Geotechnical instrumentation for tunnel and underground excavation: MRT Blue Line Extension Project

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ABSTRACT: The MRT Blue Line Extension is a 27 kilometers underground and elevated heavy rail transit system with 4 underground stations and 17 elevated stations situated along the route, 3 intervention shafts, a depot with operation control center and 1 park and ride. This paper deals with geotechnical instrumentation of Contract 2 which starts at Ch. 2+960 Sanam Chai Station (BS12) and ends at Ch. 5+530 of Cut and Cover section towards Thapra area. The extensive geotechnical instrument installation and monitoring are required in order to ensure the safety of life and assets during construction as well as the design verification. This paper describes the main features of design and construction of this project. Moreover, the geotechnical instruments installation and monitoring system giving information on the performance of the tunneling and deep excavation are also discussed.

1. INTRODUCTION

The Metropolitan Rapid Transit Authority (MRTA) was established by the Thai Government in August 1992 as a state enterprise to develop and implement the Mass Rapid Transit Initial System (Blue Line) Project as the first phase of Bangkok's Mass Transit core network, MRT Chaloem Ratchamongkhon Line by His Majesty the King of Thailand since December 1999 and the project was completed on 2004. However the traffic congestion still prevails in Bangkok due to insufficient coverage of the existing rail mass rapid transit network which does not connect most of the outer suburbs to the inner city. In recognition of this problem, the government has set forth a policy to accelerate the development of the rail mass rapid transit network to cover more areas in Bangkok with efficient and convenient services to the passengers. The MRT Blue Line Extension Project has then been established in order to alleviate the traffic congestion and also help reducing energy consumption as well.

The MRT Blue Line Extension is a 27km underground and elevated heavy rail transit system with 4 underground stations and 17 elevated stations situated along the route, 3 intervention shafts, a depot with operation control center and 1 park and ride. Fig. 1 shows the MRT network including existing and planned routes. This project was divided by 5 civil contractor contracts consisting of:

1). Hua Lamphong – Sanam Chai Section (underground)

2). Sanam Chai – Tha Phra Section (underground)

3). Tao Poon – Tha Phra Section (elevated)

4). Tha Phra – Lak Song Section (elevated)

5). Track System

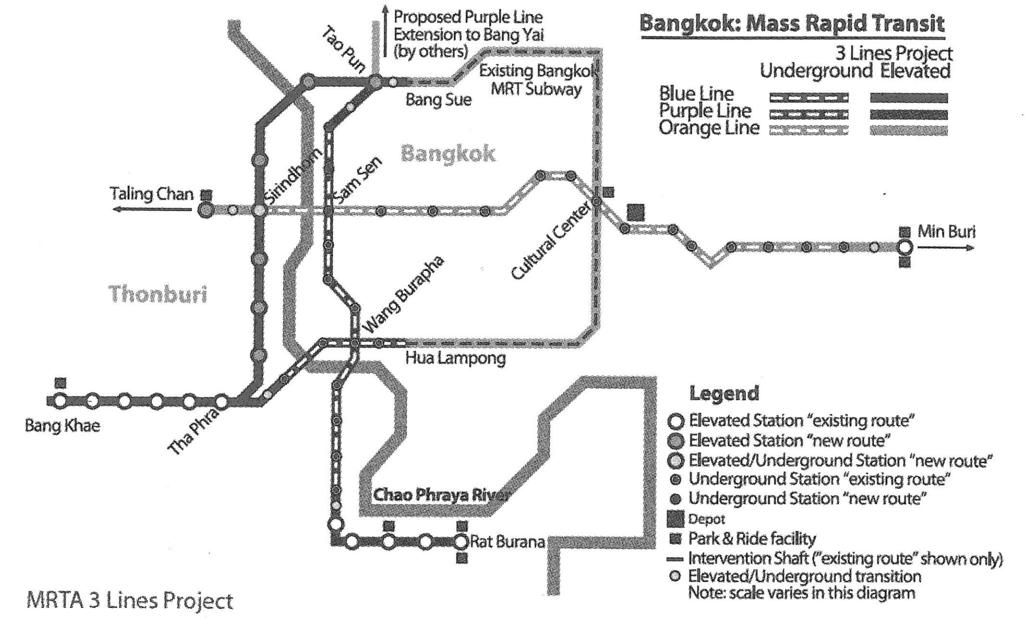

Figure 1 Bangkok MRT network

2. PROJECT BACKGROUND

Contract 2 starts at Ch. 2+960 Sanam Chai Station (BS12) and ends at Ch. 5+530 of Cut and Cover section towards Thapra. The total length of the section is approximately 2.6 kilometers. This Blue Line Section is composed of two (2) underground stations, 1 intervention shaft, cut and cover transition structure, and twin bored tunnels approximately 20 meters under existing ground. Fig.2 shows the project layout of MRT Blue Line South Underground Section (Contract 1 and 2). In order to ensure the safety of life and assets during construction as well as the design verification the geotechnical instrumentation has been implemented to the project. The geotechnical instrumentation monitoring data is one of the important information helping engineers in every stage of a project i.e. initializing site conditions, verifying design assumptions, monitoring the effects of construction, enforcing the quality of workmanship, warning of impending failures for safe evacuation and implement remedial action, providing evidence for a legal defense of designers and contractors.

3. BANGKOK SUBSOIL CONDITIONS

Bangkok area is situated in the Chao Phraya River plain. In the upper 40m zone where the excavation and foundation works of the Blue Line South Extension is located, several different soil layers can be distinguished. Beneath the 2 to 5m. thickness of uppermost weathered crust layers, the thick soft clay layer is present which generally extending from the ground surface to a depth of 12 to 15m. This soft clay is known as "Bangkok soft clay" has high water content (90-120%), high plasticity, low strength and high compressibility. The undrained shear strength of this very soft to soft clay varies from 10 to 25kPa and the water content between 60 and 105% is close to the liquid limit. The underlying stiff clay layer (the first stiff clay), thickness 5-15m, and undrained strength varies from 75 to 162kPa, with lower water contents between 15 and 32%. The stiff clay is a firm and impervious soil which is an ideal medium for tunnelling within. Below the stiff clay layer is a layer of fine to medium, dense to very dense, clayey silty sand (the first sand) which is located in a depth of 35 to 40m below the surface. The very stiff to hard clay (second stiff clay layer) is found below the first sand layer with the thickness of 35 to 40m. Second sand layer underlies the second stiff clay is found below, which consists of silty sand and poorly graded sand with silt. Fig.3 shows the typical subsoil stratigraphy using the subsoil along the MRT Blue Line Extension – South Underground Section.

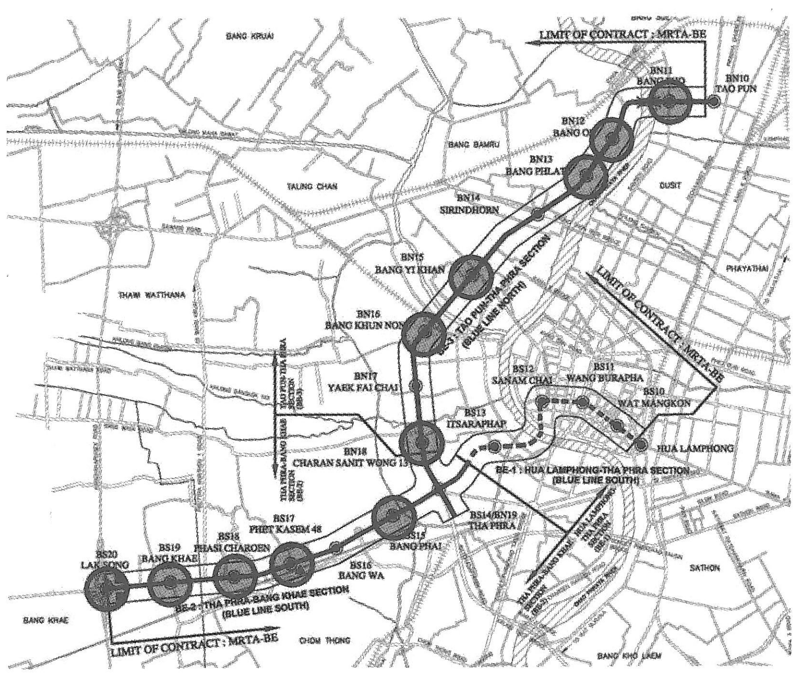

Figure 2 MRT Blue Line Extension

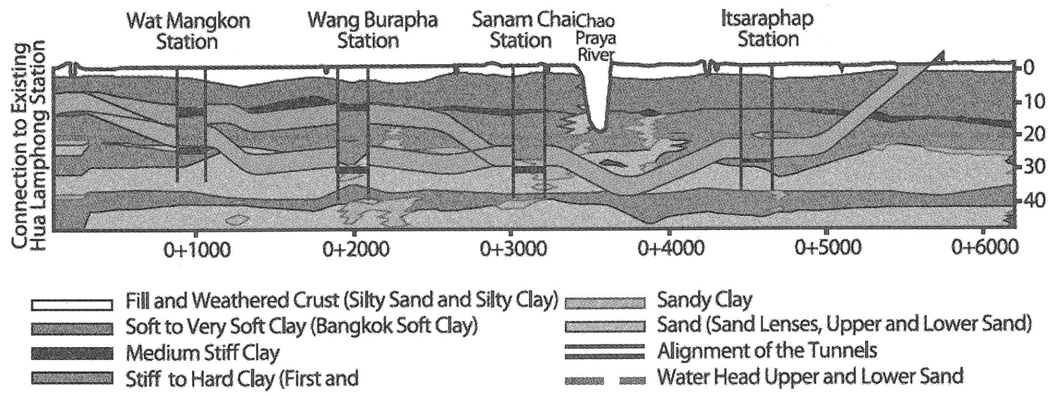

Figure 3 Geological Longitudinal Section

4. GEOTECHNICAL INSTRUMENTATION SCHEMES

Instrumentation played an important role in the tunnelling and deep underground excavation especially in congestive urban area of MRT Blue Line Extension - South Underground Section. The primary objective of the instrumentation program is to monitor the performance of the deep excavation and tunnelling operation to ensure safe execution of the construction works and that adjacent structures were not adversely affected. The types and positions of instrument shall be properly planned and installed at the most representative and critical locations to observe the influence of construction to the surrounding structures. Extensive instrumentation systems were then installed inside the predefined influence zones including station box excavation, tunnelling and associated building, structures and utilities. In addition to the major geotechnical instruments, various types of settlement markers, 3D prism, tilt-meter, crack meter and crack gauge were installed to monitor the ground and associated building-structures movement.

4.1 Settlement Monitoring

At the TBM launching, break-in and break-out station box, monitoring arrays of settlement markers

were installed in order to observe the surface settlements which are very sensitive to the tunnel excavation work. Fig.4 shows the typical layout of settlement arrays both break-in and break-out station box. Moreover, surface settlement markers along and across the tunnel alignment were periodically installed in order to observe the ground settlement during tunnel excavation by TBM.

All adjacent buildings and structures within the influence zone, 1.5Z extended width from the tunnel alignment, are also required to be installed the settlement markers. Z is for the tunnel depth.

4.2 Building Movement Instrumentation

Not only the building settlement markers, but the other instruments i.e. 3D-prism, tilt meter, and crack meter were also applied on the building structure with more than 2 stories. 3D-prism and tilt meter are generally used to monitor the movement and inclination change of the building affected from the construction. Crack meter is used to measure change in width of a surface crack.

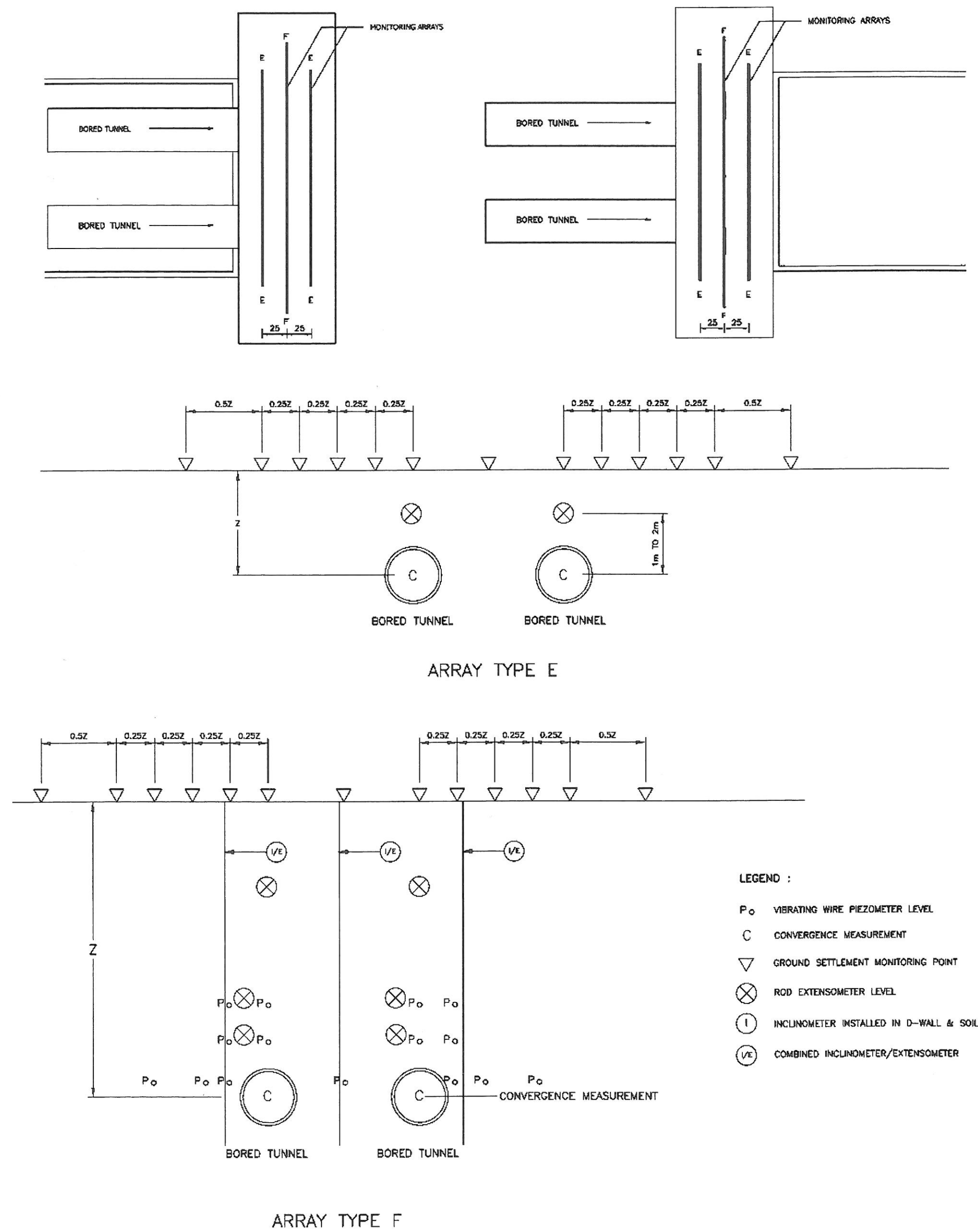

Figure 4 Settlement Marker and Instrument Arrays for break-in and break-out station

4.3 *Major Instrumentation Scheme at Top-Down Construction Structure, Transition Box, and Along Tunnel*

Three locations of Top-Down Construction Structures and One Transition Box were planned to install the extensive geotechnical instrumentation in order to monitor the structural behaviour during Top-Down excavation. These instruments are composed of inclinometer, rod extensometer, vibrating wire piezometer, vibrating wire rebar transducer, and heave stake. Fig.4 and 5 presents the typical instrument arrays for Top-Down construction structure, transition box, and Along Tunnel Alignment.

4.4 *Monitoring Program and Trigger Levels*

The performance of the Blue Line Extension – Contract 2 instrumentation will be monitored both prior to the construction and during the construction. Monitoring frequency shall be planned based on the construction sequences and also be reviewed and adjusted according to the progress of works periodically.

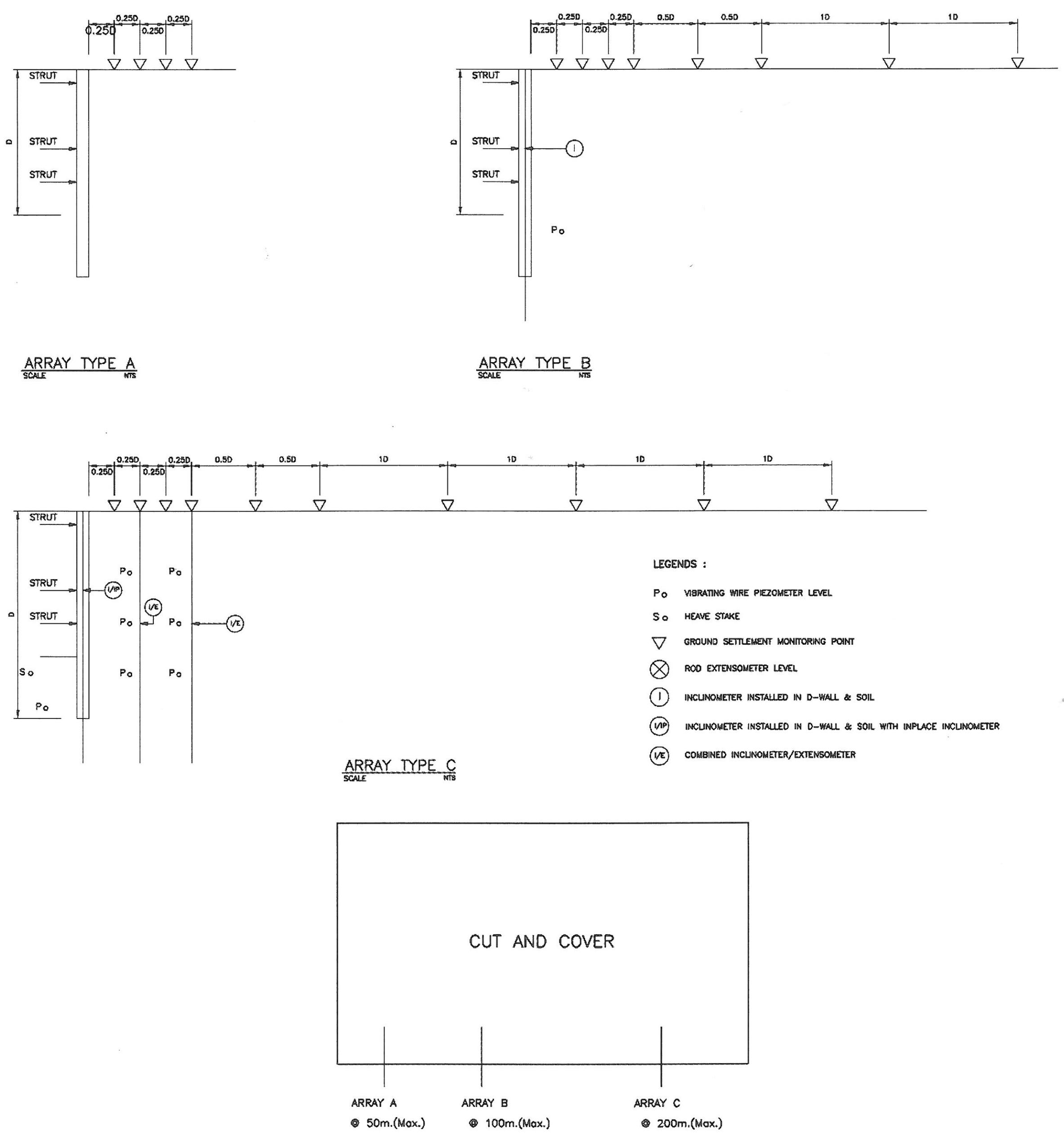

Figure 5 Settlement Marker and Instrument Arrays for Top-Down construction structure and transition box

The baseline monitoring has to be performed prior to the commencement of major construction activities in order to obtain the reference data and initial readings for further processing and interpretation. During the construction, the monitoring frequency shall be followed the requirement. Once a week monitoring shall be applied to the instrument which far away from the active construction zone, however, the monitoring frequency will be increased to check the adequacy and construction condition when those instruments are close to the critical activities area. Table 1 shows the minimum monitoring frequency program for top-down construction structure applied in this project.

Table 1 Minimum Monitoring Frequency

Measurement	Instrument	Minimum Monitoring Frequency				
		Prior to Excavation	During Excavation/ Strut Installation/ Removal	During Back Filling	After Completion of Excavation/ Back Filling	Ending of Monitoring
Ground water table and Pore water pressure	Observation Well	Once a week	Twice a week	Twice a week	Twice a week thereafter	3 months after finishing works
	Stand pipe piezometer					
	Wireless or Normal Transducer type piezometer					
Deformation of Diaphragm wall	Inclinometer in Diaphragm and Soil	Once a week	Thrice a week	Once a week	Once a week	3 months after finishing works
Stress of Diaphragm wall	Re-bar stress transducer (Brother bar)	Once a week	Daily	Once a week	Once a week	
Strut Stress	Strain gauge	Once a week	Daily	Once a week	Once a week	After removal of all struts
	Load Cell					
Adjacent Ground and Building movements	Settlement reference points, ground surface type	Once a week	Daily	Once a week	Once a week	3 months after finishing works
	Settlement reference points, masonry/concrete type	Once a week	Daily	Once a week	Once a week	
	Settlement reference points, utilities type	Once a week	Daily	Once a week	Once a week	
	Settlement reference points, shallow sub surface type	Once a week	Daily	Once a week	Once a week	
	Multiple position magnetic ring type extensometer	Once a week	Thrice a week	Once a week	Once a week	
	Inclinometer casing in Earth	Once a week	Thrice a week	Once a week	Once a week	
	Wireless EL. Tilt meter, Temporary plate, Wireless EL-beam	Once a week	Daily	Once a week	Once a week	
	Crack gauge (tell-tale type)	Once a week	Daily	Once a week	Once a week	
	Wireless Crack meter	Once a week	Daily	Once a week	Once a week	
Excavation Bottom	Subsurface settlement/Heave Indicator	Once a week	Daily	Twice a week	Twice a week	After finishing base slab
Reference	Deep Bench mark	Monthly	Monthly	Monthly	Monthly	3 months after finishing

In order to perform the instrument monitoring work with safety control properly, it is necessary to early establish the suitable control values which are determined by the results of excavation analysis, conditions of adjacent properties, and professional judgment. These control values, so called Trigger Levels, are the boundaries that need to be stimulated proper actions to the construction activities. Generally, trigger levels adopted in the excavation works consist of two (2) typical values namely Alert Level and Action Level. However, this levels can be divided into three (3) categories in the sensitive project i.e. Alert, Alarm, Action values. For Blue Line Extension Project – Contract 2, the trigger levels were generally set at 70, 80, 100% of predicted value for Alert, Alarm, Action respectively. When Alert Level is reached, it is intended to provide an opportunity of early review of monitoring and contingency measures as the value approaching the predicted maximum value. More frequent monitoring measurements will be conducted. If the reading value reached to the Alarm Level, the construction method has to be reviewed with the purpose of mitigating detrimental effects arising from ground movement. At the Action Level, it is intended to provide sufficient opportunity to consider the implementation of contingency measures to limit movement or stress before the structures around the excavation stations and tunnels reach its fully cracked condition. Temporary suspension on corresponding site works may be applied for necessary safety check and re-assessment of the design adequacy.

4.5 Database Management System for Instruments Monitoring Program

Database Management System (DMS) is a powerful tool to manage two levels of risk allowing adjustments where and when necessary during construction and operation state. The DMS which is implemented for the Project can help engineers to manage risk on two very different levels. On a strategic level, the quality, integrity and real-time delivery of data that the system provides helps reassure regulators and insurers that the projects is being managed within clearly defined safety parameters and that able to provide solid data in support of this. On an operational level the speed and responsiveness of the DMS ensures engineers are informed, quite literally up-to-the-minute, about the precise environmental and structural impact of the work in progress. The alerts alarms and actions programmed into the system to help identify potential problems before they become safety hazards or disrupt production. Fig.6 shows the feature of the DMS for instruments monitoring programs.

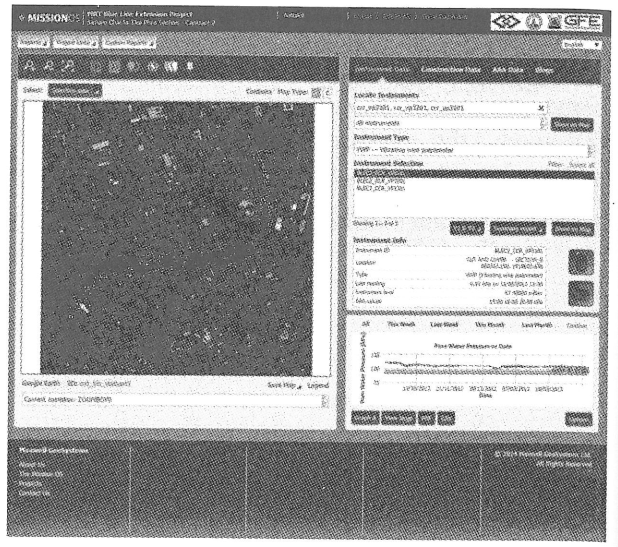

Figure 6 Database Monitoring System (DMS) for The MRT Blue Line Extension Project: Contract 2 (Instrumentation Works)

5. APPLICATION

5.1 Settlement Trough induced by Tunnelling

Empirical Greenfield settlement trough proposed by Peck (1969) has described settlement data from over twenty case histories that the shape of the surface settlement trough at right angles to a tunnel axis approximates to an inverted Gaussian distribution curve symmetrical to the tunnel axis as shown in Fig.7. The shape of the trough can be presented using the following equation:

$$\delta = \delta_{\max} \exp(-x^2/2i^2) \quad (1)$$

where δ is the surface settlement, $\delta_{\max}$ is the maximum vertical settlement, x is the transverse distance from tunnel centreline, and i is the width of settlement trough which is the distance to the point of inflection of the curve, and is determined by the ground conditions. Various expressions have been proposed for calculating i in practice, O'Reilly & New (1982) suggested that the relation will be as follows:

$$i = kz_0 \quad (2)$$

where k is a dimensionless constant, depending on soil type (0.5 for clay & 0.25 for cohesionless soles) and z_0 is the depth of the tunnel axis below ground level.

The volume of the surface settlement trough (per meter length of tunnel), V_s can be calculated using:

$$V_s = 2.5 i S_{\max} \quad (3)$$

In this case, the settlement trough across the tunnel alignment can be obtained from the monitoring program. S_{max} and i parameters can then be evaluated by fitting curve. With these two parameters, the volume of surface settlement trough can be estimated.

In this project, there are 29 ground settlement arrays installed across the tunnel alignment in order to observe the settlement through induced by tunnelling. On February 2013, TBM first drive has launched from the transition box on the west bound track and progressively excavated pass through the pre-installed ground settlement arrays which are located in front of launching position. Fig.8 shows the location of settlement arrays and TBM launching direction (break-out) and break-in station.

According to the monitored results of array no. 13C_SSE061, it showed that the observed troughs can be reasonably fitted with the Gaussian curve (Peck, 1969) as shown in Fig.9.

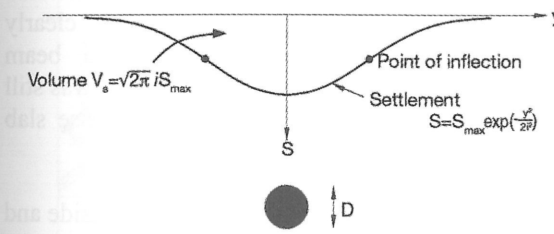

Figure 7 Transverse Settlement Profile after Peck (1969)

S_{max} and i parameters can then be evaluated to -22.34mm and 5.44 respectively. From Eq. (3), the volume of surface settlement trough per unit length is 0.3037m^3/m. Volume of excavation (V_{exc}) per unit length based on TBM configuration is 33.183m^3/m. The calculated tunnel ground loss (V_s/V_{exc}) from the observed settlement trough was then 0.92%.In the same way, the monitored results of array no. 13C_SSE052 also showed the reasonably fitted with the Gaussian curve as shown in Fig. 10. S_{max} and i parameters from the fitting curve are -10.28mm and 5.24 respectively. From Eq. (3), the volume of surface settlement trough per unit length is 0.135m^3/m. Volume of excavation (V_{exc}) per unit length based on TBM configuration is 33.183m^3/m.

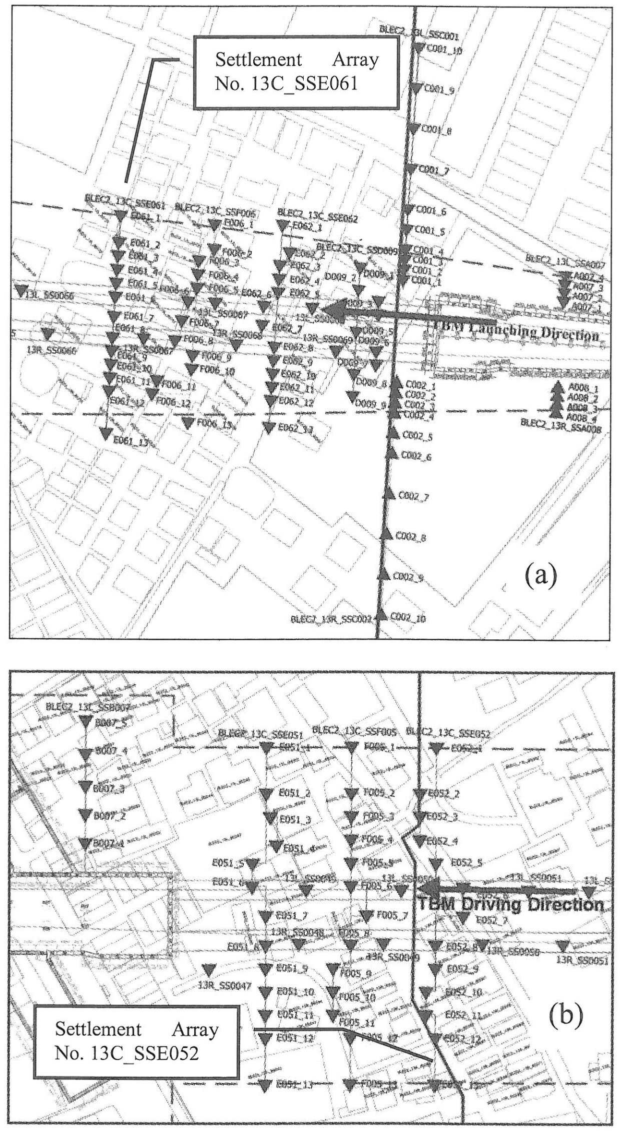

Figure 8 Surface Settlement Markers at Launching Area (a) and break-in station (b)

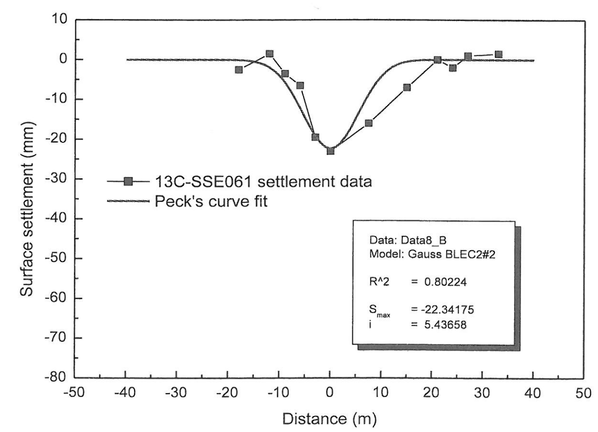

Figure 9 Surface Settlement Trough at Array 13C_SSE061

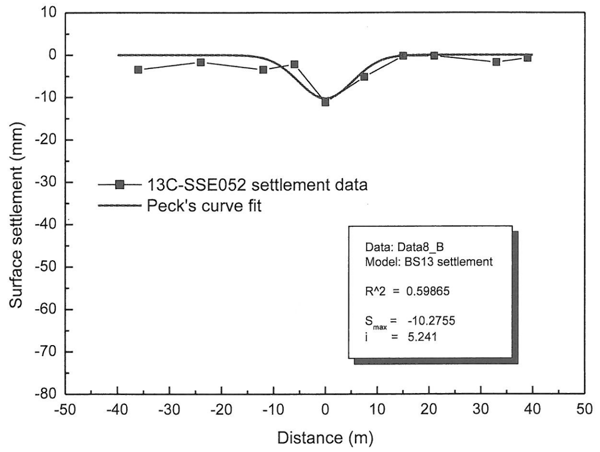

Figure 10 Surface Settlement Trough at Array 13C_SSE052

The calculated tunnel ground loss (V_s/V_{exc}) from the observed settlement trough was then 0.41%.

The larger volume loss of array 13C_SSE061 compare with the array 13C_SSE052 is caused from the tunnel excavation during the beginning which the advance rates, pressure balance determination, and other TBM machine control properties were adjusting to achieve an accurate time schedule, ground loss optimization, and safety control. Once the control properties were optimized, the volume loss will be decreased.

5.2 *Behavior of Diaphragm Wall and Adjacent Pore Water Pressure during Excavation*

The wall deflection was monitored using inclinometers installed inside diaphragm walls at all underground station and transition box. Moreover, the pore water pressure was monitored using vibrating wire piezometers installed both inside and outside excavation area. This chapter is focused on the monitoring data at transition box area. Plan and longitudinal section are shown in Fig.11. Top-down construction technique was applied in the transition box construction which composed of two (2) levels of concrete slab, roof skeleton level and base slab level. Both slab layouts are inclined from the deep underground side to the elevated side complying with railway track alignment. At the underground side, roof skeleton slab is located at 95.15mELE from ground elevation of 101.4mELE. The base slab is located at 85.0mELE. D-wall toe is levelled at 73.5mELE. A set of major instrumentation has been installed including inclinometer, vibrating wire piezometer, and combined inclinometer/extensometer as shown in Fig.12.

In order to eliminate the toe movement of inclinometer, extended length of inclinometer was employed up to the firm layer, and then the toe of inclinometer has been installed up to 64.4mELE in the second stiff clay layer. Fig.13 to 15 show the inclinometer readings of CCR_INC001 installed inside D-wall, the vibrating wire piezometer readings of CCL_VP1001 and CCR_VP1001 installed inside the excavation area, and the multiple vibrating wire piezometer readings of CCR_VP3101, CCR_VP3201 and CCR_ VP3301 installed outside the excavation area, respectively.

As the monitoring results, the wall deflection was around 2mm during the first excavation and temporary strut installation. The wall movement was around 5mm after the second excavation down to the roof skeleton level and 7mm after the roof slab casting. Once the excavation has conducted down to the base slab level, 16mm wall deflection was observed approximately at 3.0m above the base slab level. The bulge inward deflection shape clearly observed due to the wall behaves as a beam supported at upper and bottom end. The wall was still moving for 2-3mm until the complete of base slab casting.

The pore water pressure monitoring results inside and outside the excavation areas are consistent with the excavation activities. Once the excavation progressed down to the base slab level, the pore water pressure in excavation area clearly decrease. Subsequently the pressure is constant after the base slab casting. This is caused from the excavation area inside the transition box was plugged by the 1st stiff clay layer, and pore water pressure decreased in accordance with excavation activity. In contrast, all monitored pore water pressures outside the excavation area were constant during the excavation work. This incident can be implied that the 1st stiff clay effectively plugged under the transition box preventing ground water ingress to the excavation area. The water level outside excavation area is then constant. With these results, the design, construction, and safety control were completely satisfied.

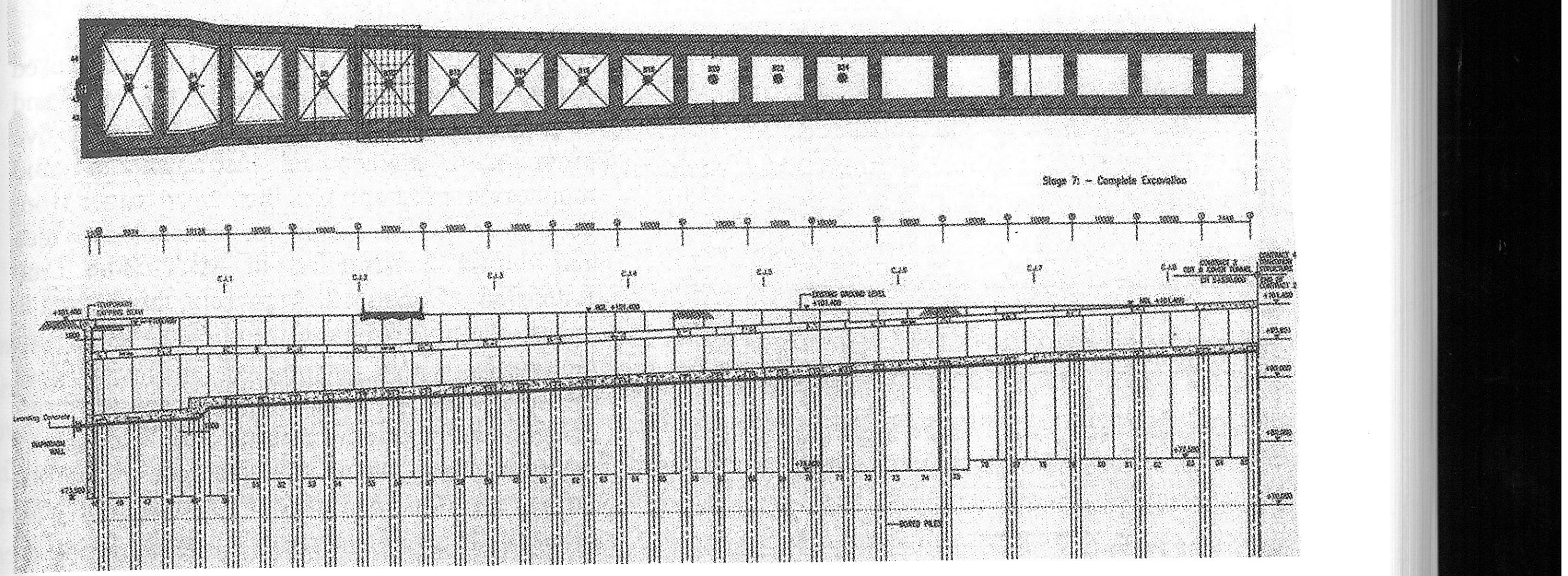

Figure 11 Transition Box Layout Plan and Longitudinal Section

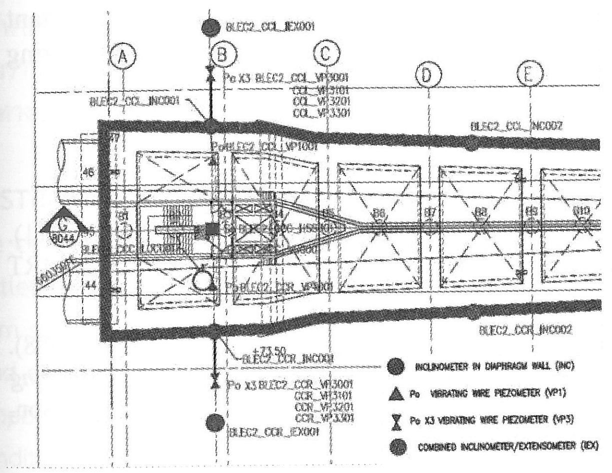

Figure 12 Layout of instrumentation at Transition Box

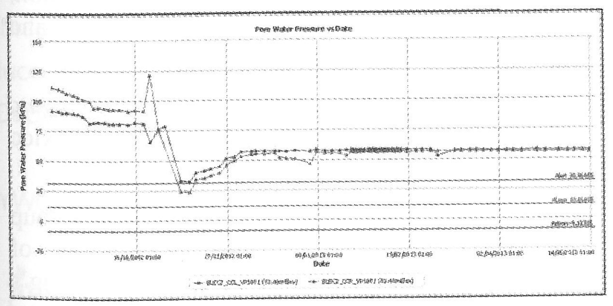

Figure 13 VW Piezometer Monitoring Results of CCL_VP1001 and CCR_VP1001

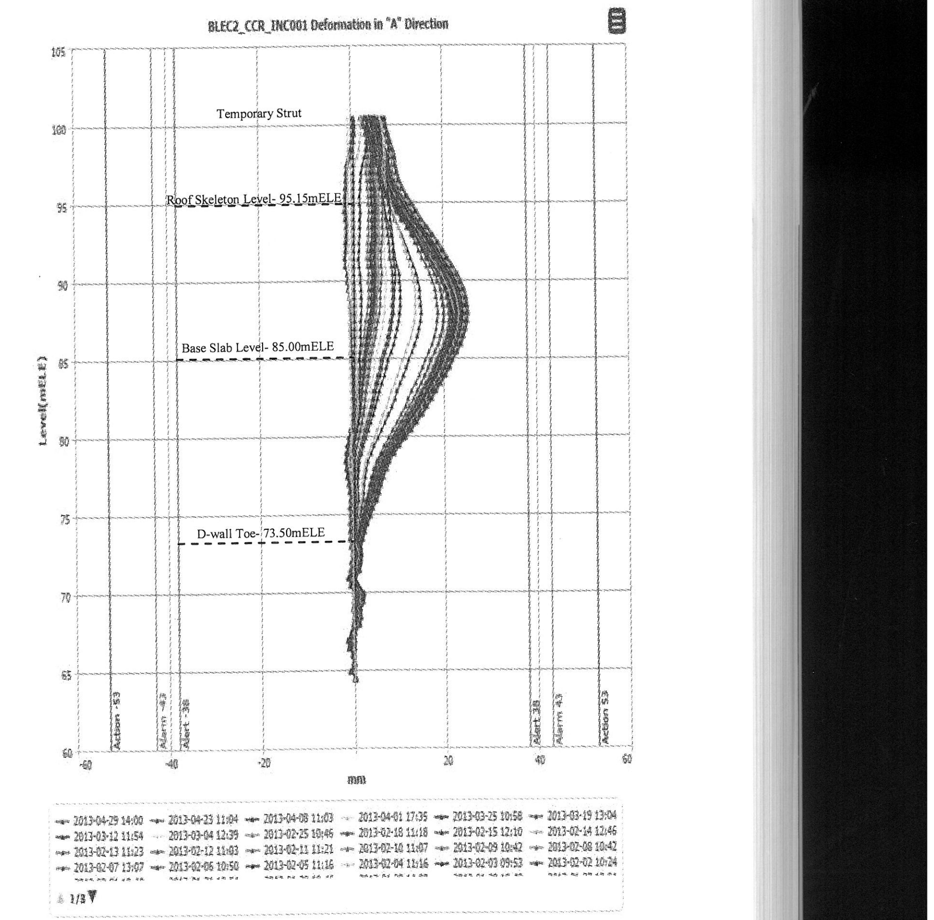

Figure 14 Inclinometer Monitoring Results of CCR_INC001

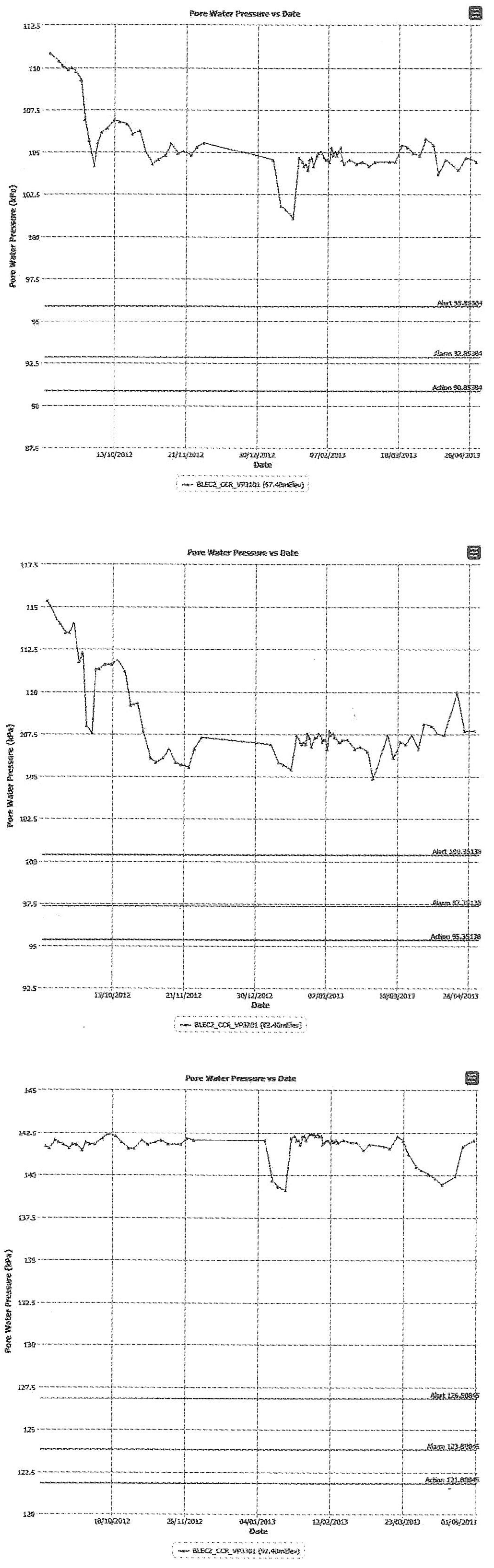

Figure 15 Multiple VW Piezometer Monitoring Results of CCR_VP3101 to CCR_ VP3301

6. CONCLUSIONS

Instrumentation is very important and used widely as a complementary tool in the tunnel and underground excavation works. The extensive program of geotechnical instrumentation and monitoring program has then been carried out both prior to the major construction activities and during construction in MRT Blue Line Extension – Contract 2. At present, this project is under the construction, and the instrument monitoring is still keeping on the track. These measurements will help the engineer to verity design assumptions, enforce the quality of workmanship, warning of impending failures for safe evacuation, and take immediate remedial measure for problems, which may be occurred during construction. However, understanding of ground condition and construction sequences, proper instrumentation planning, implementation of safety control procedures, and qualified interpretation of monitoring results are important for ensuring the effectiveness of monitoring system and construction safety control.

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