

Behaviour of Various Support Systems for Deep Excavations, Changi Airport Underground MRT Station

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ABSTRACT: For any deep excavation, it is important that the deformation of its ground support system is controlled to minimise the impact on ground movements, and its subsequent effect on the adjacent structures. This paper presents the actual behavior of various ground support systems that were utilised at the Changi Airport MRT Station construction, and makes comparison of the deformations relating to their method of construction. These include top-down and bottom-up constructions with diaphragm walls, soldier piles, sheet pile walls and timber lagging support systems. This paper also provides the original and back analyses carried out and the typical design parameters derived therefrom.

1 INTRODUCTION

Deep excavation works are becoming very common and unavoidable in many medium to large infrastructure and building developments. This is especially so in land scarce and highly buildup Singapore. Many of these excavation works are carried out near to existing structures. It is therefore critical for engineers to be able to assess the inevitable ground movements caused by the excavation and consider its effect on nearby existing structures.

The Changi Airport MRT Station is a major and prestigious project successfully implemented and completed by the Land Transport Authority of Singapore in year 2002. For the construction of this large underground station, different methods of deep excavations using various ground support systems were adopted. This paper presents in some details the results of data collected from instruments that were installed to measure the ground movements and changes in groundwater pressures due to the excavations. The behavior of the various ground support systems is compared and discussed briefly. Results of the original and back analyses done for the respective excavations are also presented and the typical soil parameters assumed in the analyses are provided.

2 PROJECT DESCRIPTION

The Changi Airport Station is located at the eastern end of Singapore and was constructed as a part of the completed Changi Airport Line Project to serve as a convenient means of transport for the high volume of commuters traveling to and from the airport. Figure 1 shows the location map. The Changi Airport Line is an extension of the existing East-West Line, which begins from Tanah Merah Station and terminates at Changi Airport Station. The total length of the extension is approximately 6 km.

The Changi Airport Station is located at about 20 m underground beneath the existing Airport Boulevard and fully integrated with the existing Airport Terminal 2 and the future Terminal 3. The construction of this large station included the Crossover Tunnels, Station Box, Terminal Atria and Over-run Tunnels. As part of the continuing development of the airport, the project also included, among other infrastructures, a new baggage tunnel which runs under the station.

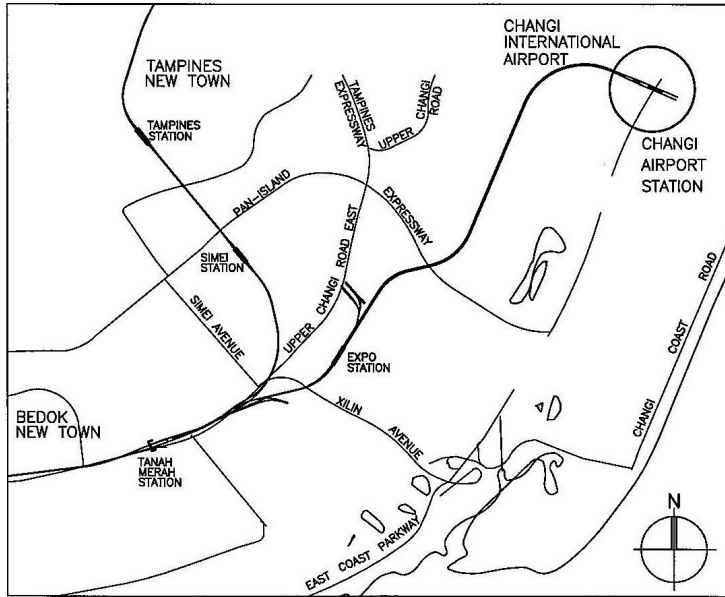
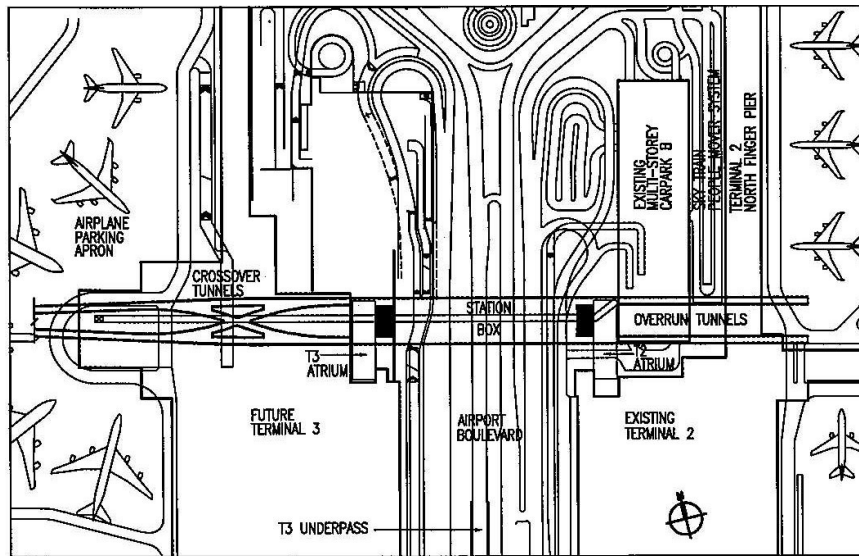


Figure 1. Location Map of Changi Airport Line.



(a) Layout Plan



(b) Perspective Views

Figure 2. Layout Plan of Changi Airport Station.

The Crossover Tunnels commence after the end of the eastbound and westbound bored tunnels from the Expo Station, and are located under the existing airplane parking apron. They consist of a pair of 4.75 m wide by 4.6 m deep cut-and-cover box tunnels, and are about 30 m apart. These twin tunnels are about 220 m long, and incorporate a crossover before entering the Station Box. The Station Box is located under the existing Airport Boulevard, and is one of the most spacious stations on the MRT System at about 35 m wide by 205 m long. At both ends of the Station Box, large Terminal Atria provide connection and integration with the Airport Terminals. These atrium structures rise from the basements to reach a height of about 28 m from the ground and are the only visible landmark structures of the station above ground. Each atrium is about 20 m wide by 60 m long. The Overrun Tunnels exit from the Station Box and again consists of a pair of parallel 4.75 m wide by 4.6 m deep cut-and-cover box tunnels, separated by about 30 m. These twin tunnels are about 135 m long and run underneath the north end of the existing Terminal 2 buildings. The tunnels clashed with the existing piled foundations of these buildings. The buildings had to be underpinned, and the affected piles removed, before the tunnels could be excavated and constructed. A new 4.75 m wide by about 5 m deep baggage tunnel begins between and below the pair of tunnels at the Crossover and continues under the center of the Station Box before making a turn to run under the eastbound tunnel at the Overrun. Figures 2a, b show the layout plan and perspective views of the Changi Airport Station respectively.

3 SITE GEOLOGY

From the site investigation conducted, it was found that the site is underlain by Old Alluvium, a soil stratum formed in the Pleistocene period (10 thousand to 1 million years ago). The Old Alluvium is massive and slightly to moderately weathered. The soils consist mainly of cemented silty sand, clayey silt or silty clay with low permeability. It was observed that the cementation often disintegrates after a few days upon exposure to the environment or when the material comes into contact with free water (LTA, 1997). The SPT N values obtained in the Old Alluvium are generally higher than 50 and in some cases exceed 100. The unconfined compressive strength ranges from about 0.5 MPa to 1.5 MPa and the elastic modulus ranges from about 100 MPa to 200 MPa (KSJV, 1999).

The Old Alluvium stratum is overlain by about 7 m to 13 m of Reclamation Fill, consisting mainly of materials derived from the Old Alluvium. The materials vary from a clayey soil to sandy gravel. The SPT N values obtained tend to be higher in the upper levels above the groundwater table but are frequently in the range of 4 to 10 below the upper few metres (KSJV, 1999).

4 INSTRUMENTATION AND MONITORING

A comprehensive package of instrumentation and monitoring was implemented during the excavation and construction of the station, primarily to assess the design assumptions, stability of the works, effects on groundwater pressures, and effects on adjacent existing buildings. Some of these instruments (not exhaustive) are listed below (KSJV, 2000):

- a) Water standpipes and vibrating wire piezometers to measure groundwater pressures
- b) Inclinerometers to measure lateral ground and wall movements
- c) Settlement markers and leveling points to measure ground settlements
- d) Strain gauges and load cells to measure strut and ground anchor forces
- e) Optical prism targets, electrolevel beams and electronic tilt sensors to measure building movements

To control the monitoring, 3 alarm levels in progressive severity were set based on the design and prediction to ensure the safety of the works.

5 DEEP EXCAVATIONS IN OLD ALLUVIUM

For the construction of the Crossover Tunnels, Station Box, Terminal Atria and Overrun Tunnels, different types and mixtures of excavation methods and ground support systems were adopted. These are described in Sections 5.1 to 5.4. Figure 3 shows the various methods of construction.

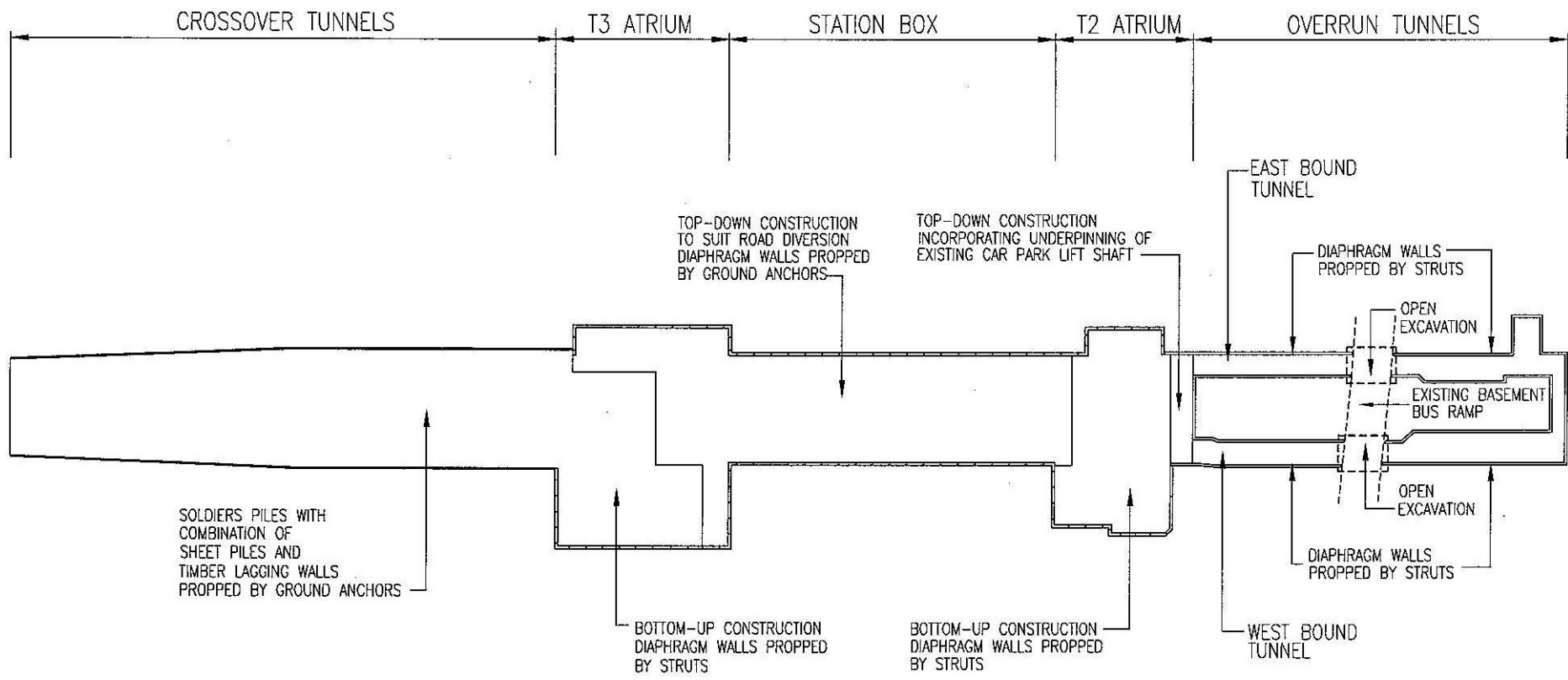
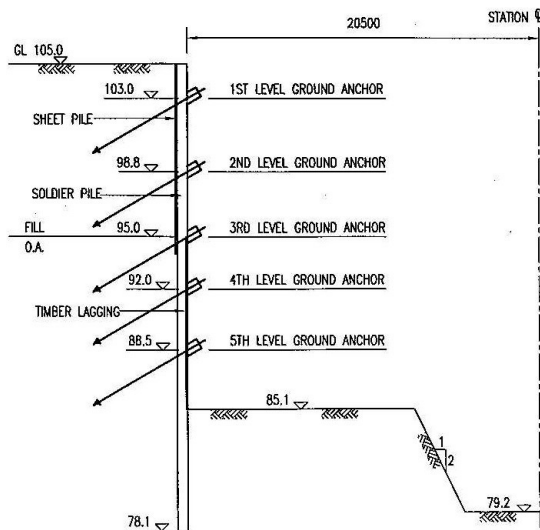


Figure 3. Plan showing Methods of Construction.

5.1 Crossover Tunnels

The Crossover Tunnels were constructed by the cut-and-cover method using a temporary excavation support system comprising of retaining walls formed by soldier piles with a combination of sheet pile walls and timber lagging. Sheet pile walls were driven behind the soldier piles above the Old Alluvium while timber lagging were installed between the soldier piles below the Old Alluvium to retain the soil and water. The retaining walls were propped by 5 levels of walers and removable ground anchors. This relatively flexible ground support system was considered adequate because the Crossover Tunnels are not located near to any existing buildings. Figures 4a, b show the section and a photograph of the excavation at the Crossover Tunnels respectively.

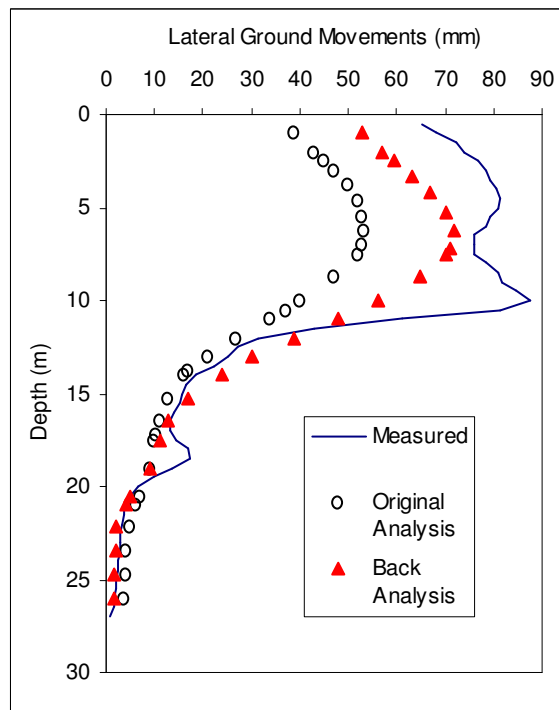


(a) Section of Excavation

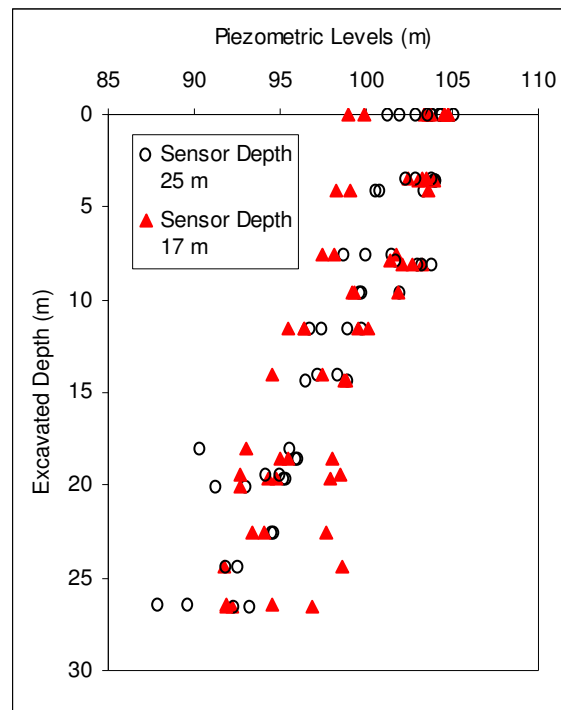


(b) Photograph of Excavation

Figure 4. (a) Section (b) Photograph of Excavation at Crossover Tunnels.



(a) Lateral Ground Movements



(b) Piezometric Levels

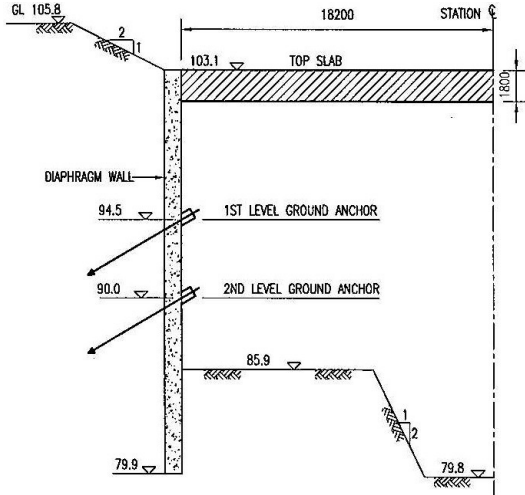
Figure 5. (a) Lateral Ground Movements (b) Piezometric Levels at Crossover Tunnels.

Figures 5a presents the upper bound of the lateral ground movements measured from 4 inclinometers installed in boreholes next to the retaining walls. The maximum lateral ground movement measured was about 87 mm and occurred at around the mid depth of the excavation. It was observed that the measured lateral ground movements were excessively higher than the predicted values. This was probably due to unforeseen pockets of Marine Clay that were encountered within the Reclamation Fill at some areas of the Crossover Tunnels. Figure 5b presents the piezometric levels measured from 18 vibrating wire piezometers installed adjacent to the excavation with the sensors located in the Old Alluvium near the formation level. The piezometric levels were lowered to a maximum of about 15 m as the excavated depth reached the formation level. The groundwater table measured from standpipes was lowered by about 4 m to 5 m.

5.2 Station Box

The Station Box was constructed by the top-down cut-and-cover method. The excavation support system comprised of permanent 1000 mm thick diaphragm walls propped by a permanent concrete top slab and 2 levels of temporary walers and removable ground anchors. The diaphragm walls form part of the station walls while the concrete top slab forms the station roof slab. After the installation of the diaphragm walls, the roof slab was first constructed and the ground backfilled. Further excavation and construction works were then carried out below the roof slab through temporary openings. This method of construction was adopted because of site and time constraints. Airport Boulevard, the only road access to the airport, is located directly above the Station Box. As such, the Station Box had to be constructed in sections for the necessary diversion of this busy road. In order for the road to be reinstated back to its original alignment and to release the affected section of the Station Box for construction, the roof slab had to be constructed and ground backfilled as early as possible. Figures 6a, b show the section and a photograph of the excavation at the Station Box respectively.

Figure 7a presents the upper bound of the lateral ground movements measured from 2 inclinometers installed in boreholes next to the diaphragm walls and 2 inclinometers installed in the diaphragm walls. The maximum lateral ground movement measured was about 11 mm and occurred at around the mid depth of the excavation. Figure 7b presents the piezometric levels measured from 12 vibrating wire piezometers installed adjacent to the excavation with the sensors located in the Old Alluvium near the formation level. The piezometric levels were lowered to a maximum of about 12 m as the excavated depth reached the formation level. The groundwater table measured from standpipes generally remained perched just below the ground level.

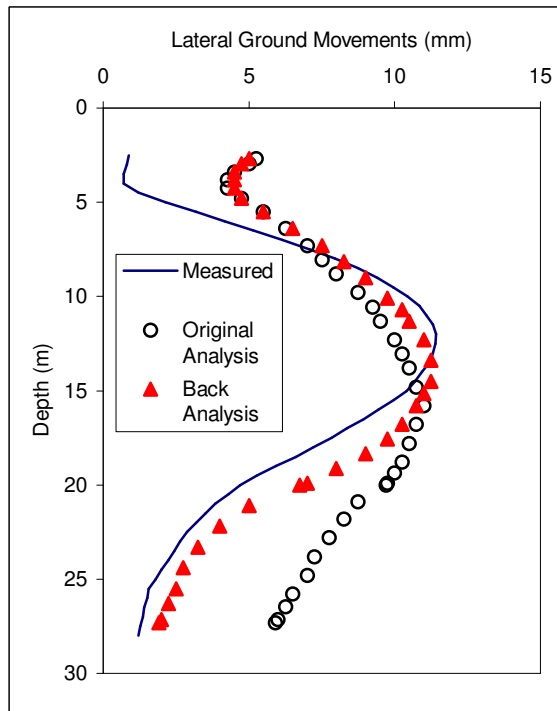


(a) Section of Excavation

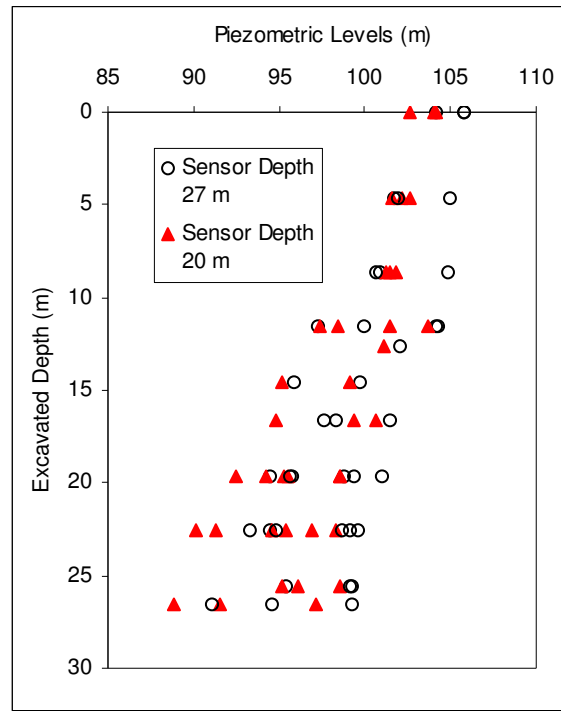


(b) Photograph of Excavation

Figure 6. (a) Section (b) Photograph of Excavation at Station Box.



(a) Lateral Ground Movements

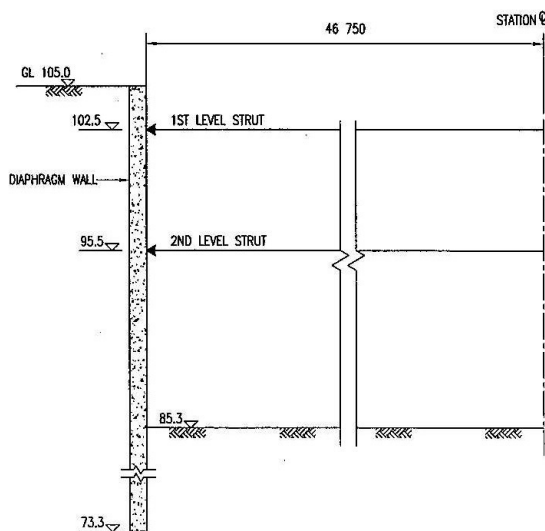


(b) Piezometric Levels

Figure 7. (a) Lateral Ground Movements (b) Piezometric Levels at Station Box.

5.3 Terminal 3 Atrium

The Terminal 3 Atrium is built within a large open box structure at the west end of the Station Box. This open box structure was constructed by the bottom-up method. The excavation support system comprised of permanent 1000 mm thick diaphragm walls propped by 2 levels of temporary walers and corner struts. Figures 8a, b show the section and a photograph of the excavation at the Terminal 3 Atrium respectively.



(a) Section of Excavation



(b) Photograph of Excavation

Figure 8. (a) Section (b) Photograph of Excavation at Terminal 3 Atrium.

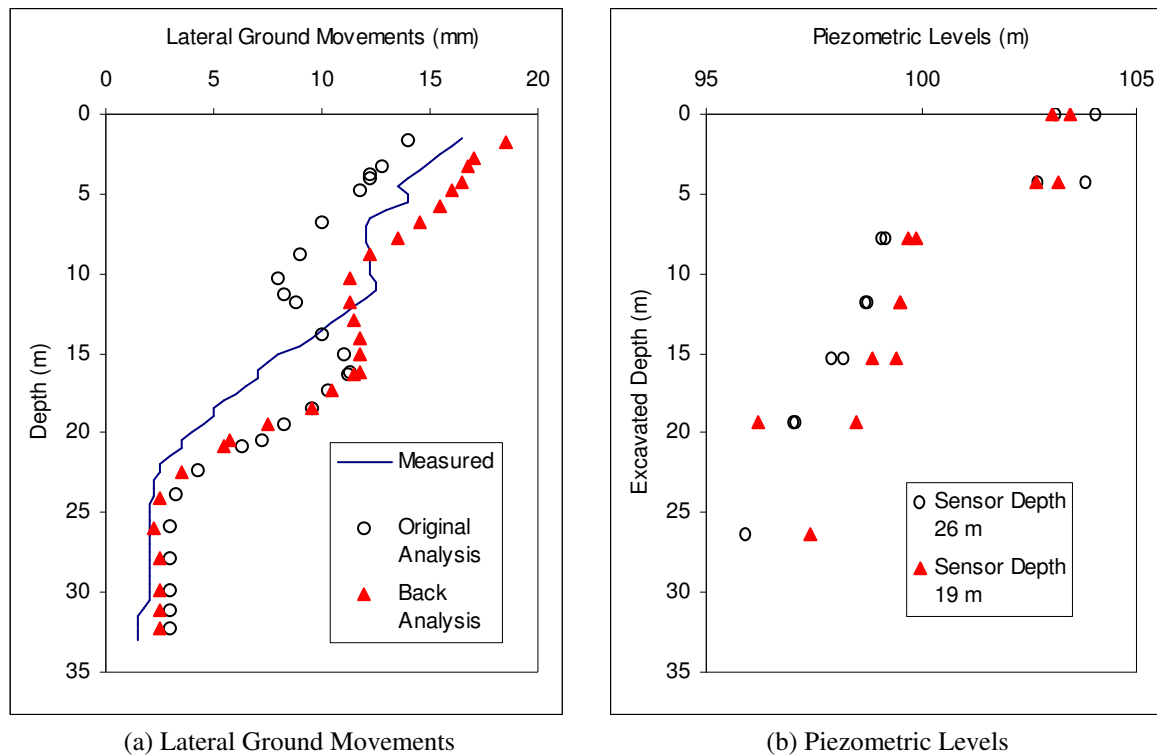


Figure 9. (a) Lateral Ground Movements (b) Piezometric Levels at Terminal 3 Atrium.

Figure 9a presents the upper bound of the lateral ground movements measured from 1 inclinometer installed in a borehole next to the diaphragm wall and 2 inclinometers installed in the diaphragm walls. The maximum lateral ground movement measured was about 17 mm and occurred near the top of the excavation. Figure 9b presents the piezometric levels measured from 4 vibrating wire piezometers installed adjacent to the excavation with the sensors located in the Old Alluvium near the formation level. The piezometric levels were lowered to a maximum of about 7 m as the excavated depth reached the formation level. The groundwater table measured from standpipes generally remained perched just below the ground level.

5.4 Eastbound Overrun Tunnel

The Eastbound Overrun Tunnel was constructed in a narrow excavation by the bottom-up cut-and-cover method. The tunnel consists of a double cell stacked box with the baggage tunnel at the bottom. The excavation support system comprised of 800 mm thick diaphragm walls propped by 2 levels of temporary walers and struts, a permanent top slab and a permanent intermediate slab. As the Overrun Tunnels pass underneath part of the existing Terminal 2 buildings (Car Park B, Basement Bus Ramp, Sky Train People Mover System and North Finger Pier) and clashed with their piled foundations, these buildings had to be underpinned and the affected foundations removed first before the construction of the tunnels could take place. The affected columns of the buildings were underpinned using the diaphragm walls, which form the new permanent foundations. Figure 10 shows the section of the excavation at the Eastbound Overrun Tunnel.

Figure 11a presents the upper bound of the lateral ground movements measured from 2 inclinometers installed in boreholes next to the diaphragm walls and 4 inclinometers installed in the diaphragm walls. The maximum lateral ground movement measured was about 9 mm and occurred near the bottom of the excavation. Figure 11b presents the piezometric levels measured from 6 vibrating wire piezometers installed adjacent to the excavation with the sensors located in the Old Alluvium near the formation level. The piezometric levels were lowered to a maximum of about 14 m as the excavated depth reached the formation level. The groundwater table measured from standpipes generally remained perched just below the ground level.

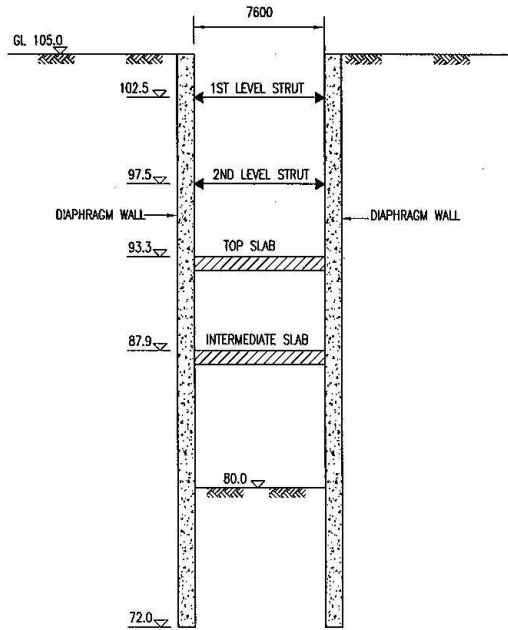


Figure 10. Section of Excavation at Eastbound Overtun Tunnel.

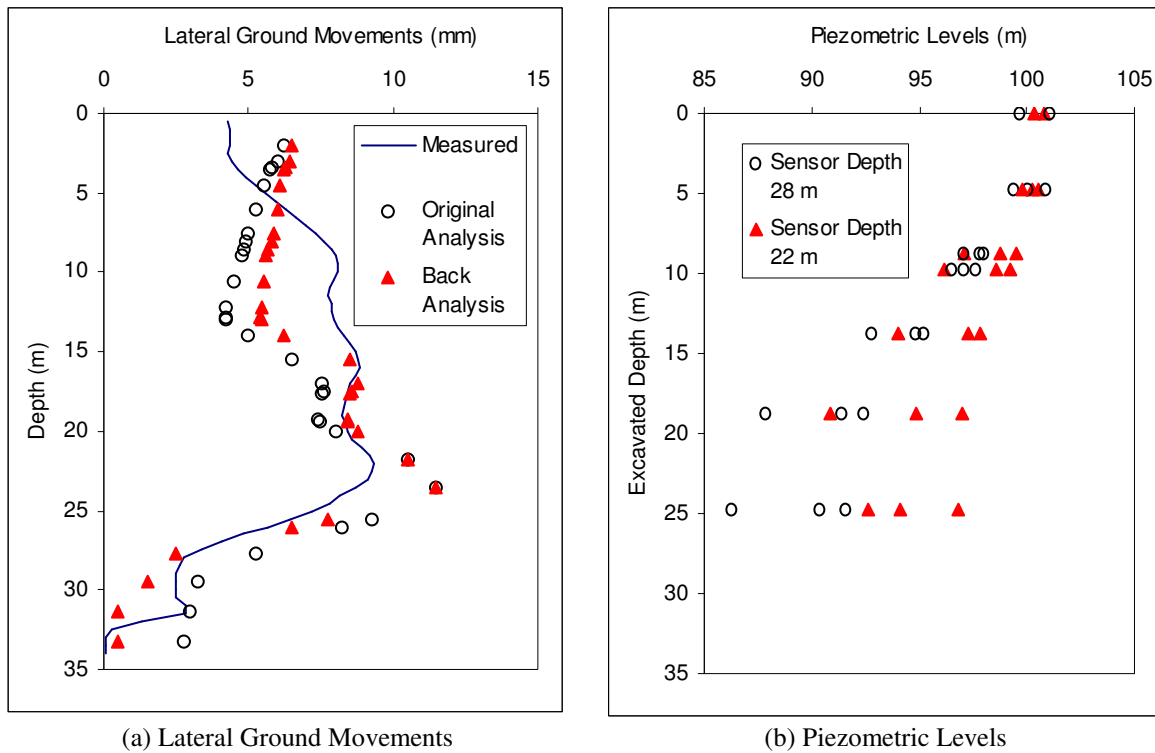


Figure 11. (a) Lateral Ground Movements (b) Piezometric Levels at Eastbound Overtun Tunnel.

6 EXCAVATION BACK ANALYSES

Original and back analyses of the excavations were carried out using WALLAP for all the case studies presented. Undrained soil strength and modulus parameters for the Old Alluvium using Mohr-Coulomb Elastic-Perfectly Plastic constitutive soil model were assumed. Table 2 summarizes the soil parameters used in the analyses.

Table 2. Summary of Soil Parameters.

Soil	Unit Weight (kN/m ³)	Friction Angle (Degree)	Undrained Shear Strength (kPa)		Elastic Modulus (MPa)	
			Original Analysis	Back Analysis	Original Analysis	Back Analysis
Reclamation Fill	19	30	-	-	5 + 1.5z *	10
Old Alluvium above Formation Level	20	-	250 (4 – 5 N)	250 (4 – 5 N)	150 (2.5 – 3 N)	125 (2 – 2.5 N)
Old Alluvium below Formation Level	20	-	250 (4 – 5 N)	250 (4 – 5 N)	150 (2.5 – 3 N)	300 (5 – 6 N)

* z is the depth from the ground level

It should be noted that for the back analyses, a higher soil modulus was assumed for the Old Alluvium below the formation level. This assumption is considered reasonable, as soil strains were significantly smaller below the formation level, hence only the small strain modulus was mobilized. The predicted lateral ground movements from the original and back analyses for the Crossover Tunnels, Station Box, T3 Atrium and Eastbound Overrun Tunnel are plotted in Figures 5a, 7a, 9a and 11a respectively.

7 OBSERVATIONS & DISCUSSIONS

It is well established that the behavior of excavations and the support systems are affected by various factors, some of which are listed below:

- Soil stratification and properties
- Depth and width of excavation
- Type of retaining wall
- Type of propping and preloading
- Method of construction and workmanship

The case studies presented in this paper have demonstrated the influence of some of these factors. The relatively uniform soil strata of the site allowed some reasonable comparisons of the various excavations and support systems. Table 3 summarizes and compares the lateral ground movements of the different excavations.

Table 3. Comparison of Maximum Lateral Ground Movements for Different Excavations.

Location	Construction Method	Structural System	Maximum Lateral Ground Movement		
			Measured (mm)	Original Analysis (mm)	Back Analysis (mm)
Crossover Tunnels	Bottom-up	Soldier piles with sheet pile walls & timber lagging propped by ground anchors	87	53	72
Station Box	Top-down	Diaphragm walls propped by ground anchors	11	11	11
T3 Atrium	Bottom-up	Diaphragm walls propped by struts	17	14	19
Eastbound Overrun Tunnel	Bottom-up	Diaphragm walls propped by struts	9	12	12

7.1 Flexible versus Rigid Retaining Walls

The ground movements of the support system using the flexible soldier piles with sheet pile walls and timber lagging at the Crossover Tunnels (Figure 5a) were much larger (more than 5 times) than those for the support system using the stiff diaphragm walls at the Station Box (Figure 7a). This clearly indicates that the stiffness of the retaining walls is a major, if not the most important, factor in controlling ground movements.

7.2 Top-Down versus Bottom-Up Methods

The comparison of ground movement profiles of the Station Box (Figure 7a) and T3 Atrium (Figure 9a) confirms that the top-down method was effective in reducing, if not practically preventing, any ground movements at the top of the excavation. This was obviously due to the very stiff concrete top slab that was constructed against the diaphragm walls before any significant excavation was started. Another major advantage of the top-down method was that it allowed works to be carried out on and above the ground level while the excavation was ongoing. This resulted in substantial timesavings as aboveground activities were undertaken concurrently. However, the top-down method did have its drawbacks. One such shortcoming was that access to the excavation was limited to the size and number of temporary openings provided in the top slab. This restriction resulted in a slower excavation and muck removal rate, and affected the subsequent construction activities. This problem was alleviated by detailed advanced planning and providing more large openings in the top slab. Waterproofing problems were also encountered during the closure of these openings.

7.3 Ground Anchors versus Struts

By comparing the magnitude of the ground movements around the mid depth (10 m to 15 m) of the excavation at the Station Box (Figure 7a) and T3 Atrium (Figure 9a), it generally appears that the strutted system at the T3 Atrium performed better in minimizing ground movements when compared to the ground anchored system at the Station Box. This is even after recognizing the fact that the excavation at the T3 Atrium was wider than the excavation at the Station Box. Although this observation is not so obvious due to the different configurations of the excavations, it is still reasonable to remark that a strutted system is normally more rigid than a ground anchored system. Hence, if all other factors remain the same, a strutted system would be more effective in controlling ground movements. However, a major disadvantage of the strutted system was that it created significant space constraints within the excavation, thus hampering the construction works. Waterproofing of the base slab was also more difficult due to the kingpost penetrations. The ground anchored system whereas offered practically no obstruction within the excavation, making it much easier and faster for the construction works to progress.

7.4 Narrow versus Wide Excavations

It can be seen that the ground movements of the narrow excavation (width is approximately one third the depth of excavation) at the Eastbound Overrun Tunnel (Figure 11a) were noticeably smaller in magnitude than the ground movements measured at the much wider (width is at least 2 times or more than the depth of excavation) Station Box (Figures 7a) and T3 Atrium (Figures 9a). All of these areas used diaphragm walls as the retaining system, although the walls were less stiff (800 mm thick) at the Eastbound Overrun Tunnel when compared to the walls (1000 mm thick) at the Station Box or T3 Atrium. The smaller ground movements could be attributed to the soil confinement within the excavation, which had the effect of increasing the soil stiffness. Another reason could be due to the smaller elastic shortening of the shorter spanning struts. In general, it should be noted that this trend of reduced ground movement in narrow excavations is only apparent where the width is less than the depth of excavation. When the width of excavation exceeds its depth, this behavior becomes less significant.

7.5 Changes in Groundwater Pressures

From all the case studies presented (Figures 5b, 7b, 9b & 11b), it can be seen that the maximum lowering of piezometric levels within the Old Alluvium was about 7 m to 15 m. At all the areas other than the Crossover Tunnels, no significant ingress of water through the retaining walls was observed. There was also no significant drawdown of the groundwater table. The substantial drop in piezometric levels in the Old Alluvium was most likely due to stress relieve in the soil during excavation. This was not a real concern as the Old Alluvium was over-consolidated and no significant ground settlement was expected to occur as a result.

At the Crossover area, there were some localized ingresses of water through the retaining walls at the soil interface between the Reclamation Fill and Old Alluvium. This was the main cause of the draw-down in groundwater table of about 4 m to 5 m at this area. As a result of the drawdown, relatively large ground settlements of up to 114 mm were observed.

8 CONCLUSION

In this paper, the behaviour of various excavation support systems used for the construction of Changi Airport Station has been contrasted. Some of the factors affecting the behaviour of excavations were also identified and discussed. One of the most effective means of reducing ground movements is by using rigid retaining walls with strutting.

Original and back analyses of the excavations were carried out using WALLAP for the case studies presented. As a general guide for the preliminary design of excavation support systems in the Old Alluvium with similar ranges of SPT N values, it is proposed to adopt an undrained shear strength of 250 kPa (4 – 5 N). An elastic modulus of 125 MPa (2 – 2.5 N) above the formation level and 300 MPa (5 – 6 N) below the formation level is suggested.

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