APPLICATION OF GEOTECHNICAL INSTRUMENTS FOR SAFETY CONTROL IN BASEMENT CONSTRUCTION WORKS

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Abstract: Instrumentation plays an important role in the underground construction activities near sensitive properties. It is advisable to monitor any soil movements or any changes in the soil stress conditions around the excavation zones and also the behavior of the retaining system and adjacent properties during excavation to ensure the safety of excavation and satisfactory performance. However, proper planning of instrumentation program and qualified interpretation of monitoring results by competent geotechnical engineer are essential in ensuring the effectiveness of the monitoring system, the accuracy/validity of the monitoring results and the proper action in preventing possible damage. This paper describes the planning and application of instrumentation system for basement construction works. The importance of installation and maintenance works and the application of engineering judgment in the interpretation/verification of monitoring results are also discussed.

1. INTRODUCTION

Due to the variable properties and behavior of soil in-situ and certain limitations involved in the site investigation works, many geotechnical designs have to adopt simplified geotechnical model and to employ some idealized assumptions, which require substantial inputs from field observations, e.g. instrumentation monitoring in order to verify its validity and to ensure satisfactory field performance. It has long been recognized that field performance records play an important part in the soil engineering practice. Application of field instrumentation system for design verification and safety control in geotechnical engineering has become more and more popular in Singapore since early 80 due to the increasing demand for underground space in the new developments. The Chartered Bank Redevelopment is considered to be one of the pioneer instrumentation projects in Singapore.

2. PURPOSES OF FIELD INSTRUMENTATION

The purposes of field instrumentation particular for application in basement construction works can be briefly described as follows.

2.1 Verification of Design Assumptions

The actual behavior of ground and retaining system recorded by the instruments during each stage of construction are very useful to the design engineers in verifying the validity of parameters and assumptions adopted in the design.

2.2 Control of Construction Safety

Defects or damages could be caused by excavation due to inadequacy of design or improper control in the sequences of excavation. The response of instruments observed during each stage of excavation will provide the engineers with valuable information in judging the safety of construction and any need for re-evaluation of design, modification of construction sequences and application of protective/precaution measures.

2.3 Upgrade of Technical Know-how

The information collected from the instrumentation monitoring works could be used for the back-analysis of design and calibration of software for improving the suitability and accuracy of the design method and the validity of the adopted design criteria.

2.4 Evidence to Damage Dispute

Frequently, the monitoring records which properly register the behavior of ground and surrounding properties throughout the entire construction period could be a powerful tool in protecting the owner from possible damage dispute.

3. PLANNING OF INSTRUMENTATION SYSTEM

Proper planning is essential in the successful application of instrumentation system for safety control in basement construction works.

3.1 Site and Project Conditions

The site and project conditions, such as soil condition, adjacent properties, depth and size of excavation and method of construction are needed to be carefully analyzed and included in the planning of instrumentation system for basement construction works. Likely excavation problems anticipated in cases associated with i) typical ground and environment, such as subsidence and basal heave in soft clay and seepage/boiling effects in loose sand, ii) excavation adjacent to sensitive properties, such as movements of structures supported on shallow or compensate foundations and iii) depth/shape of excavation related to the surrounding properties, must be properly evaluated and considered in the design of excavation and instrumentation works.

3.2 Selection of Monitoring Instruments

Only the right types of instruments will provide the engineers with the representative information on the behavior of ground and structures during excavation, which is essential in the assessment of site safety during construction. It is important to ensure that the selection of instruments is properly carried out according to the site and project conditions as described above and the purposes as shown in Table 1.

Table 1 Common Types of Instrument for Basement Construction Works

Types	Instruments	Purposes	Related Problems
Groundwater Table /Piezometric Pressure	Water Standpipe	Change in groundwater level	Seepage and ground subsidence
	Piezometer	Change in piezometric level	Consolidation settlement, uplift or weakening of soil
Lateral Movements	Inclinometer	Lateral ground movement and deflection of retaining walls	Instability of retaining system and adjacent structures
Stress/Load	Vibrating Wire Strain Gauge	Stress along strut member	Over-load of struts
	Load Cell	Axial load of strut	
	Bar Stress Transducer	Stress in rebar of concrete retaining structure	Over-load of reinforcing bars
	Earth Pressure Cell	Earth pressure distribution on retaining wall	Over-stress of earth retaining wall
Settlement / Heave	Surface Settlement Point	Ground surface settlement	Movements of surrounding ground and damage to existing utilities
	Building / Utility Settlement Point	Settlement of adjacent buildings and utilities	Instability of structures
	Settlement Gauge	Continuous settlement of structures	
	Heave Gauge	Elastic heave in soft clay	Soil weakening and instability of excavation
	Extensometer	Vertical ground movements in various depth zone	Deep ground movements
	Automatic Tunnel Monitoring Device	Movement of MRT tunnels	Ground heave, subsidence and lateral movement
Tilt / Crack	Tiltplate / Tiltmeter	Tilting of structures	Instability of structures
	Crackmeter	Cracks on structure surface	Uneven settlement of structures
Vibration	Vibration Sensor	Vibration effect to adjacent properties	Disturbance to foundation soils and structures

3.3 Layout of Instruments

The positions of instruments shall be properly planned and installed at the most representative and critical locations to capture accurately the influence of works to the surrounding properties and the representative response of ground and retaining system to ensure the safety of construction. Table 2 shows the guidelines for planning of instrument positions.

3.4 Technical Specification

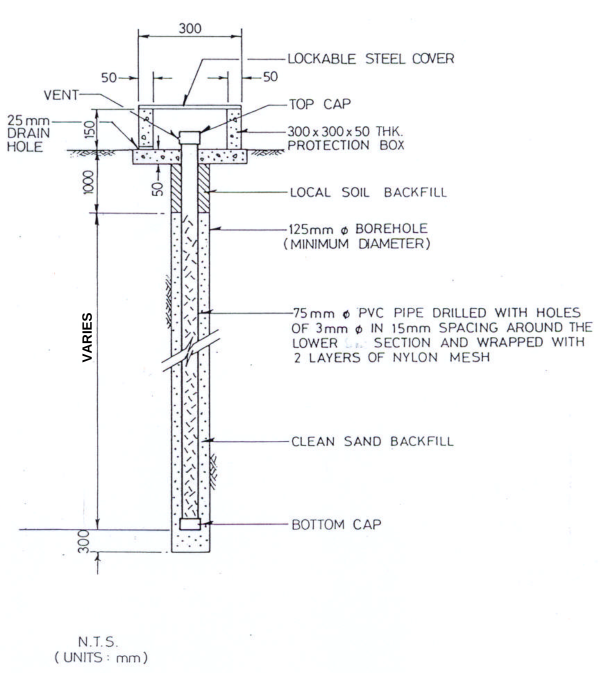
A complete technical specification for instrumentation system shall include instrument specification (e.g. precision and accuracy), sequence / procedures and important notes for installation. It is important to ensure that the required specifications are fully complied with in the installation works under the supervision of competent geotechnical engineers and the as-built condition of each installed instrument are properly recorded and reflected on plans for the reference of the engineers in the interpretation works. Some installation details which have significant influence to the accuracy of measurement and validity of interpretation such as sealing of water standpipe / piezometer, installation depth of piezometer / heave marker, orientation and depth of inclinometer and bonding surface of tiltplate, etc., must be strictly followed and ensured in the installation works. Figure 1 shows the typical installation details of some instruments.

3.5 Checking and Maintenance Procedures

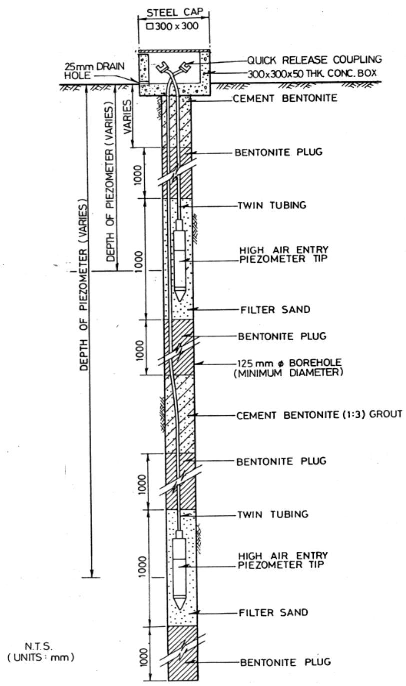
Instruments must be maintained in good functioning condition throughout the whole monitoring period in order to ensure the validity and accuracy of monitoring readings, especially after a long period of monitoring or frequent application. It is necessary to carry out regular checking and calibrations to verify the properties of instruments, including sensors, readout units and reference points used in the monitoring works. Generally, calibration of instruments consists of three (3) stages, i.e. **factory calibration**, **acceptance test** and **re-calibration**. The factory calibration provides only a quality check for products in the manufacturing process which needs to be verified by acceptance test prior to installation in view of possible disturbance involved in the shipment works. Re-calibration will help to minimize possible instrument errors attributed to the changes of instrument properties, e.g. misalignment of sensor, deviation in reference gauge reading (e.g. zero gauge reference) and elongation of measuring tape and cable. The as-built condition of instruments and any change which may be created to the installed instruments during monitoring period, such as change of top level of water standpipe and inclinometer, etc. shall be properly captured, adjusted and considered in the monitoring and interpretation works.

Table 2 General Guidelines for Installation of Instruments for Basement Construction Works

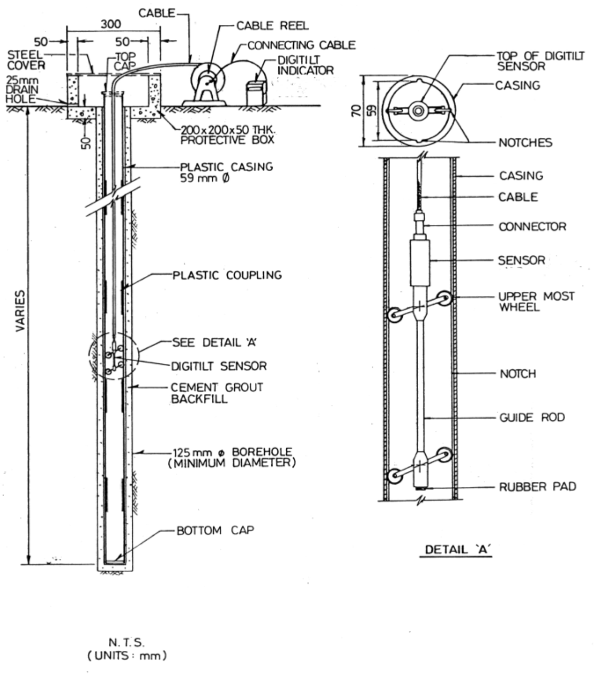
Instruments	Position	Installation
Water Standpipe	Along excavation boundaries and within anticipated groundwater drawdown zone	Not shallower than depth of excavation
Piezometer	In compressible layers where consolidation is anticipated or below base of potential uplift structures	At various depths in compressible layer or expected sensitive locations
Inclinometer	At most critical location, generally mid-span of excavation boundaries or near sensitive structures	Embedded in rigid base beyond movement influence zone but not shallower than depth of excavation
Vibrating Wire Strain Gauge	On selected strut members	Web of steel member
Load Cell	On selected strut members	Axial
Bar Stress Transducer	On selected reinforcement	Axial
Earth Pressure Cell	On selected retaining wall panel	Wall surface in contact with soil
Surface Settlement Point	Along excavation boundaries and critical sections perpendicular to excavation boundary	At 5m to 10m spacing and according to existing site condition
Building/Utility Settlement Point	On selected columns of structures	On surface of structural member after complete removal of paint and plaster
Heave Gauge	Centre and edges of excavation	At excavation level
Extensometer	Within anticipated stress influence zone	Various depth zones
Settlement Gauge	On selected columns of structures	On surface of structural member after complete removal of paint and plaster
Tiltplate/Tiltmeter	On selected columns of structures	On surface of structural member after complete removal of paint and plaster
Crackmeter	On surface of selected structural members	On surface of structural member after complete removal of paint, plaster
Vibration Sensor	At sensitive structure locations	Fixed or portable
Heave Gauge	At centre and near edge of excavation zone	At final excavation depth
Automatic Tunnel Monitoring Device	Within anticipated influence zones	Crown, base, left & right of tunnel linings at about 3m to 6m intervals



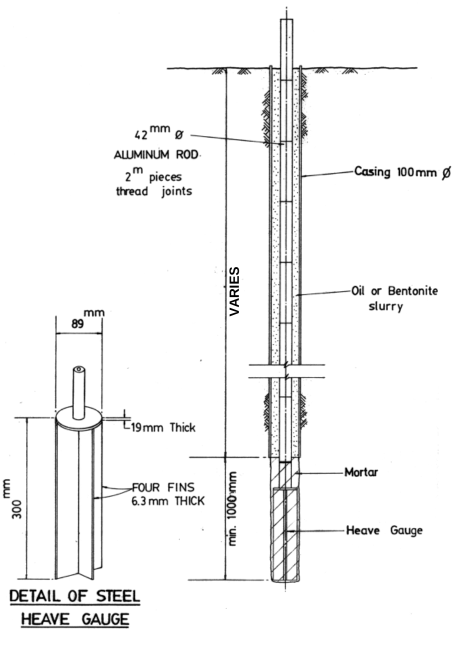
WATER STANDPIPE



PIEZOMETER



INCLINOMETER



HEAVE MARKER

Figure 1 Typical Installation Details for Instruments

3.6 Frequency of Monitoring

Monitoring frequency shall be properly planned based on the sequences of construction and the type and sensitivity of measurements, e.g. more frequent monitoring is needed for inclinometer during excavation stage in view of its sensitivity to excavation sequences, e.g. excavation and installation, pre-loading and removal of struts, and the importance of movement magnitudes to site safety. The monitoring frequency shall also be reviewed and adjusted according to the progress of works and the response of instruments and surrounding properties. Representative initial readings of all installed instruments must be properly established prior to the commencement of major site activities to ensure reliable reference for future comparison.

3.7 Control Values and Action Plans

For ensuring proper execution of instrument monitoring works and application of necessary action plan for safety control during each stage of basement construction, it is important to establish and incorporate in the instrumentation monitoring plan the suitable control values based on the results of excavation analysis, conditions of adjacent properties, project and Authority's requirements. Control values commonly adopted in the excavation works consist of two typical values namely **Alert Level** and **Action Level** which are determined by the excavation work designer based on the results of analysis and his professional judgment. When Alert Level is reached, it is necessary to closely monitor the response of excavation by increasing the frequency of monitoring and to study suitable precaution measures which may be required for keeping the site away from the critical situation (i.e. Action Level). Temporary interruption to the execution of field works for necessary re-assessment of the design adequacy / site safety and the application of action plan may be involved when Action Level is reached.

3.8 Data Processing and Interpretation

Timely analysis of instrument readings by competent geotechnical engineers is essential in the control of construction safety and effective application of prevention measures (if required) for minimizing detrimental effects and possible failure in basement excavation works. In view of the massive data involved in the monitoring works, especially for large scale project with long construction duration, a reliable database system including a set of stable and representative initial readings for each instrument has to be established in order to ensure the accuracy of computation and timely completion of data review and results interpretation which are important to the evaluation and control of construction safety. Verification of instrument readings during monitoring stage by necessary checking including top levels of water standpipe, top level and co-ordinates of inclinometer casing, reference benchmark for settlement survey and surface protection to instruments should also be included in the interpretation works.

4. SUCCESSFUL APPLICATION – New Tan Tock Seng Hospital

4.1 Project Description

The substructure works of the New Tan Tock Seng Hospital (Kong et. al 2002) consisting of the construction of 3 to 4-level basement in closely proximity to the existing MRT tunnels linking Novena Station and Toa Payoh Station and a 6-storey hospital ward block were successfully completed with remarkable contribution from the application of instrumentation monitoring system. The project site is roughly rectangular and approximately 191m by 135m (i.e. 25,785sq.m) with surface elevation varying from EL105m at north-west to EL120m at north-east (Figure 2). The excavation for basement construction went down to a max. depth of 16.5m below the existing grade. A combination of open cut and braced excavation method using stable cut slope and bored pile retaining walls (Table 3) was adopted in the basement construction of this project.

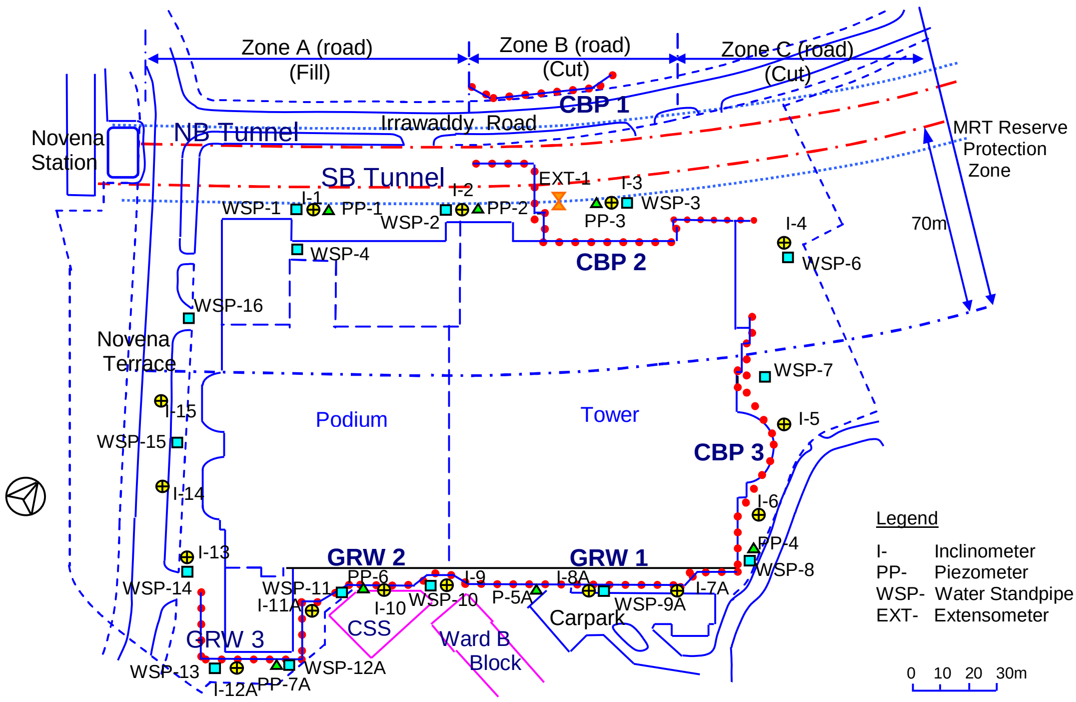


Figure 2 Site and Instruments Layout Plan

Table 3 Summary of Bored Pile Retaining Walls for Basement Excavation

Wall No.	Pile Sizes		Depth of Excavation (m)	Max. Movement Recorded (mm)	Types of Supports
	Diameter (mm)	Spacing (mm)			
GRW 1	800	1600	16.5	19.1 (I-8A)	Ground Anchors
GRW 2	1300	1600	16.5	17.3 (I-9) / 33.9 (I-10)	Ground Anchors
GRW 3	1000	1500	12.1	9.6 (I-12A) / 54.6 (I-11A)	Horizontal Struts
CBP 1	1100	1200	3.5	-	Cantilever
CBP 2	1100	1200	7.5	25.8 (I-3)	Cantilever / Rakers
CBP 3	800	900	16.5 / 15.3	32.8 (I-5) / 22.2 (I-6)	Ground Anchors

4.2 Soil Condition

The project site is situated in the Jurong Formation and the subsoils found in boreholes consist of medium dense Clayey SAND and/or stiff Sandy SILT (N=2 to 15) to dense Silty SAND and/or hard Sandy SILT (N=15 to 50) followed by a layer of very dense Silty SAND and/or very hard Sandy SILT with weathered rock (N=50 to over 100). SPT-N values over 100 were recorded at varied depth zones ranging from 18.9 to 34.5m and 3.0 to 11.0m below grade in the north-western and north-eastern parts of the site, respectively.

4.3 Instrumentation

To comply with the requirements on tunnel protection and to ensure the safety of the adjacent structures during excavation, a comprehensive instrumentation program consisting of various types of ground and tunnel monitoring instruments (Table 4) has been implemented for construction safety control of this project.

Table 4 Types and Quantities of Instruments

Type of Instruments	Quantities
Inclinometer	15
Pneumatic Piezometer	10
Water Standpipe	16
Surface Settlement Point	89
Extensometer	1
Vibration Sensor	5
Automatic Tunnel Monitoring Device (TM3000V)	2
Manual Survey	-

4.4 Wall Deflections

The behavior of walls under each stage of excavation were analyzed by using the Oasys computer program "FREW" in term of effective stress method and the performance was monitored and evaluated during each stage of excavation. Figures 3 & 4 show the change of lateral movement at selected depths recorded by two (2) typical Inclinometer Nos. I-5 and I-9, respectively during each stage of excavation. Sequential wall deflection profiles of these two inclinometers are shown in Figures 5 & 6. As indicated in Figures 3 & 4, the wall deflections increased rapidly with depth of cut and tended to be stabilized after the excavation was completed and adequate supports were provided. The characteristics of wall deflection observed in the present case was found consistent with the results of analysis and the relationship proposed by Moh et al (1999) with α value ranging from 39 to 201 (Figure 7) which show good performance and less harmful effect to the adjacent structures. The instrumentation results did provide the engineers with very useful information in the execution of construction control and the evaluation of site safety and design validity of this project.

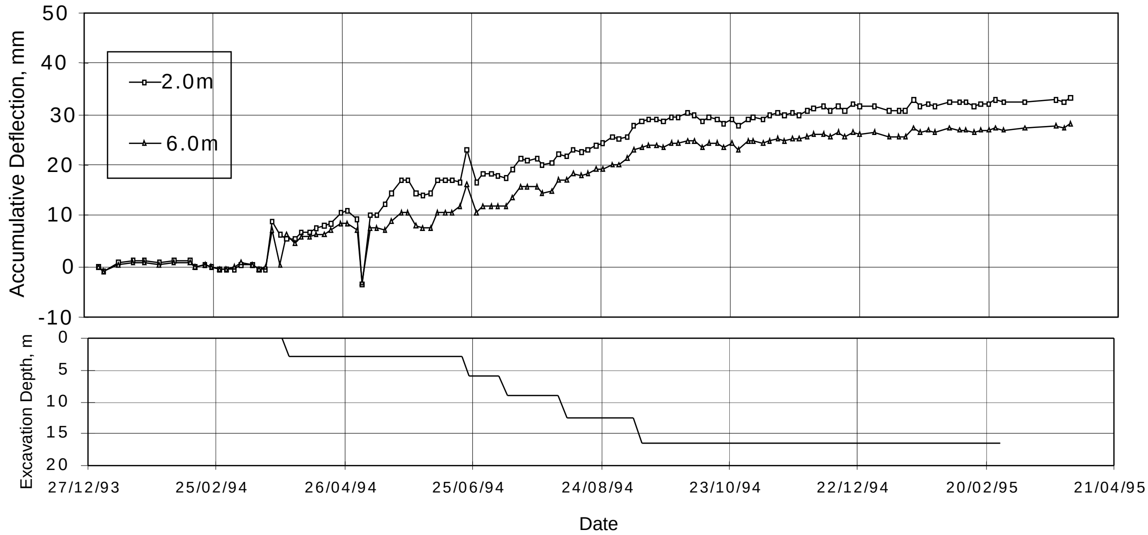


Figure 3 Change of Lateral Movement Recorded by I-5

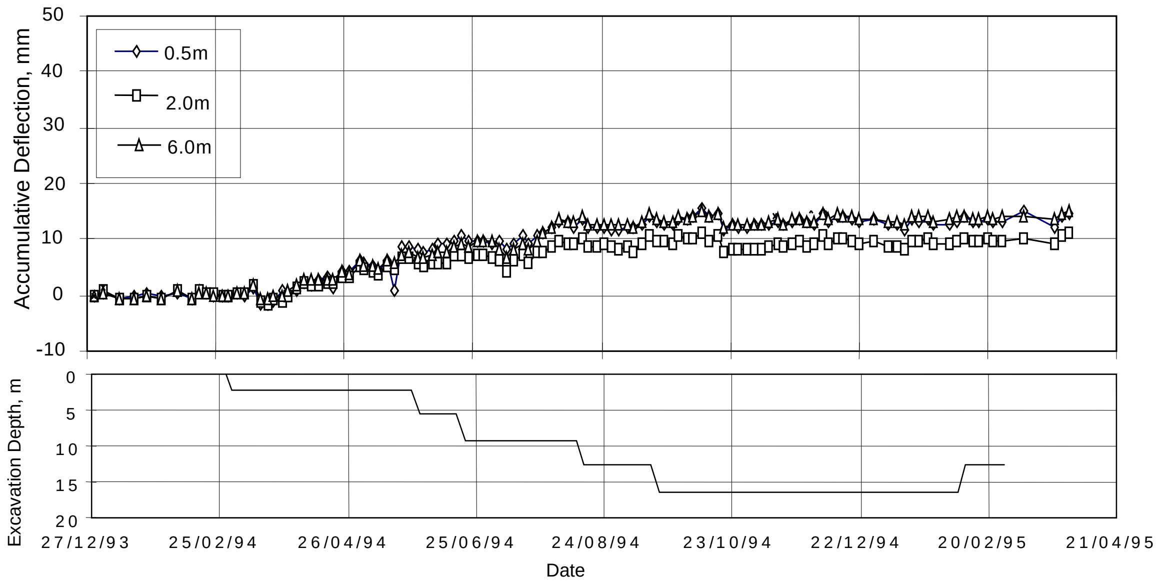


Figure 4 Change of Lateral Movement Recorded by I-9

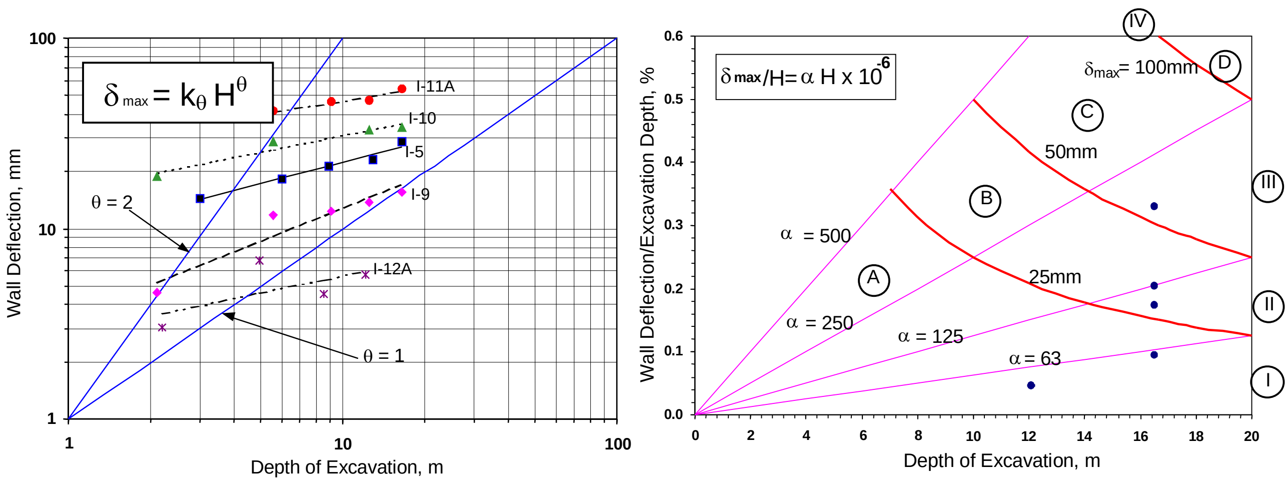


Figure 5 Plot of Wall Deflection versus Excavation Depth

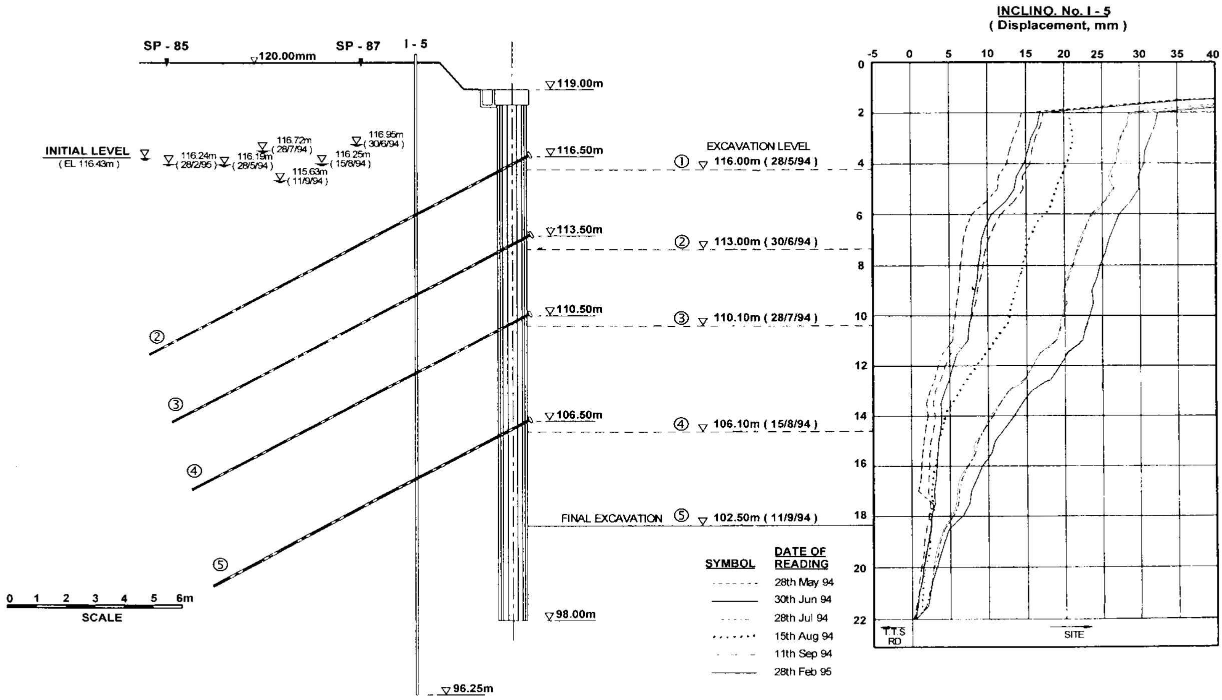


Figure 6 Typical Excavation Profile at CBP 3 (I-5)

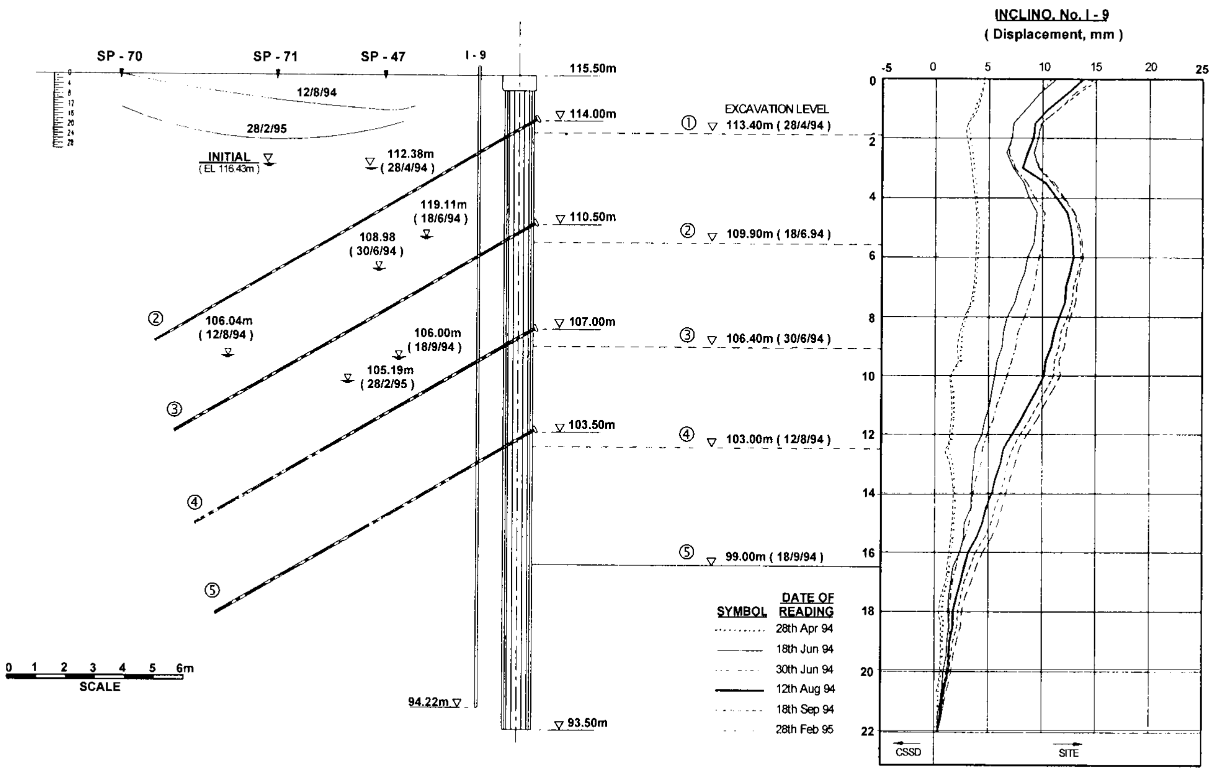


Figure 7 Typical Excavation Profile at GRW 2 (I-9)

Figure 8 shows the predicted (from FREW analysis) and measured max. lateral movements of two (2) bored pile walls with respect to each stage of excavation. The measured max deflection values appear to be reasonably close to those determined from the analysis.

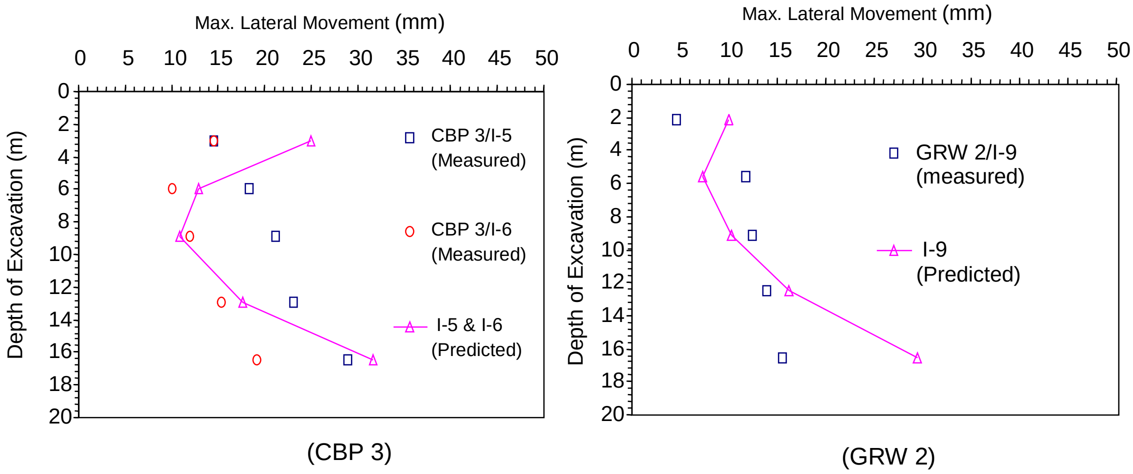


Figure 8 Comparison of Measured and Predicted Max. Wall Movement

4.5 Ground Settlement

Ground settlement behind the retaining walls were monitored by surface settlement points during each stage of excavation. Noticeable ground settlement (max. 26mm) was found within a distance of 2 x "H" (H is the excavation depth) from the excavation boundary and the magnitudes of maximum settlement were found to be about 39 to 131% (i.e. Ave. 87$\pm$40%) of the measured lateral wall movements for the present case.

4.6 Building Movements

The monitoring results of building settlement points installed on the 6-storey Ward B Block and the single storey CSSD building showed maximum settlement value of 9 and 10mm, respectively during the excavation and substructure construction period. This magnitude of building settlement is about 52 to 58% of the maximum lateral movement recorded by the adjacent Inclinometer No. I-9. No significant tilt was recorded by the tiltplates installed on Ward B Block during the excavation period.

4.7 Groundwater Levels

The monitoring results (Figures 9 & 10) of water standpipes indicate that the groundwater levels declined steadily during excavation and stabilized after earthwork activity is completed. Obvious drop in groundwater level was observed by Water Standpipe Nos. WSP-10 & WSP-11 installed at GRW 2 where the largest ground movements were observed. This observation shows that the approach of analysis adopted in the retaining system design is representative and appropriate.

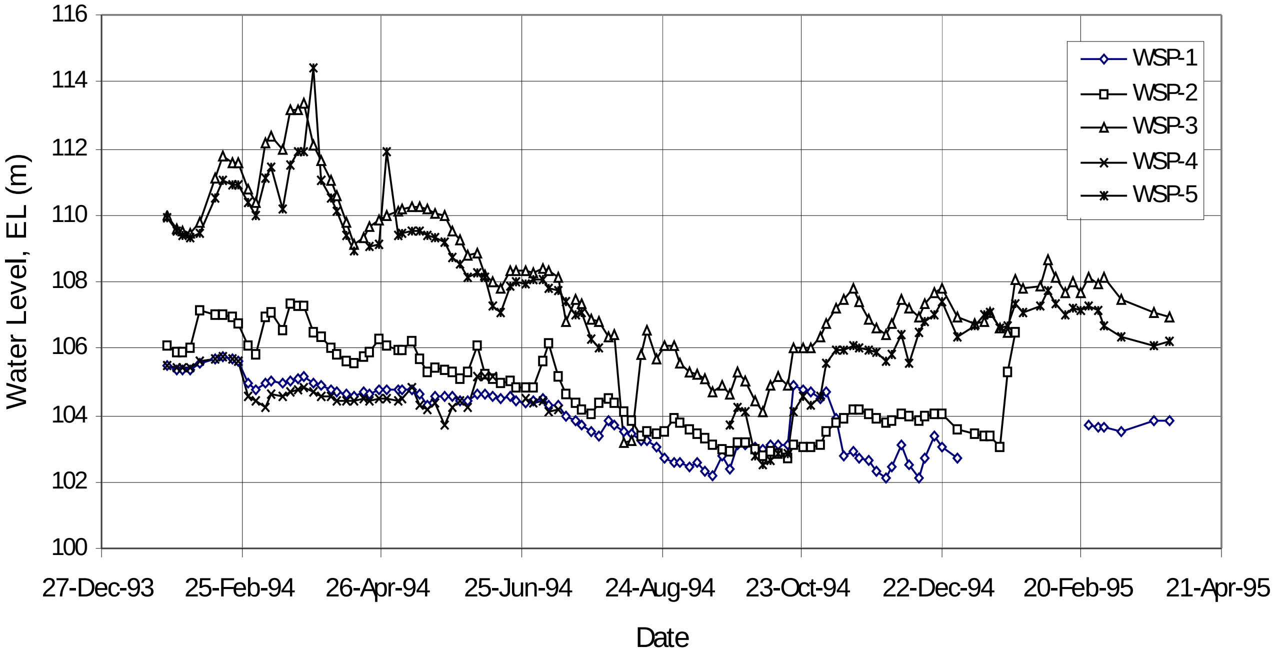


Figure 9 Groundwater Level Observation (Tunnel/CBP 2)

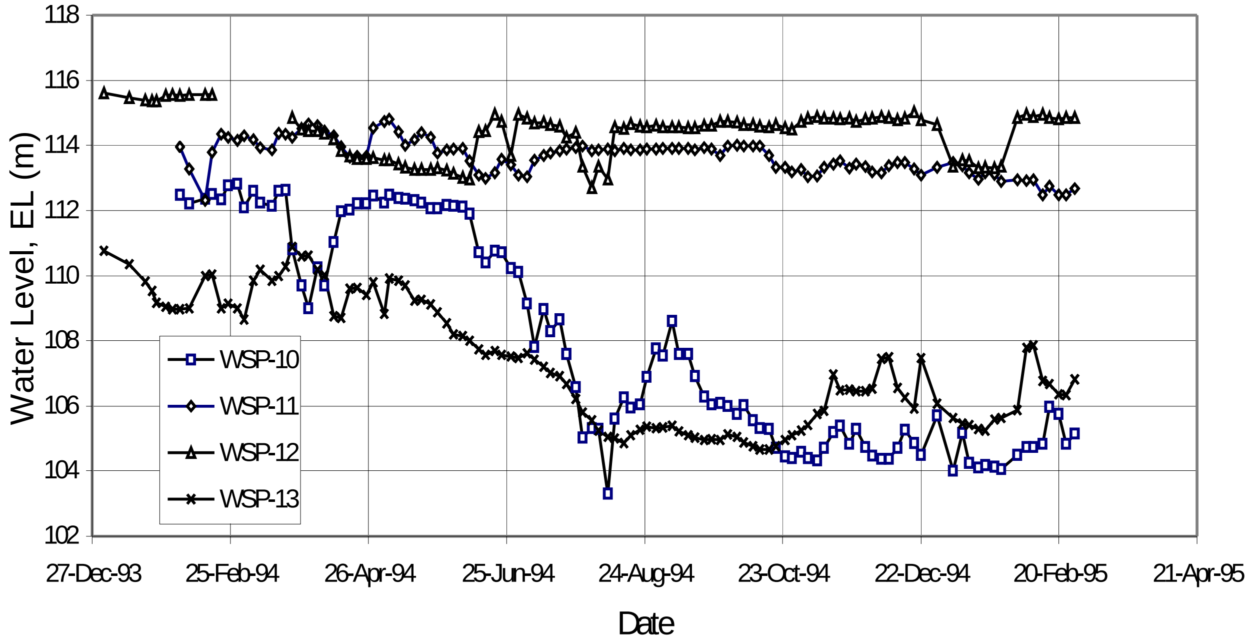


Figure 10 Groundwater Level Observation (GRW 2/3)

4.8 Tunnel Movements

Figures 11 & 12 show the trend of vertical movement readings of prisms (4 nos./section at 3 to 6m intervals) monitored by the TM3000V system in North and South Bound Tunnels, respectively. It can be clearly seen from these figures that downward movement in the fill zone and upward movement in the cut zone were recorded by the TM3000V for the two (2) existing tunnels during the construction of the proposed Irrawaddy Road with a max. movement value of 4.8mm and 7.3mm recorded at crown of the North and South Bound Tunnels, respectively. The profiles of tunnel movement measured by TM3000V are found consistent with those determined from Manual Survey (Figures 11 & 12). In general, the measured movement values of tunnels are within the values predicated from the analysis. The results of tunnel monitoring had provided the existing MRT structures with proper safety assurance during construction and the construction works with a smooth operation and timely completion.

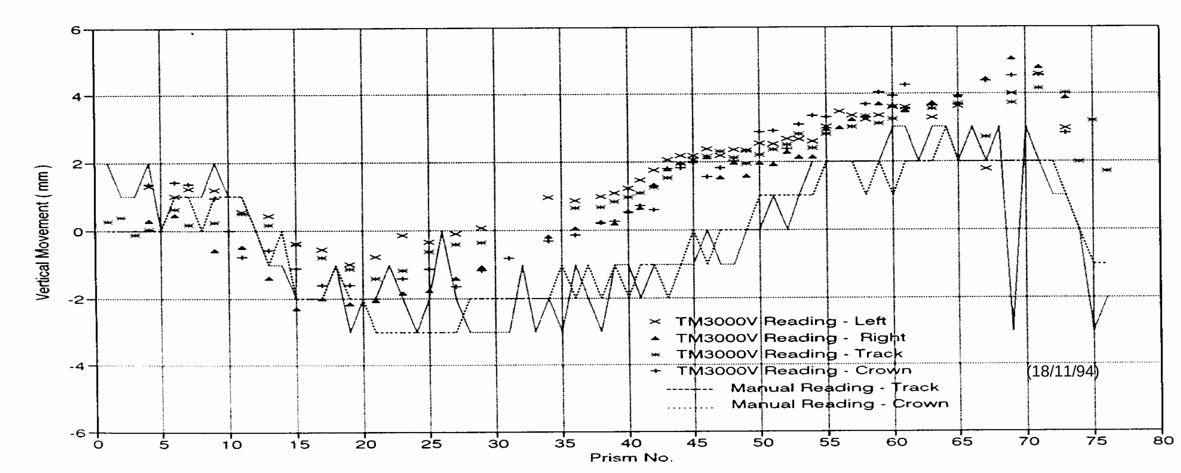


Figure 11 Vertical Movement Readings Recorded by TM3000V and Manual Survey at South Bound Tunnel

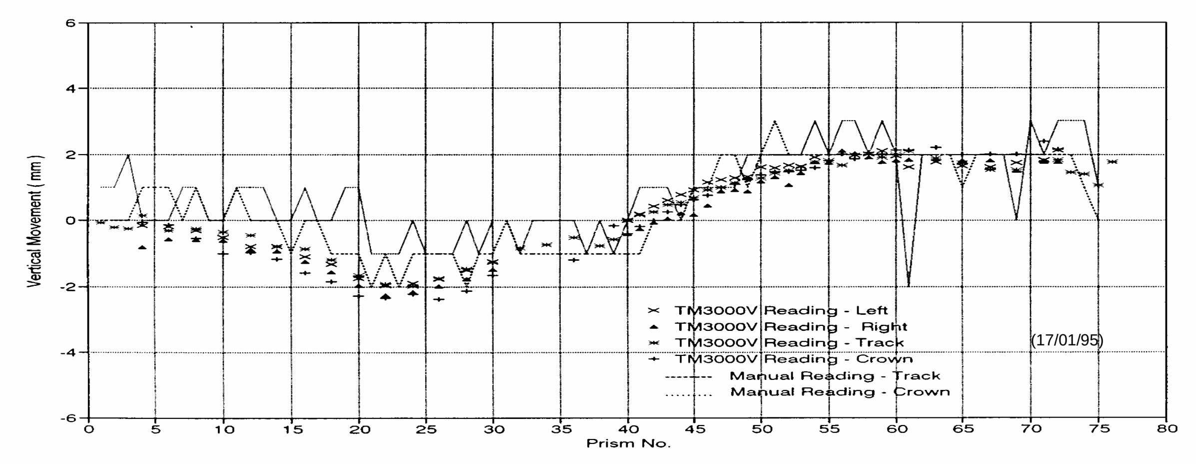


Figure 12 Vertical Movement Readings Recorded by TM3000V and Manual Survey at North Bound Tunnel

5. CONCLUSIONS

Proper planning of instrumentation program and qualified interpretation of monitoring results by competent geotechnical engineers are essential in ensuring the effectiveness of the monitoring system, the accuracy/validity of the monitoring results and the proper control of construction safety. Besides safety control, the results of monitoring will also provide valuable information for the verification of design assumptions/approach and update of technical know-how. Such measurements will also help the Engineer, on one hand, to take immediate remedial measure for problems, which may be encountered during construction; on the other hand, it can be used to assess the performance of the proposed structure during the service period. Frequently, the monitoring records could be a powerful tool in protecting the owner from possible damage dispute.

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