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Pile construction and loading effects on adjacent shield tunnels

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ABSTRACT

The Circular Line Phase I of Taipei Rapid Transit System (TRTS) is mostly an elevated system that crosses the most populated region in New Taipei City and connects or intersects with other underground or elevated TRTS lines that are currently in operation or construction. In Banqiao District where the city hall is situated, the elevated line overlaps with the operating TRTS underground line for more than 800m. The piers are thus placed in between the up- and down-track shield tunnels with the clearance between tunnels and pile foundations as close as less than 1.5 m. To investigate the soil-pile-tunnel interaction behind the case and the associated construction and loading effect, a series of 3D simulations was conducted and protection measures were proposed during design stage. Automatic monitoring instruments were implemented during construction stage to ensure the safety of the tunnels. This paper first overviews the project and briefs the environmental constraints of the study case. The 3D numerical simulations and the associated protection measures are then presented followed by the monitoring layout and results. Conclusions and suggestions are given at the end of the paper.

Keywords: casing piling; shield tunnels; soil-pile-tunnel interaction

1 INTRODUCTION

The Circular Line of TRTS is mainly located in New Taipei City that surrounds Taipei City, the capital of Taiwan. It consists of Phase I, Phase II (including the North Section and South Section), and the Eastern Section with a total of 32 stations and approximately 35.9 km long of the routes. Except for the routes in the Phase I that are mainly designed for an elevated system, others in the Circular Line are planned to travel underground (DORTS 2017).

The elevated system in the Phase I includes a total of 14 stations and approximately 15.4-km-long routes that cross the most populated regions in New Taipei City. It intersects several TRTS lines that are currently in either operation or construction. It is thus anticipated that the proximity effects (e.g., Chang et al. 2011a) or complex soil-substructure interaction may be a key issue and major concern in both design and construction stages of the project.

This paper presents one particular case in one of the design lots of the Phase I where the foundations of the elevated routes are placed in between the shield tunnels of the operating TRTS Blue Line with the smallest clearance between the piles and tunnels less than 1.5 m. To assess the piling and loading effects on the adjacent tunnels, a series of 3D simulations was conducted. The results were provided as the basis for the planning of protection measures, including low-pressure grouting and monitoring systems. Typical monitoring results are presented, followed by the conclusions and suggestions at the end of the paper.

2 REVIEW OF BACKGROUND

The coverage of the design lot starts from the east of the Banqiao Train Station in Banqiao District, crosses Dahan River to enter Xinzhuang District, and ends at Wu-Gong Industrial Park (Fig. 1), with a total of 5 stations (from Y15 to Y19 stations) and about 6.4 km in length. The alignment of the elevated routes in the design lot overlaps the underground routes of Taiwan Railway (TRA)/Taiwan High Speed Rails (THSR) and of the TRTS Blue Line on Xianmin Boulevard and Wenhua Road, respectively.

Fig. 1. Coverage of project

The study case was focused on the overlapped regions of the TRTS line on Wenhua Road. In this case, there are 20 piers (i.e., P15-9~P15-28) located in between the up- and down-track shield tunnels of the operating Blue Line. Fig. 2 shows the alignment of the piers and a typical cross-section of the layout for piles and tunnels. As illustrated by the figure, the inner (ID) and outer diameter (OD) of the tunnels is 5.6 and 6.1 m, respectively (i.e., the liner is 0.25 m thick). The overburden depths of the tunnels vary from 11.0 to 21.2 m, with an average of 16.0 m. Besides, the spacing of the tunnels varies from 7.0 to 9.3 m. The group of piles with 1.2 m in diameter was selected as the foundation type for the piers. Since the resulting gap between the piles and tunnels are as small as less than 1.5 m (Fig. 2), piles were constructed using casing methods.

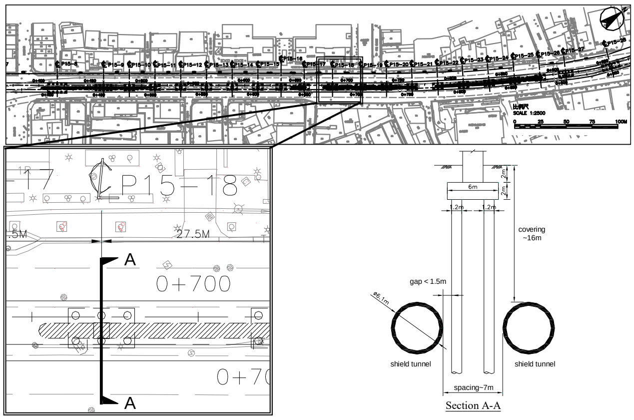

Fig. 2. Plan view and typical cross-section of study case

The near-surface ground condition of the site is the Holocene alluvium that is principally composed of interbedded sand, clay, silt layers underlain by gravels. According to the geological investigation reports (e.g., MAA/PECL 2009), the soil profile for the case, including surface fill (SF), can be primarily separated into 7 layers before a gravel layer (regarded as the bearing layer) is encountered at about 50 m below ground surface. Table 1 shows the engineering properties of the soil profile. The groundwater table is about 2 m deep below ground surface with a static hydraulic pressure distribution over depths.

Table 1 Soil profile and engineering properties of study case

Layer	Depth m	Soil Type	γ_t kN/m^3	s_u kN/m^2	N Value	ϕ' deg.	E kN/m^2
1	2.0	SF	19.6	0	5	28	20,000
2	6.0	CL	19.5	19	5	31	19,000
3	11.0	SM	19.7	0	11	30	44,000
4	20.0	CL	19.4	56	9	33	56,000
5	27.0	SM	19.8	0	20	33	80,000
6	33.0	CL	19.6	102	16	33	102,000
7	50.0	SM	20.1	0	33	34	132,000
8	70.0	GM	22.0	0	>50	35	200,000

3 NUMERICAL ANALYSIS AND RESULTS

In view of the geometry of the study case, a 3D numerical model was introduced and conducted under an 120*120*70 m soil mass, as shown in Fig. 3. The simulation was carried out over five major procedures, including (1) initial stress state; (2) construction of shied tunnels; (3) casing construction of piles; (4) pile cap construction; and (5) superstructure loading. Besides the soil mass that was modeled by a series of 4-node-tetrahedron, solid elements with Mohr-Coulomb soil criterion, the rest of structures such as liners and casings, modeled by plate elements, and piles and cap, modeled by solid elements, was simulated with elastic criteria. Details of simulation can be referred to Chang et al. (2010; 2011b).

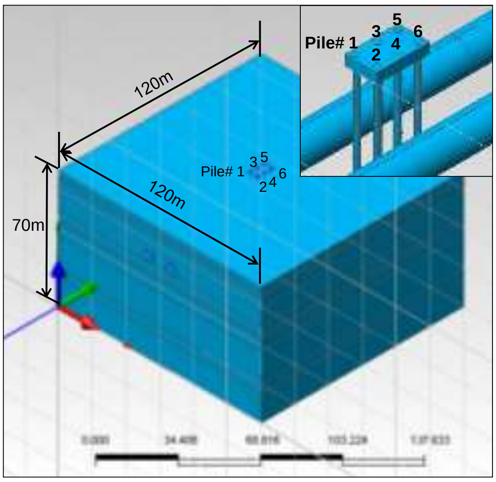

Fig. 3. 3D geometric model for study case

Table 2 Basic information of P15-18 and adjacent tunnels

Substructure	Basic Information
Tunnels	Spacing = 7.4m; Depth = 14.6m
Piles	Diameter = 1.2m; Length = 50m Arrangement = 2*3
Pile Cap	10m*6m*2m (Length*Width*Height)

The analysis results for the pier P15-18 are illustrated as a representative. The dimensions of P15-18 and the adjacent tunnels are tabulated in Table 2, and the ultimate loading on the top of cap is depicted in Fig. 4. Fig. 5 shows the tunnel deformation induced by pile construction. As shown in the figure, the tunnel was deformed almost in a symmetric manner with respect to the centerline of the pile cap in the transverse direction, with a maximum value of about 0.6 mm. Fig. 6 further shows the deformation of tunnels after the pile foundation is subject to superstructure loading. As illustrated by the figure, the maximum value of about 2.4 mm occurs at inner side of tunnel 1 that follows the resultant direction of the loading. Compared to pile construction effects, tunnel deformation induced by loading is remarkably larger. The obtained total deformation (about 3 mm) in tunnels was however proven to meet the corresponding requirement for radial deformation on tunnel's cross-section (20 mm).

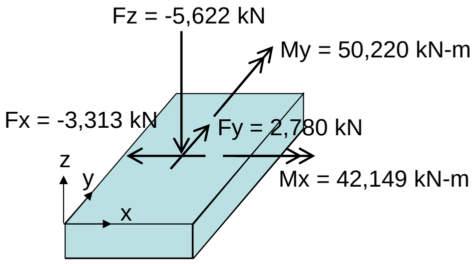

Fig. 4. Ultimate loading applied at cap of P15-18

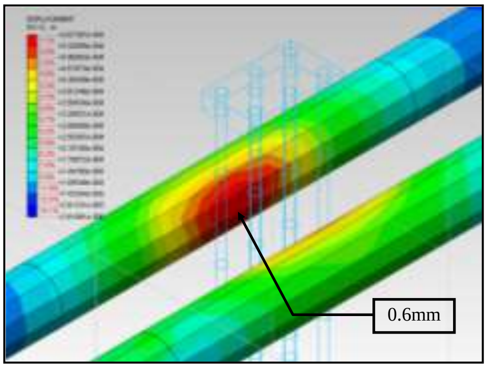

Fig. 5. Computed tunnel deformation induced by piling

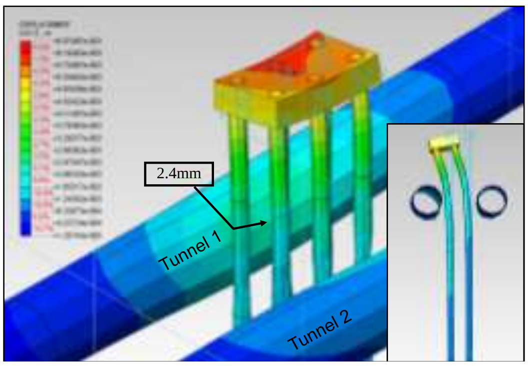

Fig. 6. Computed tunnel deformation induced by loading

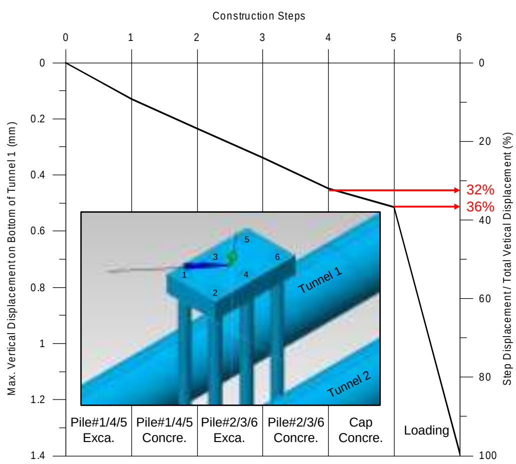

Fig. 7. Variation of maximum vertical displacement at tunnel 1

Fig. 7 shows the distribution of maximum vertical displacement on the bottom of tunnel 1 (regarded as the vertical displacement of tracks) along with construction steps. The total vertical displacement induced by both pile construction and loading is approximately 1.4 mm where pile construction and loading contributed, respectively, about 32% (0.45 mm) and 64% (0.9 mm) of the total displacement. Such degree of displacement met the safety requirement for tunnels where the allowable differential settlement over 10-m span is 12 mm.

4 DESIGN CONSIDERATIONS

To reduce unexpected piling effect on the surrounding soils and thus the shield tunnels that was not considered in the simulations, low-pressure grouting was introduced as an additional protection measure during design stage. It was aimed to enhance soil resistance against piling effect (such as vibration during casing installation or excavation-induced piping) while bringing least effect on the tunnels during implementation. The layout of the protection measure is as depicted in Fig. 8. As can be seen, the grouting was extended at least 0.25m outside the periphery of the piles and 6m (about one tunnel diameter) above and below the tunnel along the piles.

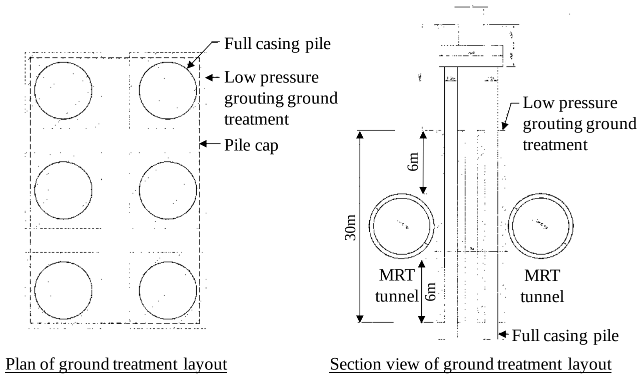

Fig. 8. Protection measure applied before piling

In addition, automatic monitoring instruments were installed as a warning system to safeguard the shield tunnels. Electronic beam sensors and prisms were introduced to monitor the differential settlement whereas electronic convergence points with total stations were introduced to observe the radial deformation of each tunnels' cross-section. Table 3 summarizes the instruments of the monitoring system and their management levels, and Fig. 9 shows the photos of instruments installed on site.

5 CONSTRUCTION AND MONITORING RESULTS

In the construction stage, the contractor proposed the double packer method (or Tube-A-Manchette, TAM) to execute the protection measure. While the double

Table 3 Summary of automatic monitoring system

Target	Instrument	Frequency	Management Level	
			Alert	Action
Tunnel deformation	horizontal electronic beam sensor	10-30 min.	0.96/1,000 (9.6mm/10m)	1.2/1,000 (12mm/10m)
	reflector prism & total station	10-30 min.	0.96/1,000 (9.6mm/10m)	1.2/1,000 (12mm/10m)
	convergence point	10-30 min.	16 mm	20 mm

Fig. 9. Instruments installed on site

packer was lowered to the planned depths inside the sleeve pipe, the grouting is controlled when either the design quantity, the pressure 3~5 kgf/cm^2 higher than the initial, or 50% of the alert level on the relevant monitoring instruments is attained. It is applied to both stages of grouting. Fig. 10 shows the photo of double packer and the illustration of grouting sequence for each pile location. As also shown in the figure, the center of the pile was assigned to conduct permeability test. The obtained hydraulic conductivity was required to lower 10^{-5} cm/sec.

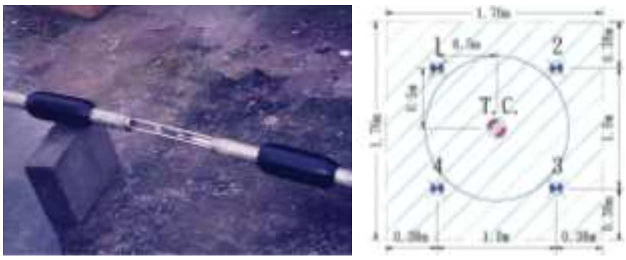

Fig. 10. The double packer and layout of grouting and test holes for piling protection (CYC, 2014)

Figs. 11~13 show the monitoring results during the implementation of ground improvement and construction of pile foundation at the pier P15-18. It happened that both operations were conducted in August 2015 with ground improvement done in the first half of the month and pile construction done in the second half. As illustrated by the figure, both readings obtained from beam sensors and prisms (Figs. 10 and 11, respectively) showed almost no differential settlement occurred over this period despite of small spikes at some spots. Similar situation was also observed in the readings derived from the convergence points (Fig. 12), implying that nearly no radial deformation on both up- and down-track tunnels induced by the construction. The results indicated that the tunnels were exempted from piling effect successfully and the service of the Blue Line was not suspended during pile construction.

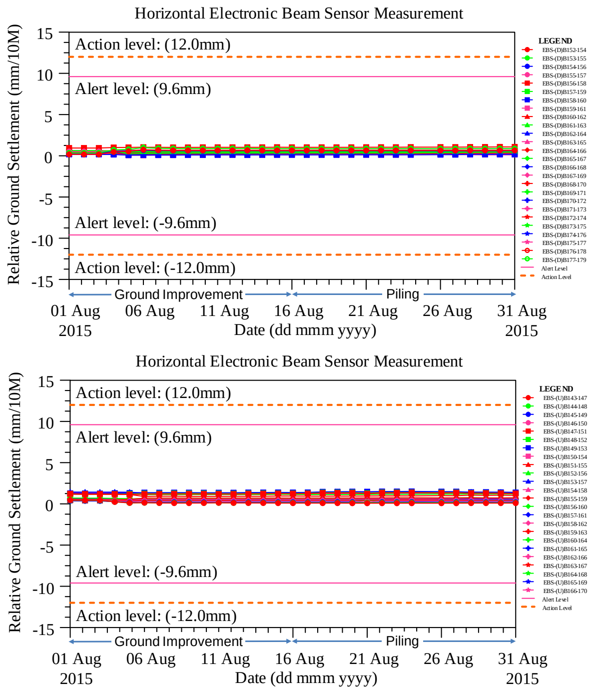

Fig. 11 Measurements from beam sensors

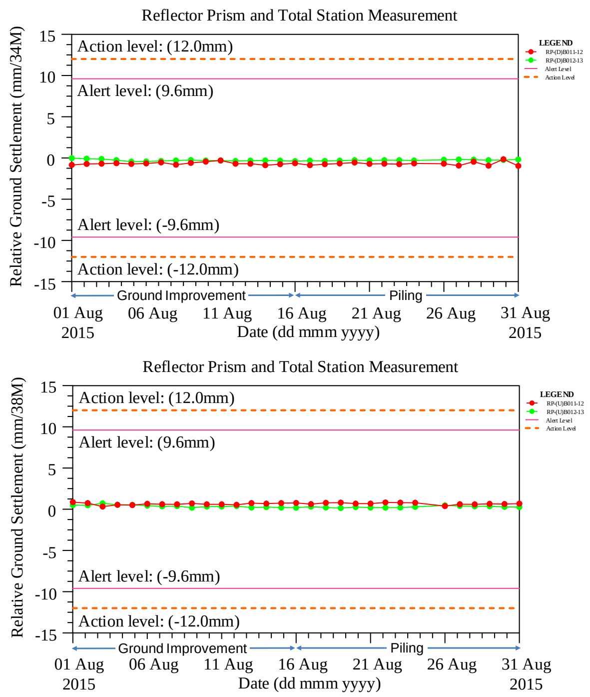

Fig. 12 Measurements from prisms and total stations

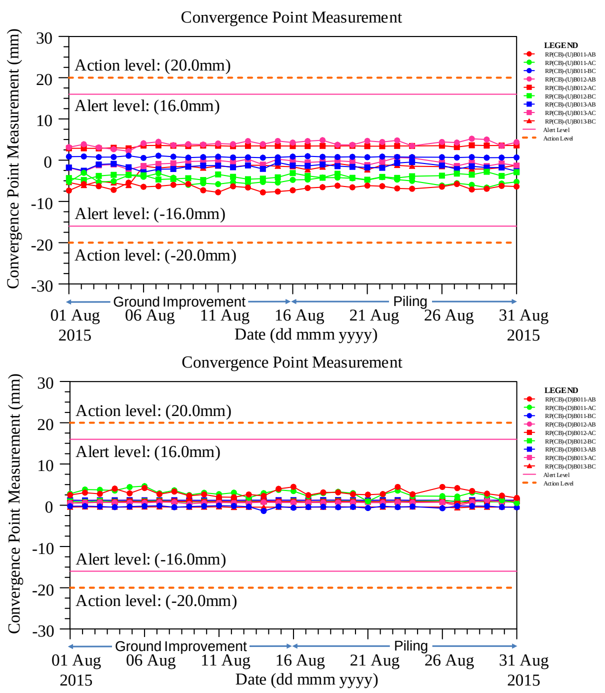

Fig. 13 Measurements from convergence points

6 CONCLUDING REMARKS

The proximity effect has become a feature in MRT projects that always exhibit complex interaction between soils and substructures. To investigate such complex interaction, a more sophisticated numerical model may be a necessity for design and construction purposes. This paper introduced a 3D numerical to evaluate piling and loading effects on the adjacent tunnels. The results were provided as references for developing protection measures and monitoring systems. Through the obtained measurements, the design was proven to be adequate in securing the tunnels.

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