Proximity Effect on Closely Spaced Shield Tunnels – Analysis, Design, and Feedback

Effet de proximité sur bouclier rapprochées Tunnels – analyse, conception et Feedback

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ABSTRACT: In soft ground tunneling, proximity effect resulted from driving-induced stress redistribution becomes significant when the clearance between two tunnels is smaller than one outer-diameter of the tunnel (i.e. 1D). For design purpose, additional surcharge would be suggested to impose upon the segments to account for proximity effect. While the clearance is smaller than 0.5D, no equivalent surcharge is suggested and sophisticated analysis is required on the case basis. This paper presents a study case in the Taipei MRT project where the route for clearance smaller than 0.5D is more than 350 m with the smallest of about 1.5 m (around 0.25D). Numerical simulations were carried out to investigate the proximity effect and reinforcement measures were introduced to protect the tunnels. Automatic monitoring system was further implemented to observe the response of preceding tunnel as boring of the succeeding tunnel proceeded on a total of 11 cross-sections. The paper first briefs the background, analysis results, and protection measures. The monitoring results are then presented for varying clearance, orientation, and even lining material between the twin tunnels. Summary and conclusion are provided as the feedbacks for the design of closely spaced shield tunnels.

RÉSUMÉ : Dans un sol mou tunneling, effet de proximité résulte de contrainte induite par conduite redistribution devient significative lorsque l'espace libre entre deux tunnels est inférieur à un diamètre extérieur du tunnel (c.-à-d., 1D). À des fins de conception, Supplément aurait proposé d'imposer les segments pour tenir compte de l'effet de proximité. Alors que la clairance est inférieure à 0,5 D, aucune surtaxe équivalente n'est suggéré et analyse sophistiquée est requise sur le cas par cas. Cet article présente une étude de cas dans le projet de MRT Taipei où la voie de dégagement inférieur à 0,5 D est plus de 350 m avec le plus petit d'environ 1,5 m (environ 0,25 D). Des simulations numériques ont été réalisées pour étudier l'effet de proximité et des mesures de renforcement ont été établies afin de protéger les tunnels. Système de surveillance automatique a été encore mis en place pour observer la réponse du tunnel qui précède dans le perçage du tunnel succédant a procédé sur un total de 11 sections. Le document informe tout d'abord le motif...

KEYWORDS: proximity effect, shield tunneling, Taipei MRT projects.

1 INTRODUCTION

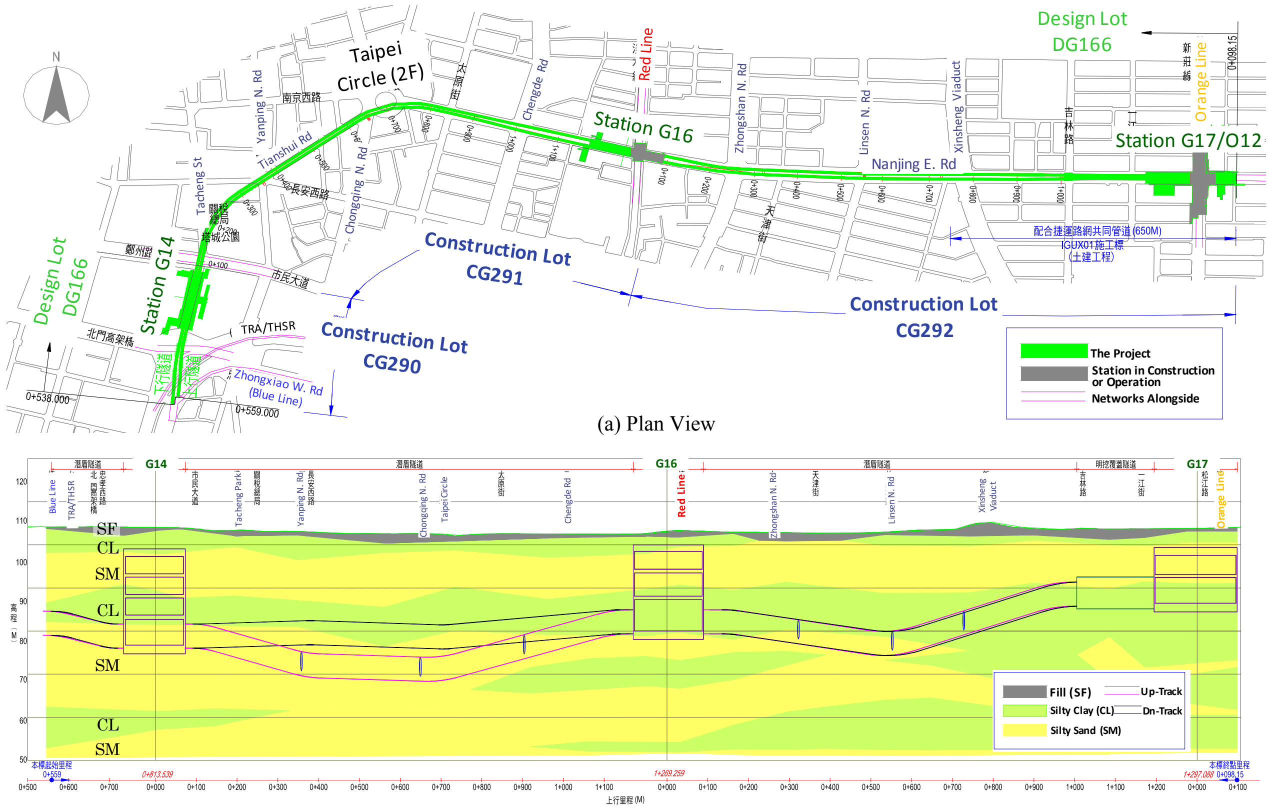
While shield tunneling is applied to alluvium or soft grounds, the stress re-distribution resulted from thrust, balancing pressure and torque on the cutterhead and tail gap between shield and segments would cause most adverse effects on the structures that are close by. In MRT projects, such proximity effect (Chang et al. 2011) would become significant when the clearance between two twin single tunnels is smaller than a certain distance. In the design code of Bay Area Rapid Transit (BART), the distance is two outer-diameter (i.e. 2D) whereas in Japan's shield tunnel design and construction guide (JRCEA 1977), it is 1D. For design purpose, JRCEA (1977) further suggests an equivalent surcharge applied onto the segments for clearance between 1D and 0.5D and requires sophisticated analysis for clearance smaller than 0.5D.

This paper presents a study case in Taipei Rapid Transit System (TRTS) projects where the route for clearance between twin single tunnels smaller than 0.5D is more than 350 m with the smallest clearance of about 1.5 m. A series of numerical simulations was conducted to investigate the interaction and protection measures, such as supplementary grouting, temporary bracing, and ductile segments (Chang et al. 2013), were introduced for tunnels with clearance smaller than 1D. Automatic monitoring system was then suggested, including earth pressure cells, pressure transducer, strain gauges or rebar stress meter installed on the segments for a total of 11 cross-sections. The paper first introduces the background and numerical simulations of the study case. The protection measures and electronic monitoring instruments installed for the proximity effect are then reviewed, followed by the results obtained from the automatic monitoring systems. Summary and conclusion are provided at the end of the paper.

2 BACKGROUND

The study case is in the DG166, one of the design lots for the green line of TRTS. The total length of the project is about 2.9 km, including 3 underground stations (i.e. Station G14, G16, and G17), 1 scissors crossover, and 3 sections of twin single tunnels with the inner diameter of 5.6 m and total length of about 2.2 km. The project is separated into 3 construction lots (i.e. CG290, CG291, and CG292), each of which principally includes 1 station and 1 section of tunnels. Except for tunnels that are constructed using shield method, the rest of the structures are constructed using cut-and-cover method. Since the project is planned under strict environmental constrains, the route for clearance between twin tunnels smaller than 1D is about 1.1 km, including about 165 m (whole section with clearance between 0.9D and 0.4D) in CG290, about 920 m in CG291 (over 350 m for clearance smaller than 0.5D with the smallest of 0.25D), and none in CG292. Figure 1 shows the plan and cross-section view of the project.

As illustrated in Figure 1, the major geological straum where the project is situated is a sandy-clayey-interbedded alluvium. It is called Songshan Formation, a Holocene deposit that is formed through a series of fluvial, lacustrine, estuarine, and brackish-water sedimentation process on the Taipei Basin (e.g. Lin 1957). In the region of the project, Songshan Formation exhibits 6 definite sublayers that are named Sublayer I to VI from the bottom to the top. Table 1 summarizes the engineering properties of the sublayers for the project.



(a) Plan View

(b) Cross-Section View

Figure 1. Plan and cross-section view of the project

Table 1. Engineering properties of Songshan Formation (after Moh & Ou 1979)

Sub-layer	*USGS*	*Thick-ness (m)*	*SPT-N*	γ_t *(kN/m³)*	w_n *(%)*	*k (cm/s)*	c_u *(kPa)*	ϕ_u *(deg)*	*c' (kPa)*	ϕ_u *(deg)*
VI	CL	3~8	3~8	19.3	31.1	(0.3~0.8) $*10^{-7}$	71	6.5	61	10
V	SM	2~20	2~26	20.1	24.3	(0.5~6.0) $*10^{-4}$	-	-	0	31~35
IV	CL	6~29	4~14	19.2	30.8	(0.5~2.0) $*10^{-7}$	49	14	310	26
III	SM	0~19	8~36	20.2	22.9	(0.5~2.0) $*10^{-4}$	-	-	0	35
II	CL	0~19	10~20	19.8	25.5	(0.3~0.8) $*10^{-7}$	64	21	0	34
I	SM	0~15	18~48	20.2	19.5	(0.5~6.0) $*10^{-4}$	-	-	0	42

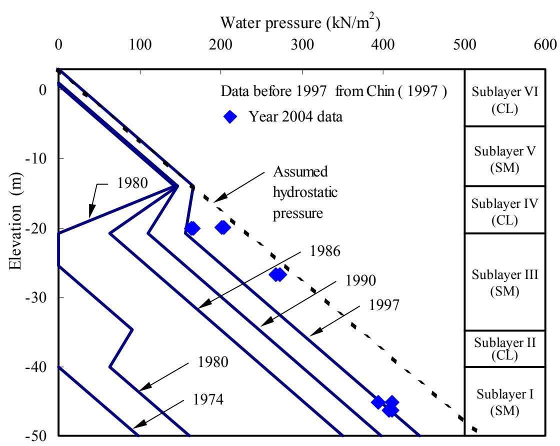


Figure 2. Historical Variation of Hydraulic Pressure Distribution with Depth in Taipei Basin (after Chin et al. 2006)

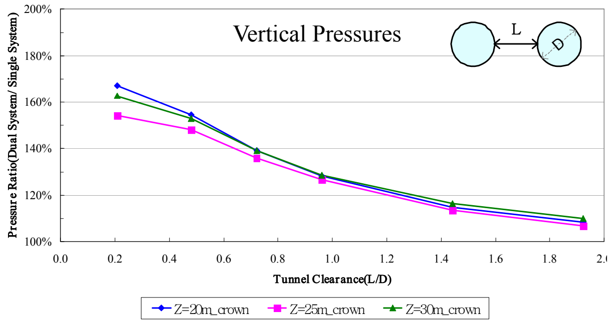
Figure 2 depicts the historical variation of hydraulic pressure distribution with depth for Taipei City. As shown in the figure, the drawback of pressure below the Sublayer IV has been gradually recovered after pumping on the Taipei Basin was banned in 1968. Nowadays, it would be expected an approximately 50 kPa of pressure drawback for the Sublayers I to IV and a hydrostatic condition for Sublayers V and VI. As the depths of the tunnels are most within the Sublayers III and IV, it is noted that higher-than-before hydraulic pressure might be encountered during tunnel boring.

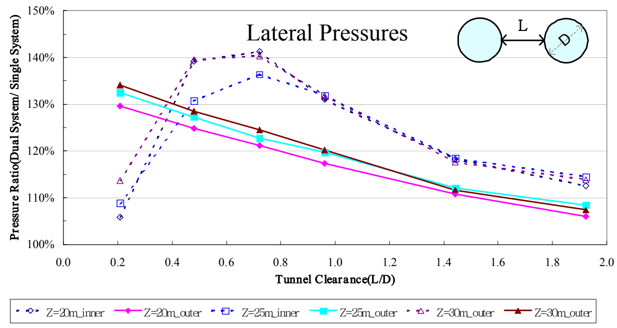
3 ANALYSIS RESULTS AND PROTECTION MEASURES

In the case of tunnels in close proximity, there are two major factors that lead to adverse effect on the preceding tunnel during the boring of the succeeding tunnel. One is the thrust and pressure imposed on the cutterhead to push tunnel boring machine (TBM) forward and balance the excavation face, respectively. According to the monitoring feedback from TRTS projects, the influence ranges within 2.5D and 1D outside the cutterhead in the longitudinal and radial directions, respectively and decays gradually as TBM passes. The other is the tail gap of about 140 to 160 mm between shield and segments that would result in stress-released deformation and permanent influence on the surrounding structures.

The numerical analyses conducted for the close-spaced tunnels focused on the permanent influence of tail gap, stress release on the excavation face, and enlarged excavation on the sides. The representative results are summarized as follows, and details can be referred to Kang et al (2007).

As illustrated by Figure 3(a), the vertical stress on the crown of the preceding tunnel increases as the clearance decreases. Such a trend follows closely with the equivalent surcharge suggested by JRCEA (1977) and a 70% of equivalent surcharge would be expected while the clearance is about 0.2D.





(a) Vertical stress on crown of preceding tunnel
(b) Lateral stress on sides of preceding tunnel

Figure 3. Variation of stress with clearance around preceding tunnel (after Kang et al. 2007)

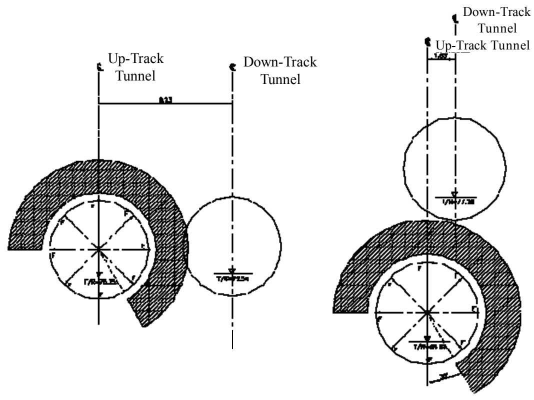
Figure 3(b) shows the corresponding lateral stress. It is noted that the trend of stress variation on the outside follows that for the vertical stress whereas the inside stress varies somehow differently. The obtained stress ratio is larger than the corresponding vertical stress ratio for clearance larger than 0.8D. It drops significantly as clearance smaller than 0.8D and becomes 20% smaller than the outside counterpart, indicative of imbalance on the side of the tunnel.

Based on the analysis results, the protection measures were planned for tunnels in close proximity: (1) temporary bracing was erected in the preceding tunnel to ensure the interior space requirement for clearance smaller than 5 m (about 0.8D); (2) grouting was implemented and ductile segments (e.g. Kang et al. 2009; Chang et al. 2013) was employed for clearance smaller than 3 m (about 0.5D); (3) in addition to general instruments (e.g. settlement point, tiltmeter, observation well, piezometer, and extensometer) installed to observe the construction effect, this project planned a total of 11 tunnel cross-sections to install electronic earth pressure, pressure transducer, and strain gauge (for ductile segments) or rebar stress meter (for RC segments) to automatically monitor the variation of preceding tunnel with construction stage.

Figure 4 shows the photos for temporary bracing, supplementary grouting, and ductile segments implemented in the project. Figure 5 sketches the range of supplementary grouting outside the preceding tunnel. Figure 6 outlines the instruments installed on the preceding tunnel and Figure 7 illustrates the location of the 11 cross-sections.

(a) Temporary bracing (b) Supplementary grouting (c) Ductile segment

Figure 4. Protection measures for tunnels in close proximity

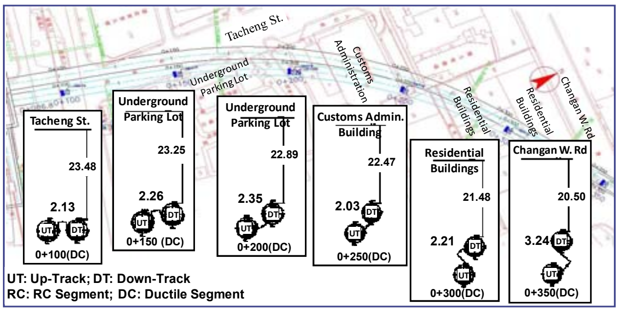


(a) Parallel pattern (b) Stacked pattern

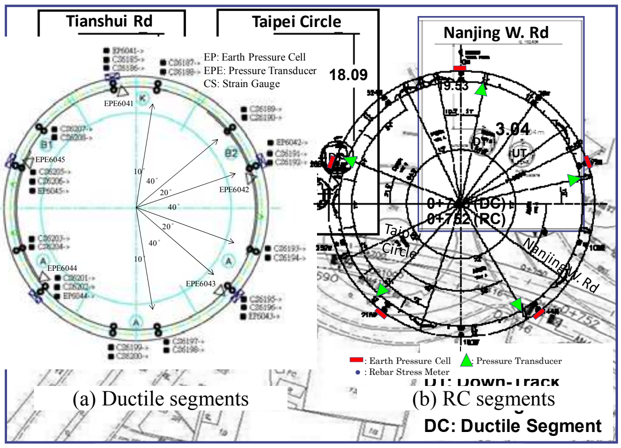
4 MONITORING RESULTS

Figure 5. Rang of supplementary grouting

Figure 6. Instruments installed on the preceding tunnel



(a) Cross-sections for ductile segments



(b) Cross-sections for ductile and RC segments

Figure 7. Cross-sections for automatic monitoring

Figure 8 presents the representative monitoring results obtained from the cross-section at chainage 0+690 m for CG291 where the closest clearance is encountered. Observations from the figure and the other 10 cross-section results are summarized as follows.

(1) The passage of succeeding tunnel induced a considerable reaction in the recordings. The data first stayed at a relative high level when the segments were erected and supplementary grouting was implemented in the preceding tunnel. They then dropped gradually to a level that is equivalent to the in-situ stress condition until an immediate jump in response to tunnel passage.

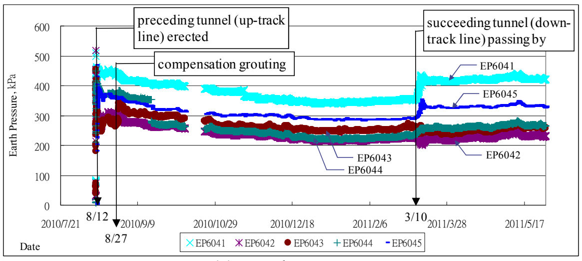
(2) The reaction of readings to TBM passage often occurred during one week before and after TBM was close by. Most of results exhibited permanent influence and did not return to the original stress condition with time.

(3) The maximum induced pressure occurred following closely with the orientation of the succeeding tunnel.

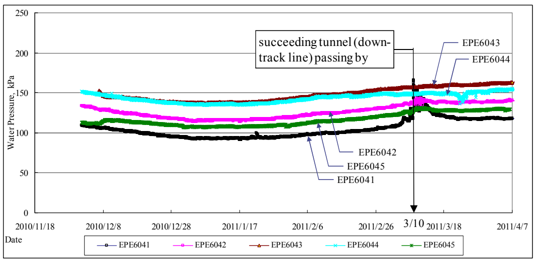
(4) Regardless of results from stacked arrangement of tunnels, the increase in total stress and hydraulic pressure was about 80 to 200 kPa and 40 to 110 kPa, respectively. Though the results might be affected by supplementary grouting or other constructions, it is observed that they intended to increase with decrease in clearance. The change in hydraulic pressure was however apparently smaller than the total stress, indicative of increase in effective stress.

(5) With respect to tunnels in parallel pattern, the total stress at the crown of preceding tunnel for stacked pattern (orientation between +30 and -30 degree) tended to decrease (within a range of 40 to 110 kPa). The variation of the corresponding hydraulic pressure was relatively small (within a range of 1 to 6 kPa), implying a decrease tendency in effective stress.

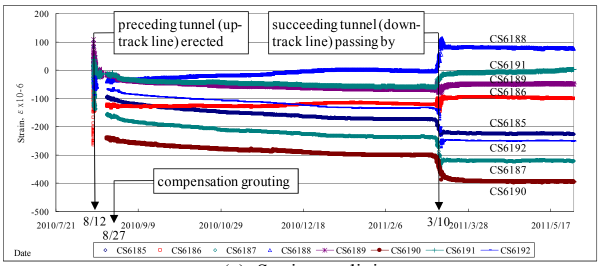
(6) Regardless of ductile or RC segments or supplementary grouting, the variation of strain on the inside or outside of the preceding tunnel fell within a range of $(+128\sim-128)*10^{-6}$, implying that the segments might be possibly subject to both tension and compression loadings.Thank you for following these instructions.



(a) Earth pressure



(b) Hydraulic pressure



(c) Strain on lining

Figure 8. Monitoring results for cross-section with the closest clearance (Chang et al. 2013)

5 SUMMARY AND CONCLUSION

As the network of the MRT or pipeline system keeps developing, proximity effect on tunnels would become much more significant. The paper presents a study case in TRTS projects where the clearance between twin tunnels is mostly smaller than 1D with the smallest of 0.25D. Based on analysis results, the suggested protection measures included temporary bracing, supplementary grouting, and ductile segments.

According to monitoring results, the variation of total stress and hydraulic pressure around the preceding tunnel is affected by the orientation of the succeeding tunnel relative to the preceding one. The trend of imbalance stress on the sides of the tunnel shows fair agreement with the numerical predictions. It is however observed that the variation in stress tended to be permanent. Further observations include tension loadings on segments, and stress release at the crown of the preceding tunnel for stacked pattern. These findings are suggested as additional consideration for segment design and construction.

6 ACKNOWLEDGEMENTS

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