Monitoring of Existing Roadway and Metro Tunnels During Urban Development Project Construction

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ABSTRACT

This paper presents instrumentation and monitoring (I&M) program developed and implemented for a large urban development project in the Middle East. An existing metro and a busy roadway tunnel crossing through nearby canal were located within the close vicinity of the construction site. In addition to monitoring the performance and safety of the construction activities, monitoring the safety of the both tunnels are the objectives of the instrumentation program. Following the brief overview of the project with salient features of the construction methodologies, the I&M scheme is presented in this paper. The instrumentation scheme included in-place inclinometers (IPI), vibrating wire piezometers, strain gauge, beam sensors, tilt sensors, vibrations sensors, crack meters, magnetic extensometers, settlement points and vibrating wire load cells. Details of key parameters to be monitored and instrument selection basis for specific purpose has been described. During the implementation and installation of the instruments, many challenges were encountered in active tunnels. These challenges and methods used to overcome these difficulties with practical solutions are presented. Near real time data acquisition, processing techniques are used during the construction. Real time data monitoring enabled early detection of a failure at the site. During the construction, deformations from an in-place inclinometer exceeding action levels were reported timely. The location of the excessive movement was near the road tunnel and the measures were taken prior to any catastrophe.

1. INTRODUCTION

Many signature projects are constantly under development in the large Gulf states cities in the Middle East. The construction of these large structures in the vicinity of existing infrastructure requires extreme care and due diligence. The mixed-use development discussed in the paper was located in one of the modern megacities of the Middle East and was aimed at the expansion of the urban fabric of a busy and relatively old community, and comprised of construction of hotels, residential and commercial towers, marina, storage facilities, loading and unloading bays, parking lots etc. The project, located at the sea shore, involved heavy construction activities including deep excavations of up to 10 m supported by shoring systems. A comprehensive monitoring program was carried out in the project for the safety of the neighbouring structures, mainly of an existing underground metro tunnel and a road tunnel. The nearest edge of the shoring works was at 10 m from the metro tunnel and 15 m

from the road tunnel. The metro tunnel is single tube tunnel with *** diameter and constructed in 2006. The road tunnel was a four lane (20.4 m wide) canal underpass.
Due to proximity of the deep excavation to the existing critical infrastructure, near real time automated online monitoring is included to the project requirements. The project designer, consultant, contractor, instrumentation contractor and tunnel/roadway regulator have worked in the close coordination during the design and implementation of the monitoring program. Near real time online monitoring is commonly used during all major large construction projects in the area.

2. MONITORING DESIGN

The structural stability and risk assessment of both tunnels against the deep excavation as well as the stability analysis of the diaphragm wall was performed by the project's geotechnical consultant considering the results of soil/structure interaction assessment, detailed finite element soil-structure interaction model, piling and excavation design and the local Railway Protection Code of Practice.

Monitoring scheme with instruments proposed to ensure the safety of the existing metro and road tunnels are summarized in **Table 1** below:

Table 1. Monitoring requirements and proposed instruments

Instrument Type	Instrument Location	Monitored Parameter
In-place inclinometer	Embedded within the shoring wall adjacent to the tunnels	Lateral deformation of soil between the excavation and the tunnel
Standpipe piezometer	In boreholes between the development and the tunnels	Groundwater drawdown during construction
Ground settlement point	In arrays placed 20 m apart approximately	Potential surface settlement of the soil due to excavation and dewatering activities
Strain gage	At the tunnel walls	Stress in tunnel linings/supporting walls
Beam sensor/tiltmeter	At the tunnel walls and roof	Differential movement/change in diameter under unbalanced loading & tilting in tunnels
Beam sensor/tiltmeter	Between the rails transverse to the metro tunnel's long axis	Lateral displacement across the adjacent rails
Beam sensor/tiltmeter	Between the rails along the metro tunnel's long axis	Differential settlements along the rails
Triaxial vibration sensor	Within tunnel at closest point to the development	Effect of piling operations on tunnel s
Prism target	At the tunnel walls	Displacements in the tunnels
Tape extensometer	At the road tunnel walls	Convergence in tunnel
Crack meter	On the existing cracks within the tunnels	Change in width of existing cracks
Temperature gage	Adjacent to VW strain gages	Temperature induced changes in the in-tunnel monitoring points
Magnetic extensometer	In boreholes between the development and the tunnels	Sub-surface settlements
Anchor load cells	Within the plot's excavation	Loads on ground anchors

		supporting the shoring system

Location of the instruments in plan and section are shown in **Figures 1 to 3** below:

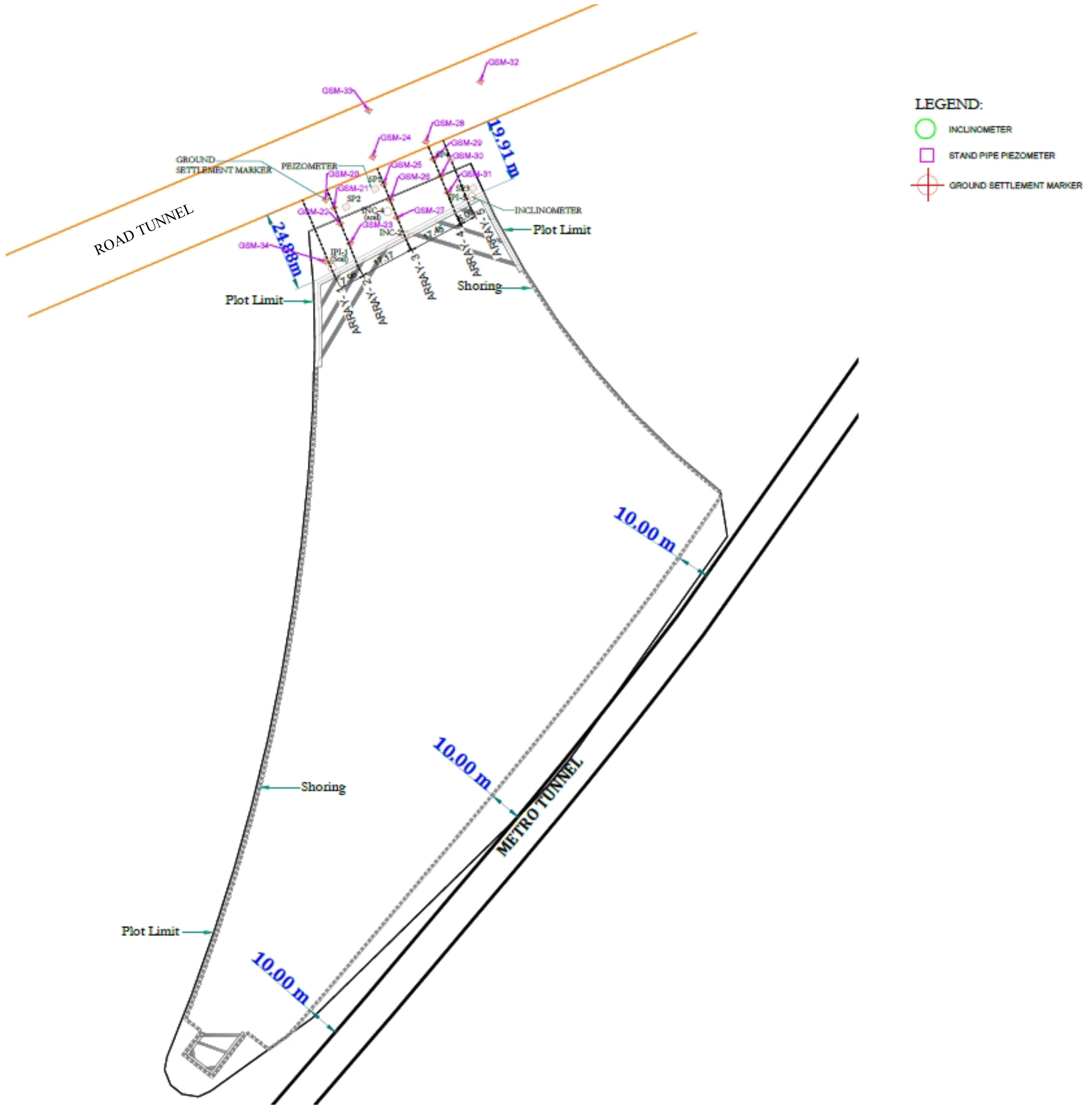
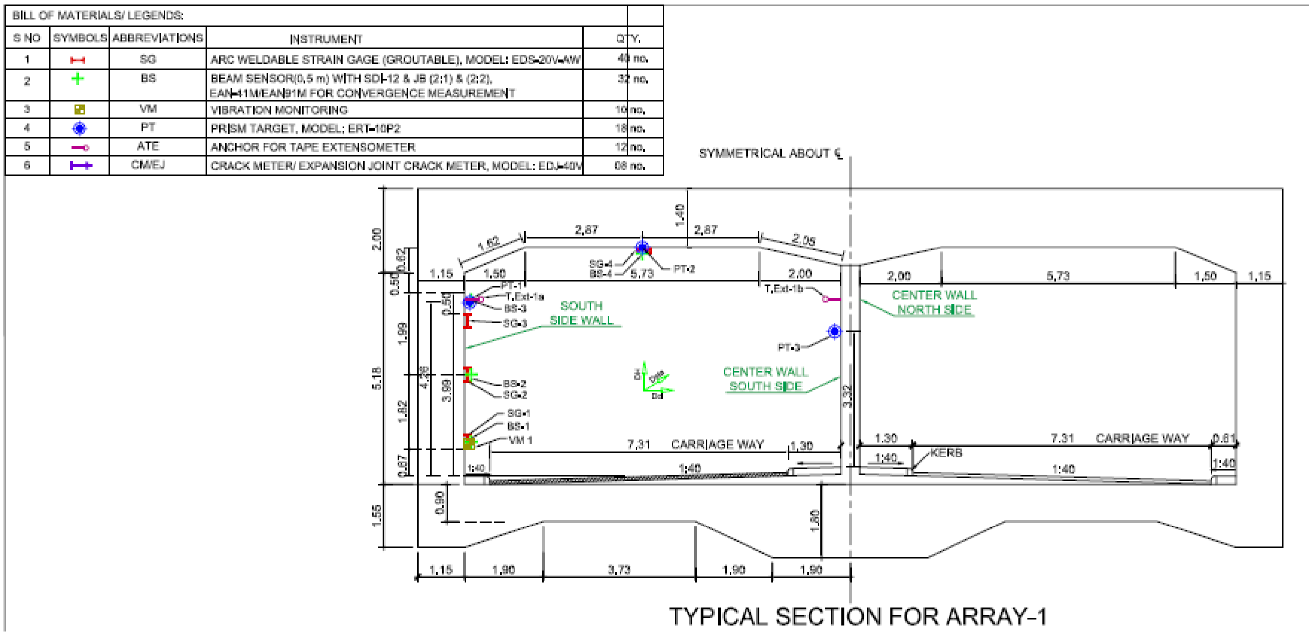


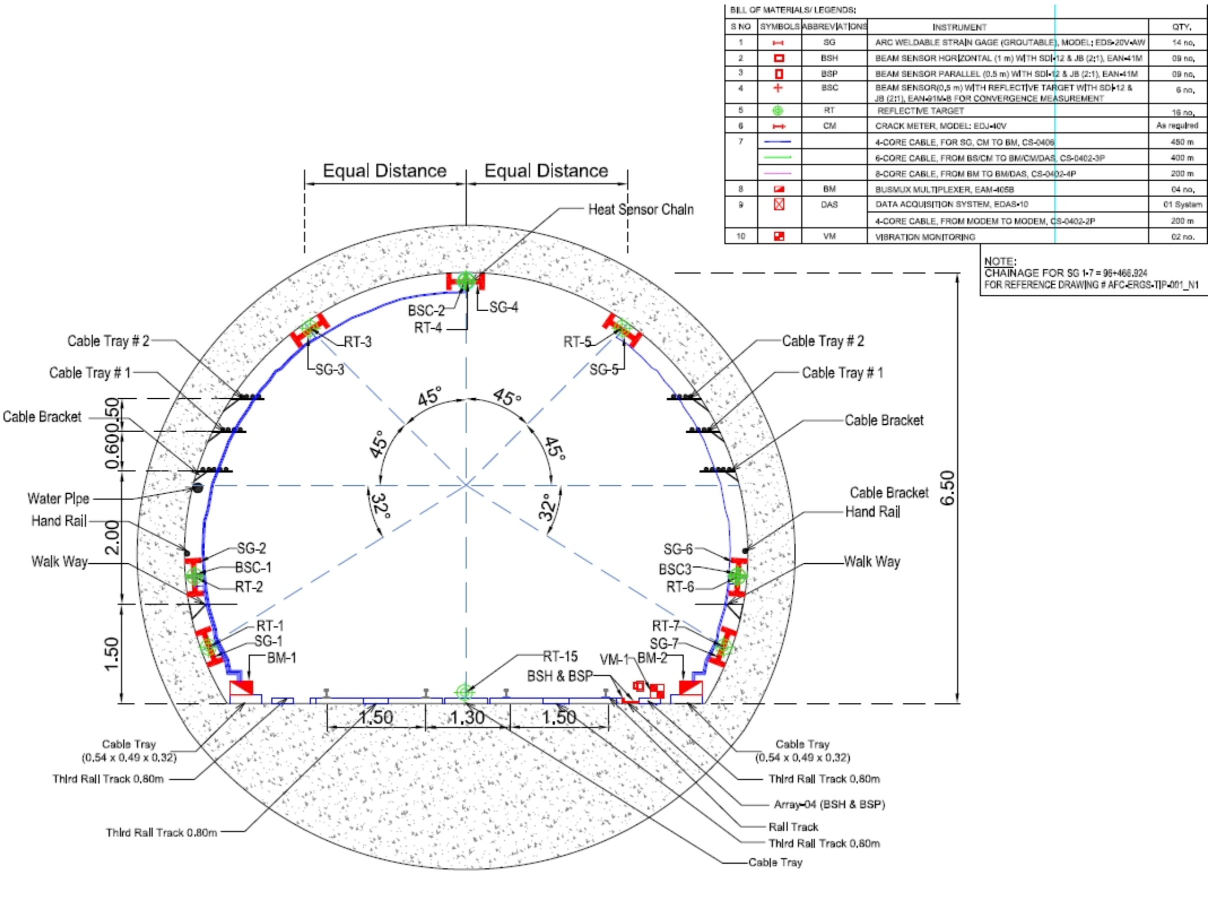
Figure 1. Instrumentation plan for the road tunnel



BILL OF MATERIALS/ LEGENDS:

S NO	SYMBOLS	ABBREVIATIONS	INSTRUMENT	QTY.
1	↔	SG	ARC WELDABLE STRAIN GAGE (GROUTABLE), MODEL: EDS-20V-AW	40 no.
2	+	BS	BEAM SENSOR(0.5 m) WITH SDI-12 & JB (2:1) & (2:2), EAN-41M/EAN91M FOR CONVERGENCE MEASUREMENT	32 no.
3	▨	VM	VIBRATION MONITORING	10 no.
4	●	PT	PRISM TARGET, MODEL; ERT-10P2	18 no.
5	⊸	ATE	ANCHOR FOR TAPE EXTENSOMETER	12 no.
6	↔	CM/EJ	CRACK METER/ EXPANSION JOINT CRACK METER, MODEL: EDJ-40V	08 no.

Figure 2. Instrumentation section of the road tunnel



BILL OF MATERIALS/ LEGENDS:

S NO	SYMBOLS	ABBREVIATIONS	INSTRUMENT	QTY.
1	↔	SG	ARC WELDABLE STRAIN GAGE (GROUTABLE), MODEL: EDS-20V-AW	14 no.
2	□	BSH	BEAM SENSOR HORIZONTAL (1 m) WITH SDI-12 & JB (2:1), EAN-41M	09 no.
3	▯	BSP	BEAM SENSOR PARALLEL (0.5 m) WITH SDI-12 & JB (2:1), EAN-41M	09 no.
4	+	BSC	BEAM SENSOR(0,5 m) WITH REFLECTIVE TARGET WITH SDI-12 & JB (2:1), EAN-91M-B FOR CONVERGENCE MEASUREMENT	6 no.
5	◎	RT	REFLECTIVE TARGET	16 no.
6	↔	CM	CRACK METER, MODEL: EDJ-40V	As required
7	—		4-CORE CABLE, FOR SG, CM TO BM, CS-0406	450 m
	—		6-CORE CABLE, FROM BS/CM TO BM/CM/DAS, CS-0402-3P	400 m
	—		8-CORE CABLE, FROM BM TO BM/DAS, CS-0402-4P	200 m
8	◪	BM	BUSMUX MULTIPLEXER, EAM-405B	04 no.
9	☒	DAS	DATA ACQUISITION SYSTEM, EDAS-10	01 System
			4-CORE CABLE, FROM MODEM TO MODEM, CS-0402-2P	200 m
10	▣	VM	VIBRATION MONITORING	02 no.

NOTE:
CHAINAGE FOR SG 1-7 = 96+466.924
FOR REFERENCE DRAWING # AFC-ERGS-TIP-001_N1

Figure 3. Instrumentation section of the metro tunnel

As shown on **Table 1**, following is the distinct features of some of the key instruments included to the I&M plan:

In-Place Inclinometer (IPI): IPI system consists of a string of inclination sensors. This string of sensors is positioned inside the inclinometer casing to span the movement zone. The digital inclinometer sensor has a measuring range of ± 30 degrees with a resolution of ± 10 arc seconds. The IPI system uses a 24 bit ADC that measures the MEMS sensor output with a resolution of over 1 million counts. The system is equipped with SDI-12 interface so that only a single 3 core bus cable needs to be threaded in a daisy chain fashion connecting each sensor to its next immediate neighbour and finally to the top of borehole and directly to the datalogger (without any multiplexer).

Beam Sensor/Tiltmeter: Beam Sensor consists of a tiltmeter, mounted inside a compact, weatherproof enclosure. The sensor output is 4 V nominal at ± 15°. This output can be transmitted over long distances without any signal degradation. The tiltmeter is attached to a beam with various lengths (1 m, 2 m, and 3 m) and used for monitoring of differential movement and rotation in rail track in the metro tunnel.

Triaxial Vibration Sensor:

The monitoring trigger values and minimum recommended monitoring frequencies for the installed instruments above were also provided under the I&M plan.

3. INSTRUMENTATION & MONITORING IMPLEMENTATION

The scope of the instrumentation contractor as for the monitoring program includes the following tasks:

- Weekly monitoring to establish a firm set of initial readings prior to construction
- Automatic as well as manual monitoring of geotechnical instruments and surveying during deep excavation
- Online data availability of critical parameters with continual live updates
- Daily & weekly reporting with data processing and interpretations
- Post-construction condition monitoring of both tunnels

Select data from the project are presented in the following figures.

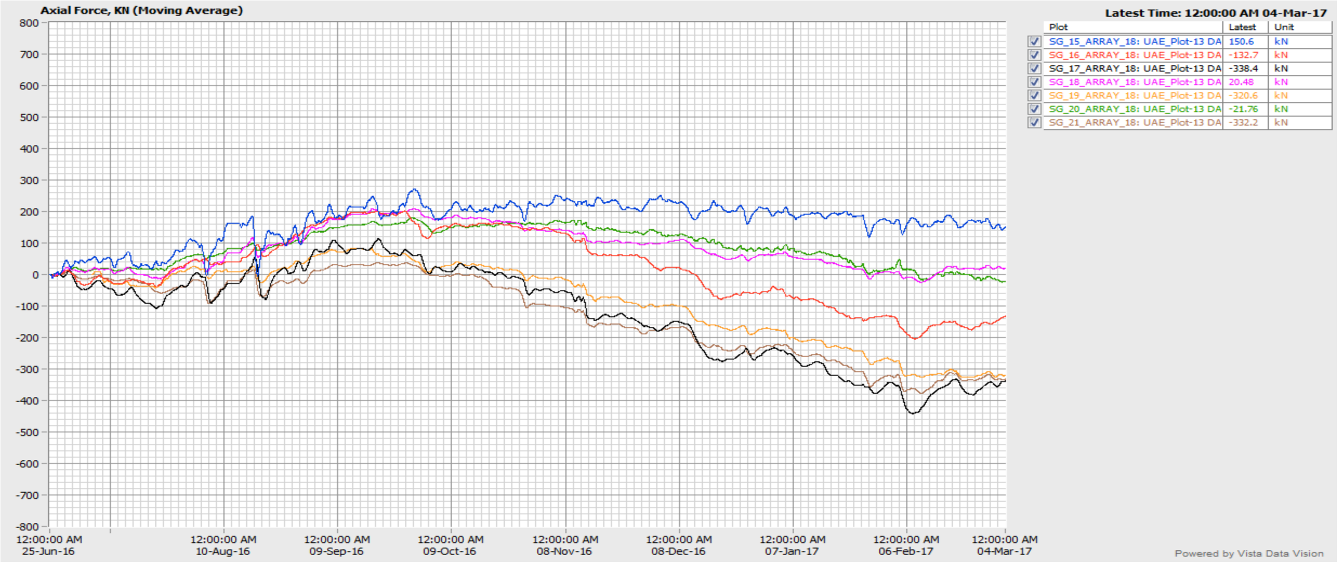


Figure 4 Strain gage measurements between 25 Jun 2016 and 4 Mar 2017 at seven locations inside Metro tunnel

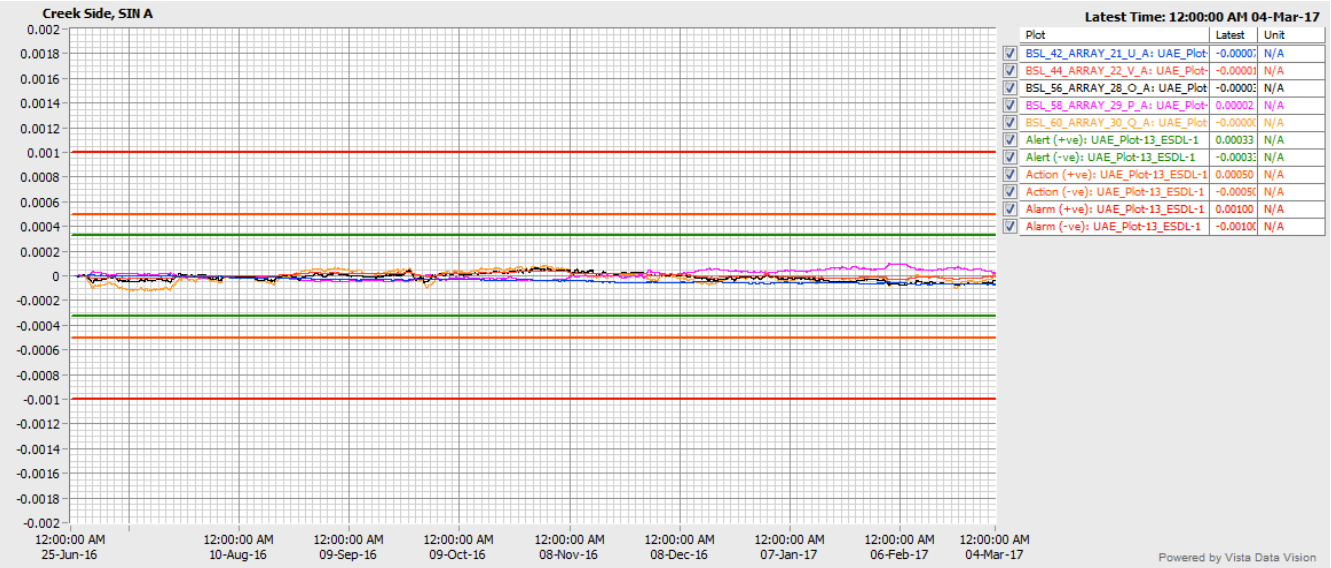
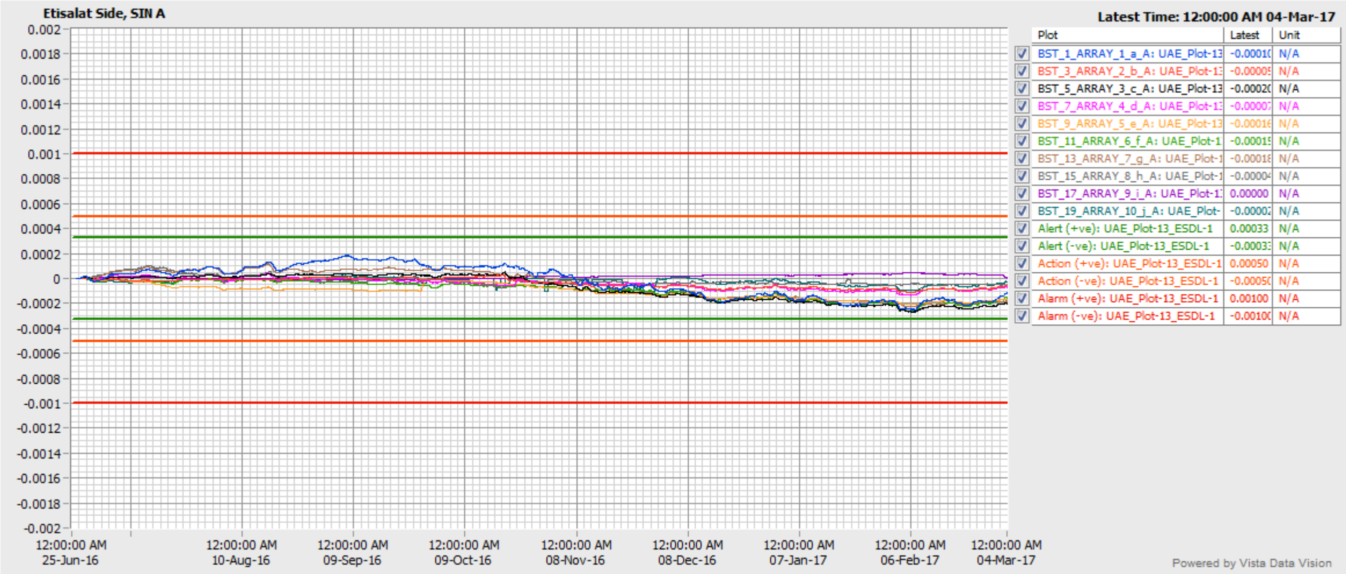


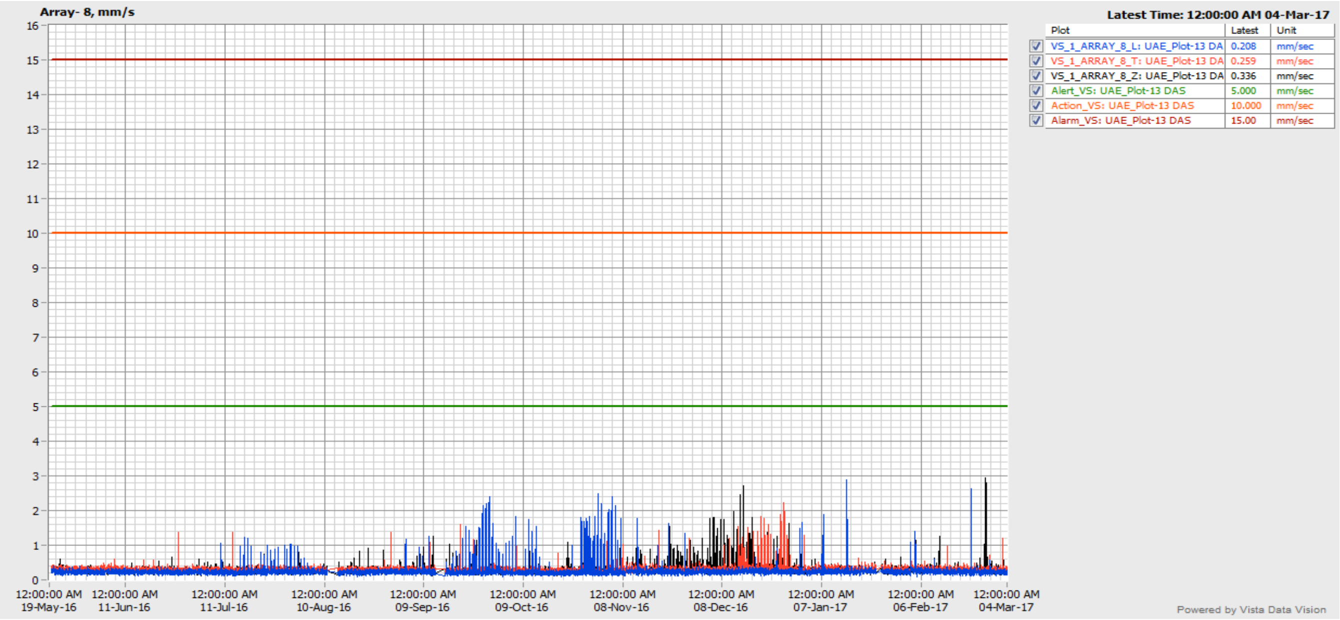
Figure 5 Beam sensor longitudinal deformation with Alert, Action and Alarm Levels in the Metro Tunnel



Latest Time: 12:00:00 AM 04-Mar-17

	Plot	Latest	Unit
☑	BST_1_ARRAY_1_a_A: UAE_Plot-13	-0.0001	N/A
☑	BST_3_ARRAY_2_b_A: UAE_Plot-1	-0.0000	N/A
☑	BST_5_ARRAY_3_c_A: UAE_Plot-13	-0.0002	N/A
☑	BST_7_ARRAY_4_d_A: UAE_Plot-1	-0.0000	N/A
☑	BST_9_ARRAY_5_e_A: UAE_Plot-13	-0.0001	N/A
☑	BST_11_ARRAY_6_f_A: UAE_Plot-1	-0.0001	N/A
☑	BST_13_ARRAY_7_g_A: UAE_Plot-1	-0.0001	N/A
☑	BST_15_ARRAY_8_h_A: UAE_Plot-1	-0.0000	N/A
☑	BST_17_ARRAY_9_i_A: UAE_Plot-1	0.00000	N/A
☑	BST_19_ARRAY_10_j_A: UAE_Plot-	-0.0000	N/A
☑	Alert (+ve): UAE_Plot-13_ESDL-1	0.00033	N/A
☑	Alert (-ve): UAE_Plot-13_ESDL-1	-0.0003	N/A
☑	Action (+ve): UAE_Plot-13_ESDL-1	0.00050	N/A
☑	Action (-ve): UAE_Plot-13_ESDL-1	-0.0005	N/A
☑	Alarm (+ve): UAE_Plot-13_ESDL-1	0.00100	N/A
☑	Alarm (-ve): UAE_Plot-13_ESDL-1	-0.0010	N/A

Figure 6 Beam sensor transverse with Alert, Action and Alarm Levels in the Metro Tunnel



Latest Time: 12:00:00 AM 04-Mar-17

	Plot	Latest	Unit
☑	VS_1_ARRAY_8_L: UAE_Plot-13 DA	0.208	mm/sec
☑	VS_1_ARRAY_8_T: UAE_Plot-13 DA	0.259	mm/sec
☑	VS_1_ARRAY_8_Z: UAE_Plot-13 DA	0.336	mm/sec
☑	Alert_VS: UAE_Plot-13 DAS	5.000	mm/sec
☑	Action_VS: UAE_Plot-13 DAS	10.000	mm/sec
☑	Alarm_VS: UAE_Plot-13 DAS	15.00	mm/sec

Figure 7 Vibration sensors with Alert, Action and Alarm Levels in the Metro Tunnel

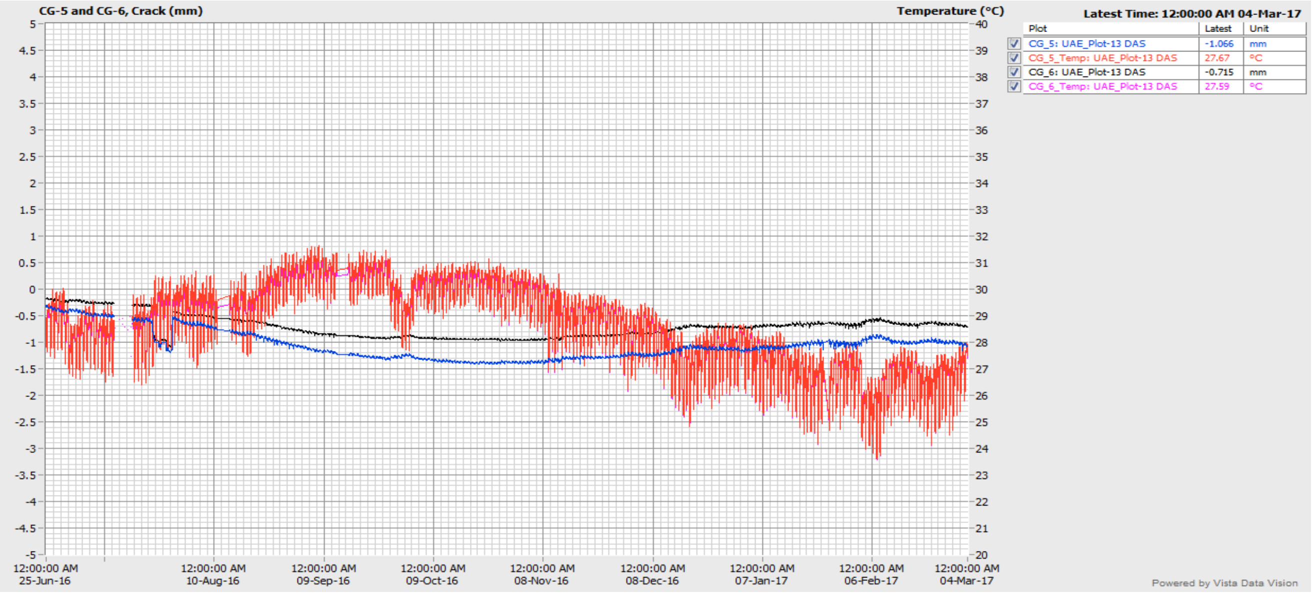


Figure 8 Crack meter with Temperature Reading

4. CHALLENGES FOR INSTRUMENTATION PROGRAM

The following summarized the challenges faced and lessons learned during the execution of the project.

- Installation of sensors in the existing metro tunnel was very critical, as the running metro trains allowed a window of just 2 hours around the midnight for the installation works.
- Drilling on the lining segments of the metro tunnel was not allowed. thus, a special frame was designed to fit the existing holes on the lining segments for installation of the beam sensors.
- Strain gages were fixed to the wall using epoxy.
- Beam sensors cannot be installed in chain due to existing utilities, cable trays, tracks, tunnel curvature etc.
- “Moving Average” method was applied smoothen out fluctuations for better presentation of graphs.
- While using joint boxes/converters/multiplexers ensure proper sealing of the cable gland if any port is left empty.
- Cable lying should be done properly with cable holders every 1 m to ensure no slacks are left in the cables which might entangle with other objects.
- Meticulous housekeeping is required inside the tunnel during installation.
- For dataloggers, there should be proper power backup such as generator which can supply in case of mains power failure inside the tunnel.

5. DATA MANAGEMENT

Monitored data was available on-line through the public cloud-based web data management service (WDMS) to the construction contractor, owner as well as the consultant on their desktops or mobile devices.

A typical data flow diagram of geotechnical sensors under the WDMS is given in **Figure 8** below:

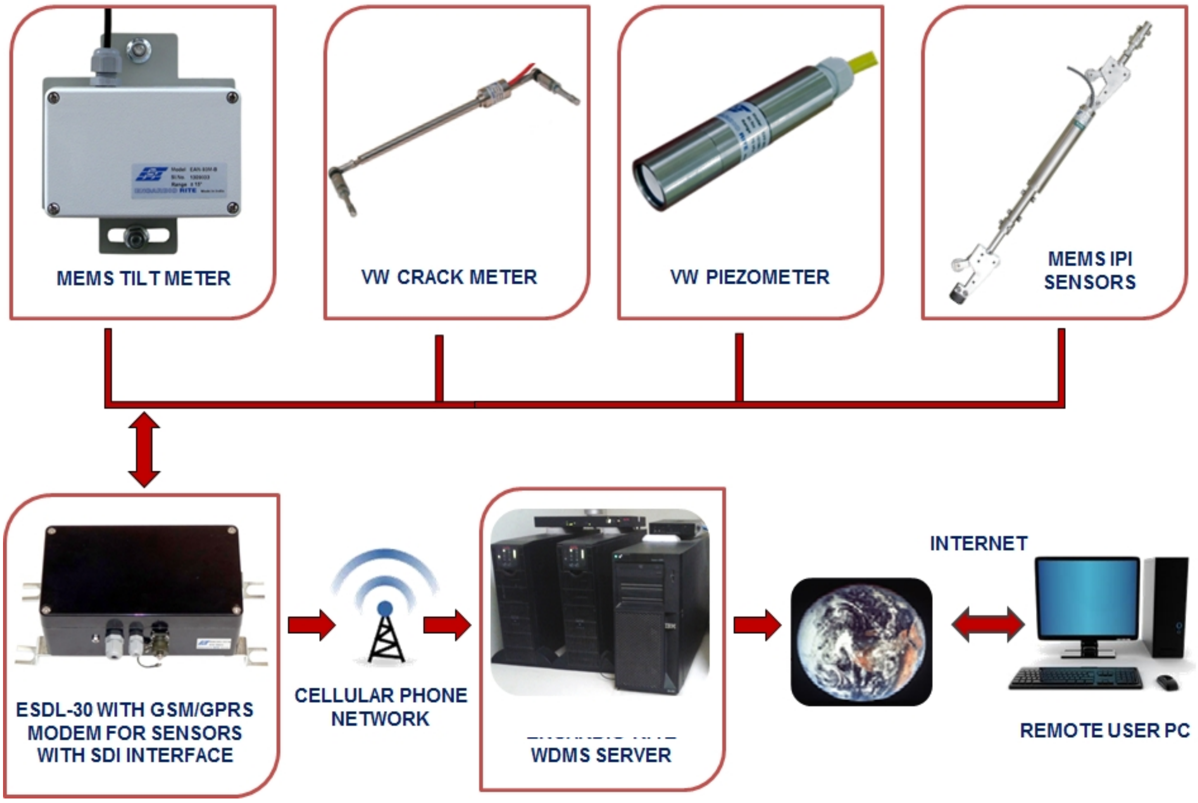


Figure 9. Data flow diagram for WDMS

The WDMS retrieved data from the SDI-12 sensors and automated total station (ATS) control boxes fitted through cellular network, archives the retrieved data in a SQL database, processes data and presents it in tabular and most suitable graphical forms for easy interpretation.

Features of the WDMS used can be summarized as follows:

- Data from multiple sensor types were converted into meaningful information in graphical as well as numerical format
- Project's layout plan was incorporated into the real-time display window with locations of each monitoring sensor. Through layout plan, the user easily navigated to the graphical & tabular data of any sensor with a few mouse clicks
- Access to all sensors in one platform
- Instant automatic alerts via SMS or e-mail to authorized personnel
- Create graphs from any combination of parameters and time period
- Variety of visualization and analysis tools to identify potential failure scenarios
- No special software was required for accessing the monitoring sites as information was viewed using popular web browsers

Monitoring reports were also submitted with a summary of the monitoring data on a daily and weekly basis. These reports comprised of basic interpretation of the results, correlating these with the construction activities in their vicinity.

Discussion on the IPI data

As the shoring wall construction progresses, significant movements were noted in one of the in-place inclinometers (IPI) installed in the shoring wall in the vicinity of the existing road tunnel (**Figure 10**). Upon breach of trigger level, to verify the readings, the IPI chain was removed. Subsequently, the readings were continued with the same manual inclinometer system, using which baseline reading of the inclinometer was established prior to installation of the IPI chain. The results confirmed the movement observed through IPI readings. One to one match between IPI and manual inclinometer could not be expected due to the difference in reading methodologies-tilt readings every 0.5 m in case of the manual system and at every 2 m in case of IPIs. Readings collected from survey targets installed in the same section of the inclinometer on the shoring wall also confirmed the movements recorded.

The construction contractor took preventive measures by providing additional anchoring and horizontal support at the section of the shoring system showing excessive deformation, based on the monitoring results.

Upon further analysis of the cause of deformation, the recharge method using pressure jetting deployed at the site was determined to be the factor contributing to the deformations observed. It was also observed that the standpipe piezometer's trigger limits, breach of which was the reason behind the recharging were also at the fault. These were reworked using new sets of ground investigation data.

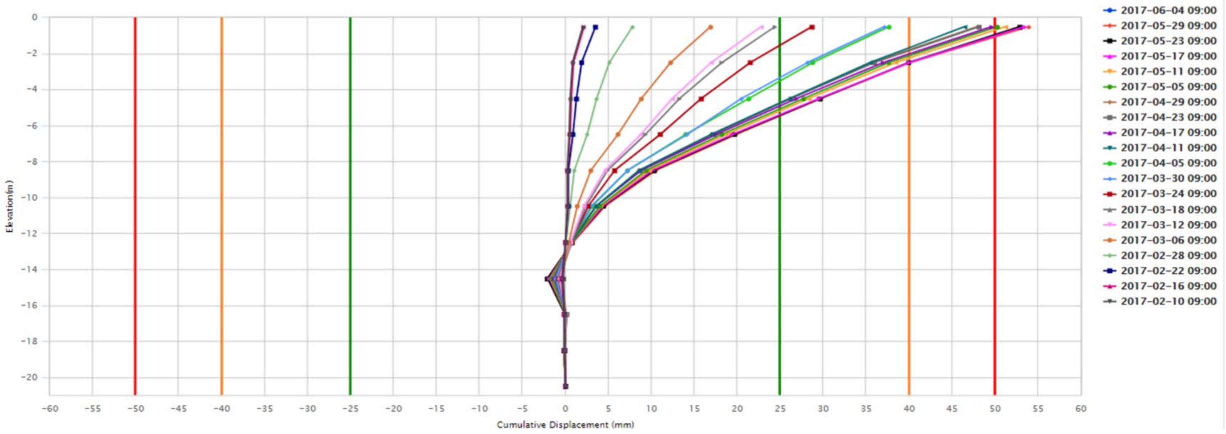


Figure 10. Results of inclinometer in the shoring system in breach of the trigger values

6. CONCLUSION

Monitoring played an important role in ensuring the safety of the critical tunnel assets in the urban construction project discussed in the paper. It helped the main contractor to advance the construction with confidence. Corrective measures were taken based on the instrumentation data avoiding any failure.

Trigger value calculation for instrumentation is critical. Consideration should also be given while working out the same to any special installation practices used at site and site-specific constraints. Unrealistic trigger values could lead to unnecessary delays, add to the project cost on top of that the safety of the project is jeopardized. Money spent on instrumentation and monitoring is not only a small fraction of the total project cost but also an investment which pays for itself in the long run. Moreover, it also generates useful data to refer to while undertaking projects of a similar nature in future.