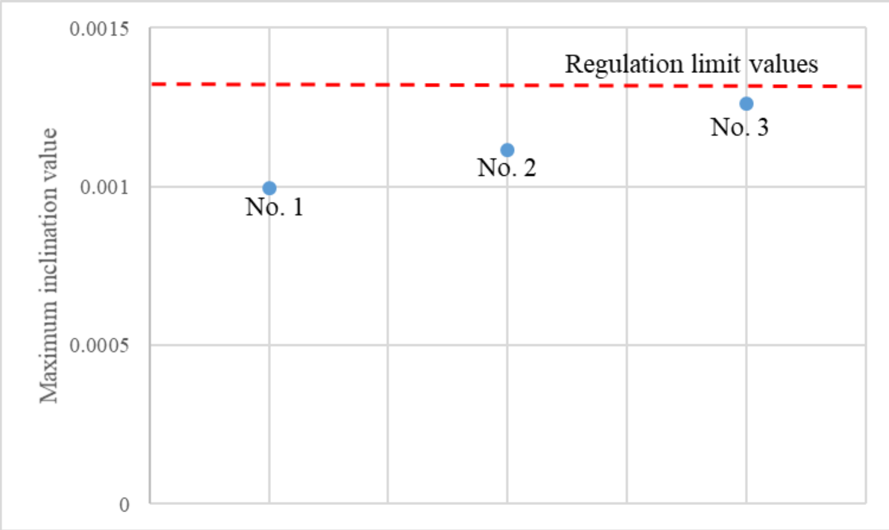


Figure 10: Existing foundations maximum inclination value due to deep excavation for scheme 3

5 Conclusion

In this paper, the displacements and the inclination values of the existing foundations induced by the excavation of a new underground station have been studied with various protection measures. Two dimensional analyses have been performed to identify the sensitivities of parameters and arrangement of ground improvement. Preliminary results of two dimensional analysis have been evaluated and additional three protection meres have been developed and studied with more accurate three dimensional numerical models. According to the results of three dimensional numerical analyses, strengthened existing pile foundation with enlargement pile cap and installation of pre-packed piles provide best protection of MRT line in operation.

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