DESIGN AND IMPLEMENTATION OF AUTOMATIC DEFORMATION MONITORING SYSTEM FOR THE CONSTRUCTION OF RAILWAY TUNNEL: A CASE STUDY IN WEST ISLAND LINE

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ABSTRACT:

Automatic Deformation Monitoring System (ADMS) has proven to be an effective method to determine the deformed objects in space by measuring their spatial coordinates periodically with minimal human intervention. To ensure the information acquired by the ADMS is true and accurate in producing a reliable report, detailed planning with an overview of the project requirement is necessary in order to come up with an optimal design of the system meeting the need of all concerned parties. The site constraint and the interest of stakeholders should be carefully reviewed and considered.

The West Island Line (WIL) in Hong Kong is a railway project undertaken by MTR Corporation to extend the existing Island Line beneath the busy and densely populated areas in the western part of Hong Kong Island. The ADMS is installed to monitor the tunnels and the building structures during construction activities at different stages of the WIL.

In this paper, the application of ADMS in the operating railway overrun tunnel will be discussed. The discussion will elaborate on the design of the survey reference network, defining an appropriate alarm system, incident reporting and analysis, and challenges of the constraints on site.

1. INTRODUCTION

1.1 Project Background

The West Island Line (WIL) is an extension of the existing MTR Island Line from Sheung Wan to Kennedy Town to serve the community in the area. It provides an approximately 3 kilometres long electrified double-track railway system with three railway stations at Sai Yung Pun, Hong Kong University and Kennedy Town (Figure 1).

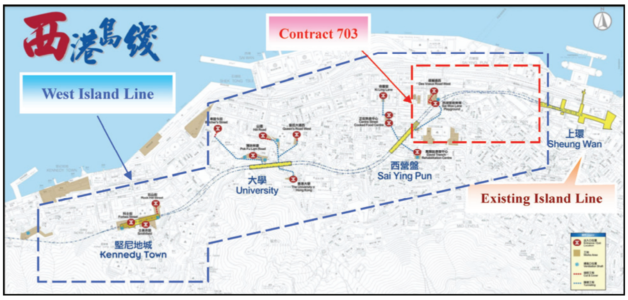

Figure 1. Layout plan of the West Island Line (WIL).

Contract 703 is one of the main civil works contracts in West Island Line including the construction of an 0.3km long underground bored tunnel (westbound tunnel) connecting to the overrun tunnel of the existing MTR Sheung Wan Station and an approximately 0.5km long underground bored tunnel (eastbound tunnel) connecting to the existing MTR Sheung Wan Station (Figure 2).

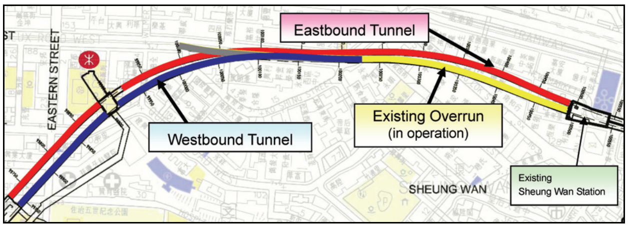

Figure 2. WIL Contract 703 Tunnel Construction and Interface with Existing Tunnel Structures.

1.2 Railway Protection

Railway Protection Plans have been gazetted under the Building Ordinance (Chapter 123) in defining Railway Protection Area which in general falls within the 30m zone beyond the railway structures, fence and wall. The objective of Railway Protection is to safeguard the operating railway structures and facilities from the effects of construction works carried out within the Railway Protection Area.

In case one or more of the construction activities shown in Figure 3 is carried out within the Railway Protection Area, it is required to establish a monitoring schedule to capture the stress/strain, deformation and movement induced to the railway facilities so as to ensure that the safety and stability of the operating railway will not be jeopardized by the adjacent construction activities.

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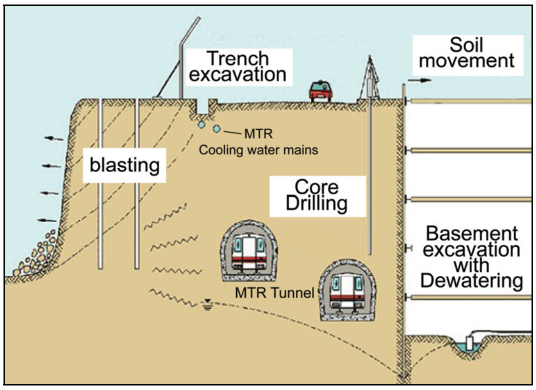

Figure 3. Examples of construction works potentially causing damage or displacement to MTR tunnel.

1.3 Automatic Deformation Monitoring System (ADMS)

ADMS had been widely deployed in Hong Kong over the years to monitor the movement of different types of structures including buildings, flyover carriageways and railway tracks. The monitoring system is capable of measuring reference points and monitoring points continuously and automatically to determine real time deformation with accurate results.

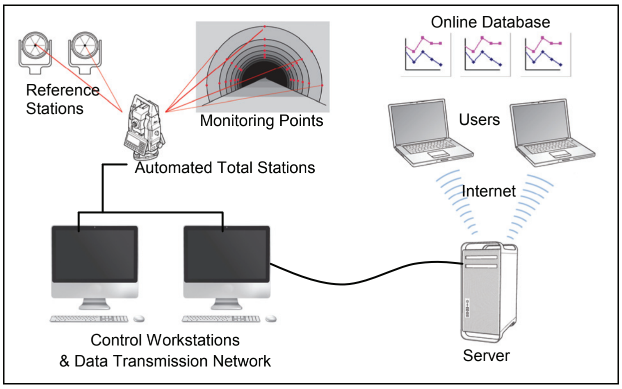

Figure 4. Components of ADMS.

Figure 4 shows the schematic layout of the ADMS system which consists of the following major components:

1) Automated Total Stations: A motorised Total Station to perform target recognition, angles and distance measurement and recording. The instrument is linked to communicate with the Control Workstations.
2) Reference Stations: Target prisms installed in stable area. These are the known points for position fixing measured by Automated Total Station.
3) Monitoring Points: Array of prisms installed on structures required to be monitored.
4) Control Workstations: Computer to communicate and control the operation of the Automated Total Station; to receive and process the measurement data and to produce the report in numerical and graphical formats with a third party software.
5) Data Transmission Network: Cables and the associated equipment to allow data communications between Control Workstations and Server via telephone network and internet connections.
6) Online Database: Data collected by the Automated Total Station and processed by Control Workstation is archived in the Database and they are accessible by authorized users via a website on the internet. The plot of trend of movement of the monitoring points in graphs is made readily available to the interested parties.
7) Automatic Warning System: Should ADMS detect the movement of the monitoring points beyond the predefined level, an email and message generated automatically by the system would be sent to the monitoring team. The message contains customized information of the monitoring point in detail, including number, type, description, location, amount exceeding the predefined level and so on. The monitoring team would respond by taking appropriate action.

ADMS is well developed in terms of the integration of survey science and information technology and will provide highly reliable information under the laboratory condition. However, ADMS may not function equally well in the site conditions where the constraints of work sequence and environment can impact accuracy. Special attention in planning the ADMS is essential to overcome the constraints as not to mislead the monitoring team by the faulty information.

2. CASE STUDY IN WEST ISLAND LINE (WIL)

2.1 ADMS in West Island Line

About 300m of Eastbound Tunnel driven by Tunnel Boring Machine (TBM) heading to Sheung Wan Station is constructed just 8m north of and parallel to the operating Westbound Overrun Tunnel of MTR (Fig. 5). ADMS is installed in the Westbound Overrun Tunnel to monitor the potential structural movement induced by the TBM, thereby protecting the railway.

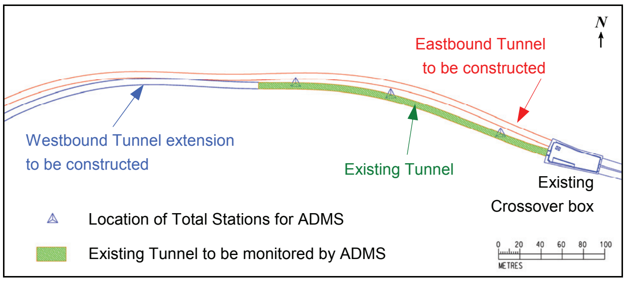

Figure 5. Layout Plan of ADMS in WIL Contract 703.

2.2 Network Design and Analysis

The 300m operating Overrun Tunnel is installed with 30 arrays of monitoring points 10m apart which requires three setups of Automated Total Stations to cover the monitoring zone itself (Figure 6). The accessibility and stability of the locations of the Automated Total Stations and Reference Prisms affecting the precision of the survey are some of the main considerations in designing the network of ADMS.

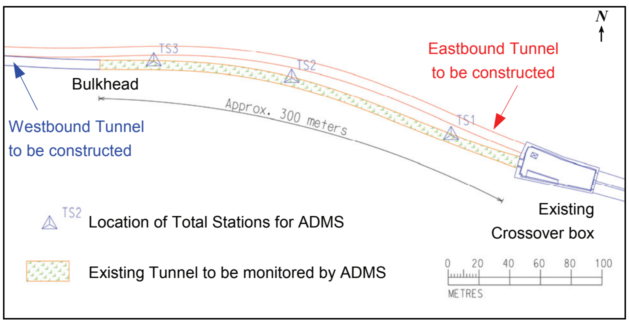

Figure 6. Proposed layout of ADMS in existing railway tunnel.

Leica TM30 with angle measurement accuracy of 0.5" and distance measurement accuracy of 1mm+1ppm is chosen to be the Automated Total Station in this ADMS project. Error analysis for the ADMS is then carried out based on the instrument accuracy on two networks geometry Option 1 and Option 2 for evaluation.

Design Option 1: Survey Network with 360° Prisms System. The design option is to establish a survey network in the Overrun Tunnel. Automated Total Stations are linked up by the 360° prisms within the 300m unstable monitoring zone when the TBM drive is in close range. Reference Stations are installed at the stable Crossover Box of Sheung Wan Station and they are the fixed points of the system. The 360° prisms improve the measuring accuracy by allowing observations to be taken simultaneously from the two Automated Total Stations ahead and behind. (Figure 7)

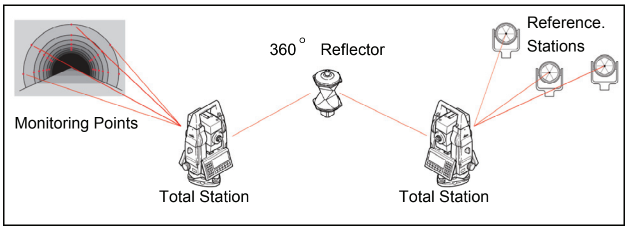

Figure 7. Survey Network for ADMS.

Analysis: Analysis was conducted using Least Squares Survey Network Adjustment Technique based on the configuration of the survey network. Only the points at the Crossover Box at Sheung Wan Station are held fixed, the points at the Bulkhead at the other end 300m away are hanging(Figure 8).

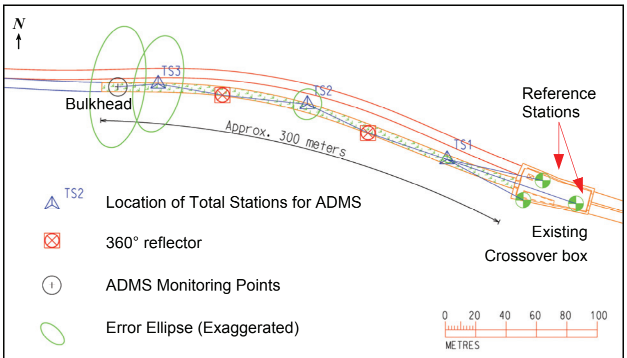

Figure 8. Analysis for Design Option 1 with error ellipse.

The error ellipses of Monitoring Points adjacent to the bulkhead were computed to be 10mm which exceeded the 5mm required accuracy for the ADMS. The commonly seen long and slender configuration of the tunnel network accounted for the error which propagated in transverse direction despite the use of precise instruments and accessories (TM30 and 360° prism) meant to strengthen the network. This is the typical constraint in carrying out a survey in tunnel.

Design Option 2: Localized Monitoring System
This design option is to divide the construction of Eastbound Tunnel (TBM) into three Phases I, II and III in accordance with the progress of construction with the following assumption:

1) The unstable monitoring zone in the Westbound Overrun Tunnel is 50m from the excavation face of Eastbound Tunnel (TBM) travelling east;

2) The stable area is 10m away from the unstable monitoring zone in the Westbound Overrun Tunnel. Reference Prisms located in the stable area could be held fixed.

3) The Crossover Box with foundations at Sheung Wan Station is stable throughout the construction.

As the tunnel is constructed progressively by the TBM heading east, the unstable monitoring zone shifted eastward accordingly. Three separate local ADMS are established in the Westbound Overrun Tunnel to correspond to Phase I, II and III of Eastbound Tunnel (TBM) construction

Phase I in Design Option 2: In Phase I of construction of Eastbound Tunnel (TBM), the area and location of monitoring concern in the Westbound Overrun Tunnel is listed in Table 1 and illustrated in Figure 9:

Area	Location
Face of Excavation by TBM :	CH 100200 – CH 100270 (70m)
Monitoring Zone:	From tunnel bulkhead CH 100200 to CH 100320 (120 m)
Stable Area:	CH 100330 and east

Table 1. Monitoring Area in Phase I.

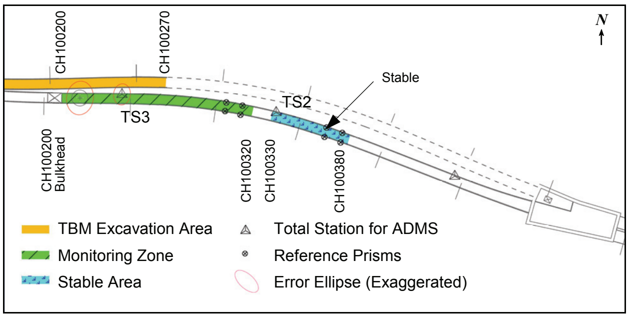

Figure 9. Total Station TS2 for ADMS in Phase I.

In conducting deformation measurement on the Monitoring Points located at the monitoring zone, the Automated Total Station TS3 is considered a floating point and the Automated Total Station TS2 and Reference Prisms in the stable area are held fixed points.

Phase II in Design Option 2: In Phase II of construction of Eastbound Tunnel (TBM), the area and location of monitoring concern in the Westbound Overrun Tunnel is shifted accordingly. They are listed in Table 2 and illustrated in Figure 10.

Area	Location
Face of Excavation by TBM :	CH 100270 – CH 100390 (120m)
Monitoring Zone:	CH 100220 – CH 100440 (220m)
Stable Area:	CH 100200 at Tunnel Bulkhead and CH 100500 at Crossover Box

Table 2. Monitoring Area in Phase II

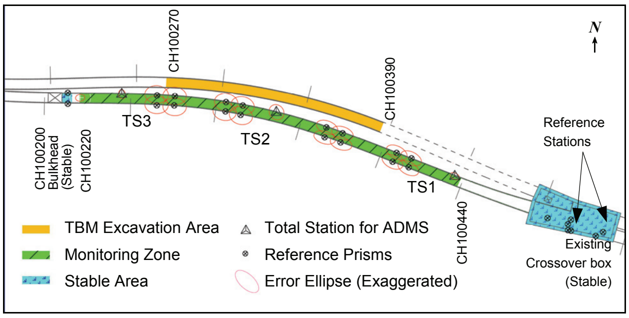

Figure 10. Total Station TS1, TS2 & TS3 for ADMS in Phase II.

The survey network in Phase II would adopt Reference Prisms at bulkhead and crossover box as fixed points. The Reference Prisms are linked to Automated Total Station TS1, TS2 and TS3, forming a closed end survey control network in determining the deformation.

Phase III in Design Option 2: In Phase III of construction of Eastbound Tunnel (TBM), the area and location of monitoring concern in Westbound Overrun Tunnel is shifted further east. (Table 3 and Figure 11)

Area	Location
Face of Excavation by TBM :	CH 100390 – CH 100500 (110m)
Monitoring Zone:	CH 100340 – CH 100500 (160m)
Stable Area:	CH 100260-100330 and Crossover Box at CH 100500

Table 3. Monitoring Area in Phase III.

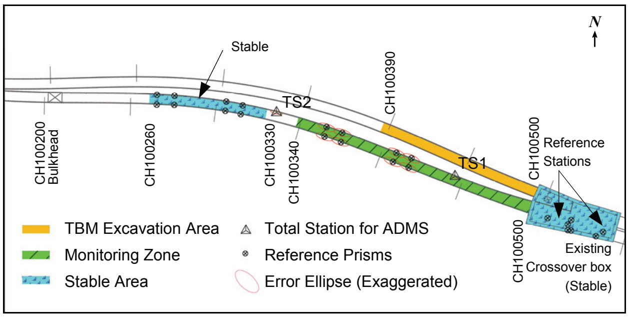

Figure 11. Automatic Total Station TS1 & TS2 in Phase III.

The survey network in Phase III would adopt Reference Prisms at CH 100260-CH 100330 and those in Crossover Box as fixed points. The Reference Prisms are linked to Automatic Total Station TS1 and TS2 to establish a closed end survey control traverse in determining the deformation.

Comparison of Analysis Results: The magnitude of semi-major axis of error ellipse for the Monitoring Points at 95% confidence level located in the respective monitoring zones of Westbound Overrun Tunnel in relationship to Phase I, II and III of Eastbound Tunnel (TBM) derived from Design Option 1 and 2 are summarized for comparison (Table 4).

The estimated error ellipse of monitoring points in Design Option 1 is as large as 10mm at the bulkhead region CH 100220-CH 100270 while those by Design Option 2 is approximately 3mm in general. The Localized Monitoring System of Design Option 2 produces more accurate measurement than Survey Network with 360^{o} Prism System of Design Option 1, meeting the 5mm accuracy requirement of the survey.

Monitoring Zone	Design Option 1	Design Option 2		
		Phase I	Phase II	Phase III
CH 100200 - CH 100270	10mm	3mm	3mm	Not Applicable
CH 100270- CH 100390	5mm	3mm	2mm	2mm
CH 100390 - CH 100500	3mm	Not Applicable	3mm	3mm

Table 4. Semi-Major Axis of Error Ellipse.

Manual Checking and Backup System: Localized Monitoring System is adopted and the baseline reading of the Monitoring Points is established well ahead of the initial drive of Eastbound Tunnel (TBM). Manual survey is normally required to verify the monitoring data on monthly basis to counter-check against the data produced by ADMS. Survey errors and disturbed Monitoring Points and Reference Prisms are usually spotted by examining the data of ADMS and manual survey. The manual checking is performed by running an independent traverse to observe all the Monitoring Points and Reference Prisms by the conventional survey technique.

In addition, strain gauge monitoring and manual precise levelling on rail level are also conducted to supplement ADMS. They become the secondary measures in backing up the ADMS if it fails to collect the information timely in the poor environment of the site. A good example is the line of sight to the points is blocked by a stalled train.

2.3 Response Levels and Response Actions

Alert, Action and Alarm movement levels are the values reflecting different levels of serviceability limit movements and response actions to be carried out during construction.

A set of Response Levels with 6mm / 8mm / 10mm for Alert, Action and Alarm Level is developed for the Monitoring Points based on the logic that

“Alert Level” is set at 0.5 times of the serviceability limit movement for the monitored elements. When reaching “Alert Level”, Contractor shall inform Engineer and review the movement, assess the effects on adjacent structures and predict further movements. Contractor shall submit a “Detailed Plan of Action” to the Engineer, stating the actions to be implemented for reaching “Alert Level” and “Action Level”, before “Action Level” is reached.

“Action Level” is set at 0.8 times of the serviceability limit movement for the monitored elements. When reaching “Action Level”, Contractor shall immediately investigate the remedial measures in the action plan proposed at the “Alert Level” stage, and limit further movement. Work can only proceed if the remedial measures have been implemented and approved by the Engineer to be effective.

“Alarm Level” is the entire serviceability limit movement for the monitored elements. When reaching “Alarm Level”, Contractor shall suspend all construction activities and submit a review report on construction methods, movement history and remedial measures to be taken related to construction sequence for the Engineer’s approval.

3. INSTALLATION

3.1 Monitoring Points and Structure Gauge

Structure Gauge is the profile related to the defined track alignments into which no part of any structure or fixed equipment may penetrate. ADMS installations at the Westbound Overrun Tunnel shall not obstruct the structural gauge and it is important to confirm adequate clearance between the installations and the structure gauge.

The installations for ADMS including Automated Total Stations, Prisms, Datalogger Box, Strain Gauge etc are drawn to scale (Figure 12) and their positions relative to the Structure Gauge are summarized in tabular form (Figure13) for clearance check.

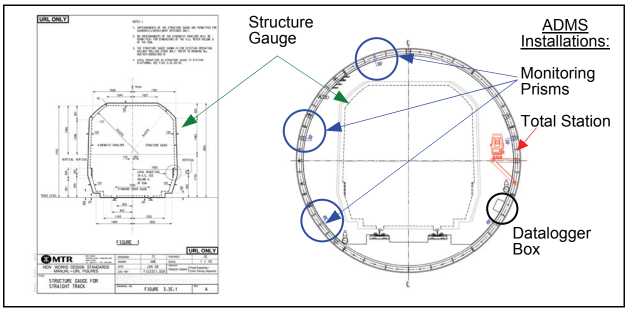

Figure 12. Clearance check against Structure Gauge profile in Graphical Format.

Line	Location (CH)	Object	Hand of Object (SHW station to Overrun)	Proposed X (mm)	Proposed Y (mm)	Infringe to S.G. (mm)	Intrude to Rail grinding zone
ISL Dn	100474	ADMS	L.H.S	817	**4052**	N.A.	N.A.
		ADMS		1966	2279	No	N.A.
		ADMS		1471	189	No	N.A.
		ADMS		83	-62	N.A.	No
		ADMS	R.H.S	83	-62	N.A.	No
		ADMS		-180	**4314**	N.A.	N.A.
	100441	ADMS	L.H.S	605	**4058**	N.A.	N.A.
		ADMS		1753	2285	No	N.A.
		ADMS		1260	247	No	N.A.
		ADMS		83	-62	N.A.	No
		ADMS	R.H.S	83	-62	N.A.	No
		ADMS		32	**4331**	N.A.	N.A.
	100488 to 100493	ADMS	L.H.S	109	**4452**	N.A.	N.A.
		ADMS		-730	-104	N.A.	No
		ADMS	R.H.S	-711	-104	N.A.	No
		ADMS		-671	**4773**	N.A.	N.A.

Figure 13. Clearance check against Structure Gauge profile in Tabular Format

3.2 Overhead Line Safety

The surveyor in installing the ADMS and conducting the routine survey of the manual survey and precise rail levelling is required to pay extra attention to the safety working in the vicinity of overhead line. The surveyor is not allow to carry out any work which may require any part of his body or any tool or material, to be used within 2m from the overhead line equipment, unless the overhead line equipment has been isolated and earthed properly.

4. SYSTEM COMPONENTS

4.1 Software Control

The Software in Control Workstations for the ADMS processes the large volume of measurement data including:

1) Best fit position fixing of the Automated Total Station by angles and distances resection method measured to the Reference Stations.
2) Transformation of coordinates of the Monitoring Points to express their spatial deformation with reference to the tunnel alignment. They are the longitudinal (along tunnel alignment), transverse (perpendicular to tunnel alignment), and vertical displacement.

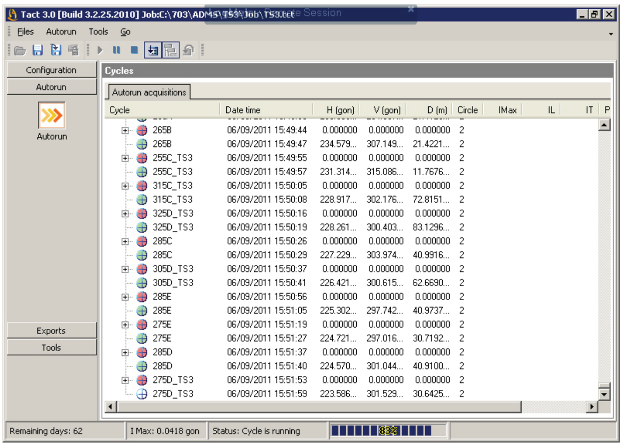

Figure 14. Software interface for control and monitor ADMS data acquisition.

The software is also able to analyse the quality of data captured by the Automated Total Station. In handling the large amount of data, the software could highlight the movement of the Monitoring Point of large variance which requires the surveyor to investigate. The train operations in the tunnel does not allow the site inspection be carried out immediately. However, the monitoring team would further assess the movement of the monitoring point by reviewing the adjacent ADMS monitoring points and strain gauge monitoring data to draw a preliminary conclusion. It is very often that the dusty reflective surface of the prism; dislocation of the prism and so on account for the large variance. Manual survey would be carried out in the next available session to confirm the findings.

4.2 Online Database

The survey raw data, processed result and the deformation record are archived in an orderly manner to build a database. Information such as baseline reading; date; time and directions of deformation extracted from the database are customized in a number of formats to suit the view of the monitoring team in retrieving the information off-site via the internet connection.

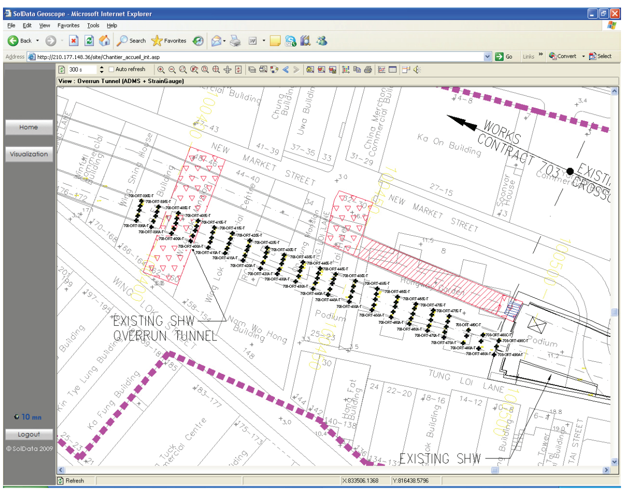

Figure 15. User interface of ADMS on-line database.

5. BASELINE AND BACKGROUND READING

5.1 Baseline Reading and Manual Checking

Upon the completion of the installation of the ADMS, the spatial coordinates of the Monitoring Points are repeatedly learnt by the Automated Total Stations. It would take three days to complete the learning process in measuring every point fifty times. The average of the fifty measurements is adopted as the Baseline Reading to compare against the future measurement in the monitoring exercise. The Baseline Reading is also counter checked by an independent manual survey to confirm it is free from error.

Figure 16. Independent checking for ADMS Initial Value.

5.2 Background Reading

Despite the establishment of the Baseline Reading, the ADMS is still required to register if there is any background reading over one month period as an initial phase to examine existing tunnel condition under normal situation prior to commencement of construction works. Background monitoring also caters for the natural variations and repeatability of the monitoring to be established. The period of background monitoring may need to be extended if there is any change in monitoring plan, for example, prism relocation and installation of new prism.

6. IMPLEMENTATION

6.1 Interpretation of Survey Results and Reporting

ADMS performs continuous monitoring 24 hours a day, 7 days a week to cope with the progress of the Eastbound Tunnel (TBM). The controller is the person of the monitoring team dedicated to review, analyze, and filter the noise of the monitoring data and to ensure the ADMS is functioning properly. For example, monitoring points with abnormal rapid change as compared to previous readings shall be examined to determine whether it is an observation error or an actual movement of the points.

For example the ADMS reading of lateral movement as shown in Figure 17 below, one might need to verify the 'abnormal' reading by reviewing adjacent monitoring points or compare sufficient sets of instrument readings to ensure that observation error are discovered and quantified.

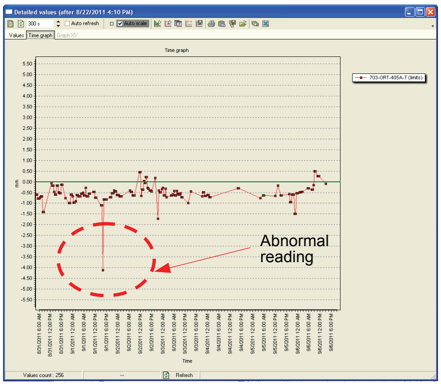

Figure 17. ADMS data with 'abnormal' observation.

Another example; the ADMS reading is shown in Figure 18 below with an occurrence of rapid change in movement record and no trend of movement was observed. One might examine the monitoring data of Strain Gauge and determine whether the monitoring point was being disturbed or there is actual tunnel movement.

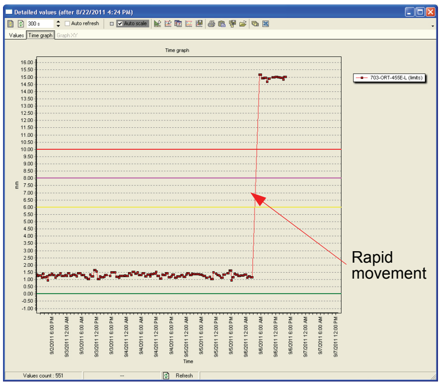

Figure 18. ADMS data with rapid change in lateral movement.

The controller would consider the likelihood of Monitoring Points getting disturbed unknowingly by workers in the tunnel. (Figure 19). He would examine closely the trend of movement of the points in conjunction with the readings of the Strain Gauge and rail level survey in the region in assisting him to draw a conclusion.

If it is a false alarm, the controller would send a follow up message within 30 minutes to report the cause of observation error and rectify the previous alarm message sent out by the Automatic Warning System.

Figure 19. ADMS prisms may be disturbed by others in tunnel.

6.2 Manual Checking

Manual checking would be carried out on a monthly basis as described in Section 5.1. The survey would also include an inspection of the prisms to verify that they are not disturbed or damaged; cleaning of dust on reflective prisms may sometimes be required. Precise levelling on rail level would also be carried out as a supplement to the ADMS system.

7. CONCLUSION

ADMS has become a standard requirement for some major engineering projects; especially for the MTR in protecting the railway in operation from being damaged by works in the Railway Protection Zone.

There were times when the construction site constraint was not visualized, and the significance of error propagation was not in control. Poor survey network was setup in conducting the monitoring survey and as a result questionable, misleading deformation information were provided to the users, defeating the purpose and intent of the ADMS. The implementation of the ADMS on the WIL project has overcome these shortcomings. The surveyor is fully aware of the site constraints and work sequence. He is able to devise an optimal workable survey network by testing and pre-analysis of the different models to meet the 5mm required accuracy.

With the ever-changing survey technology and speed of computers, the ADMS is becoming more user-friendly. However, it does not take away the expert survey knowledge required in setting up a strong and rigid survey network to work in conjunction with ADMS to ensure accurate measurement data is gathered and the reliable monitoring information is produced.

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