

# INSTRUMENTATION & MONITORING OF CRITICAL TUNNELLING INFRASTRUCTURE IN URBAN ENVIRONS

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## ABSTRACT

As megacities struggle to provide infrastructure, residential and commercial spaces to its increasing number of residents in a limited land mass, existing structures- both surface and underground are bound to get affected by new constructions. In such a scenario, implementing an effective instrumentation and monitoring (I&M) programme for the structures within the zone of influence of construction, becomes extremely essential. Benefits of a well-executed I&M program are manifold- from providing design verification to ensuring safety during and after the construction.

In the paper, the author presents a case study of I&M program executed by his organization in a megacity in the Middle East. An existing metro and a busy road tunnel under water were located within the zone of influence of the project's construction activities. Ensuring their safety during the construction was on the top propriety of all project stakeholders as well as the asset owners.

The paper starts off with a brief overview of the project with salient features of the construction methodologies deployed, followed by the instrumentation & monitoring scheme finalized by the project designers. Details of key parameters to be monitored and which instruments were selected for the purpose, has been described. Challenges faced during the installation campaign in active tunnels and how these were overcome with practical solutions, are described in the subsequent section. Mention is made about the setup of data transmission and its centralized collection in the same section.

Fast processing of the collected data, its lucid presentation for easy assimilation and its instant access-not restricted by geographical boundaries -is the key feature of a successful I&M programme. This aspect is covered in the next section along with a discussion of the observed data. Unusual data observed from an in-place inclinometer installed in the vicinity of the road tunnel is showcased. The paper ends with the key lessons learnt during execution of the project and the conclusions drawn.

**Key Words:** Instrumentation, Monitoring, In-tunnel Instruments, In-place Inclinometer, Web-based data monitoring service

## 1. INTRODUCTION

The mixed-use development considered 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. It comprised of construction of hotels, residential and commercial towers, marina, storage facilities, loading and unloading bays, parking lots etc. The project 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.

## 2. MONITORING REQUIREMENTS

A risk assessment was done by the project's geotechnical consultant using the following inputs to work out instrumentation & monitoring (I&M) requirements:

- Soil/structure interaction assessment report
- Detailed finite element soil-structure interaction model
- Method statement for the construction works for the piling and excavation
- Local Railway Protection Code of Practice

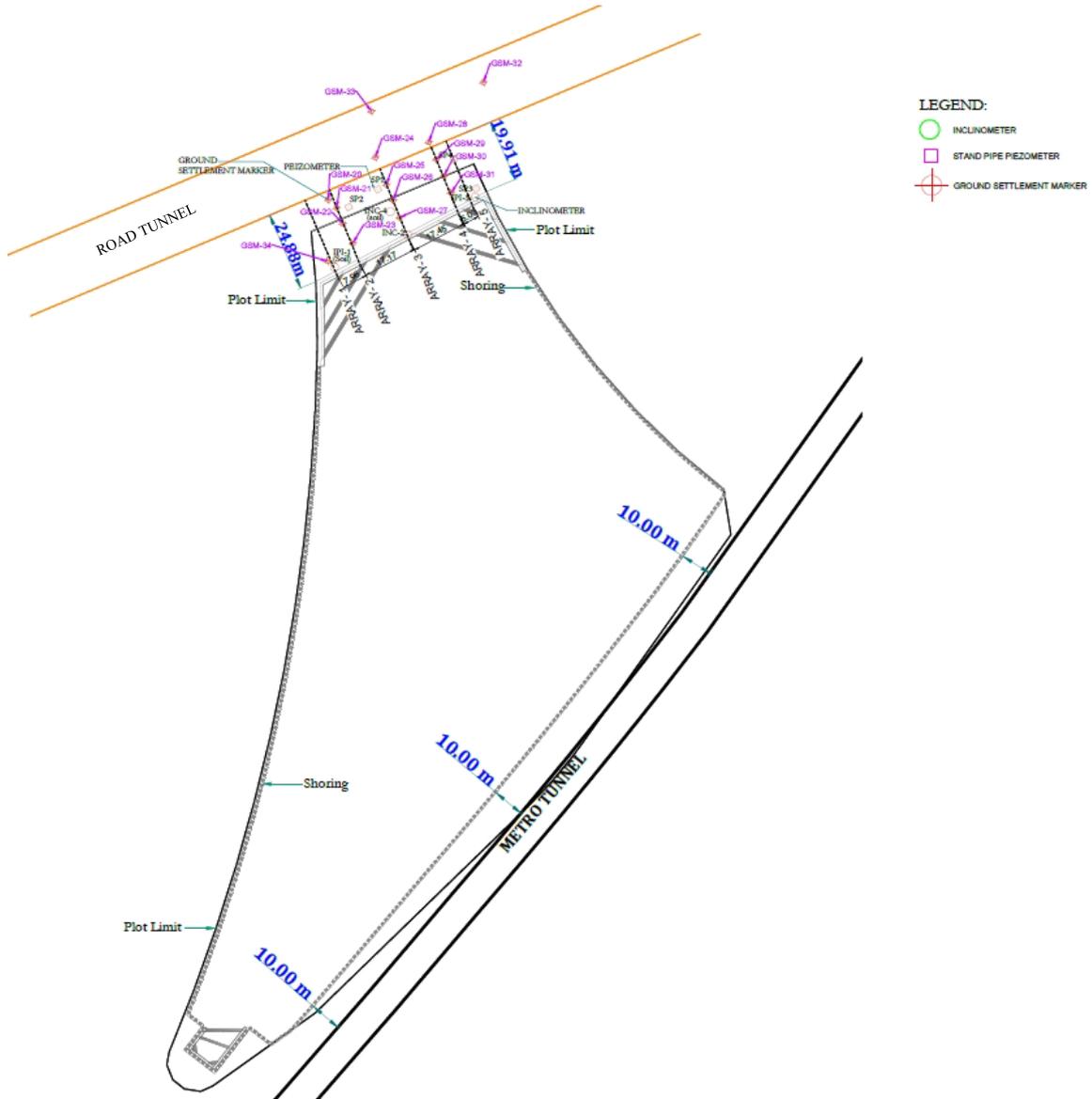
Monitoring requirements with instruments proposed to ensure the safety of the existing metro and road tunnels are summarized in table 1 below:

**Table 1.** Monitoring requirements and proposed instruments

Sl. No.	Purpose	Instruments	Location
1.	Monitoring of lateral deformation of soil between the excavation and the tunnel	In-place inclinometer	Embedded within the shoring wall adjacent to the tunnels
2.	Monitoring of groundwater drawdown during construction	Standpipe piezometer	In boreholes between the development and the tunnels
3.	Monitoring of potential surface settlement of the soil due to excavation and dewatering activities	Ground settlement point	In arrays placed 20 m apart approximately
4.	Monitoring of stress in tunnel linings/supporting walls	Strain gage	Located internally at the tunnel walls
5.	Monitoring of differential movement/change in diameter under unbalanced loading & tilting in tunnels	Beam sensor	Located internally at the tunnel walls and roof
6.	Monitoring lateral displacement across the adjacent rails	Beam sensor	Located between the rails transverse to the metro tunnel's long axis
7.	Monitoring differential settlements along the rails	Beam sensor	Located between the rails along the metro tunnel's long axis
8.	Effect of piling operations on tunnels	Triaxial vibration sensor	Within tunnel at closest point to the development
9.	Monitoring of displacements in the tunnels	Prism target	Located internally at the tunnel walls
10.	Monitoring of convergence in tunnel	Tape extensometer	Located internally in the road tunnel
11.	To monitor change in width of existing cracks	Crack meter	On the existing cracks within the tunnels
12.	Assessment of temperature induced changes in the in-tunnel monitoring points	Temperature gage	Adjacent to VW strain gages

13.	Sub-surface settlements	Magnetic extensometer	In boreholes between the development and the tunnels
14.	Loads on ground anchors supporting the shoring system	Anchor load cells	Within the plot's excavation

Location of the instruments in plan and section are shown in figures 1 to 4 below:



**Figure 1.** Instrumentation plan for the road tunnel

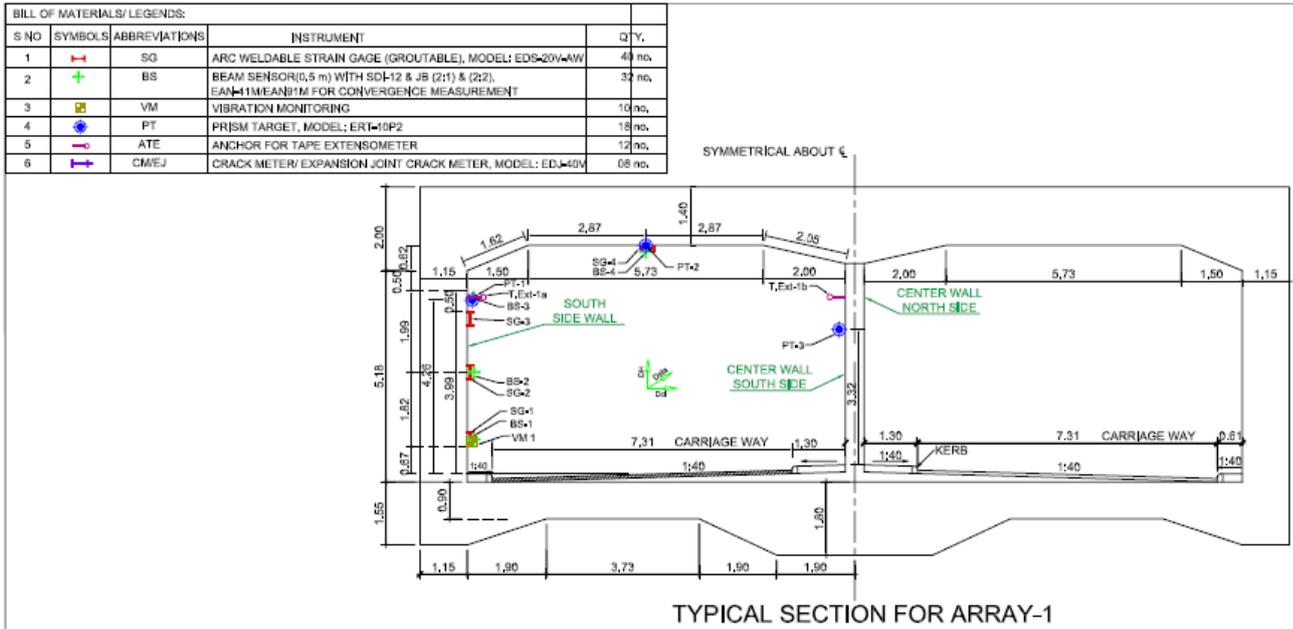
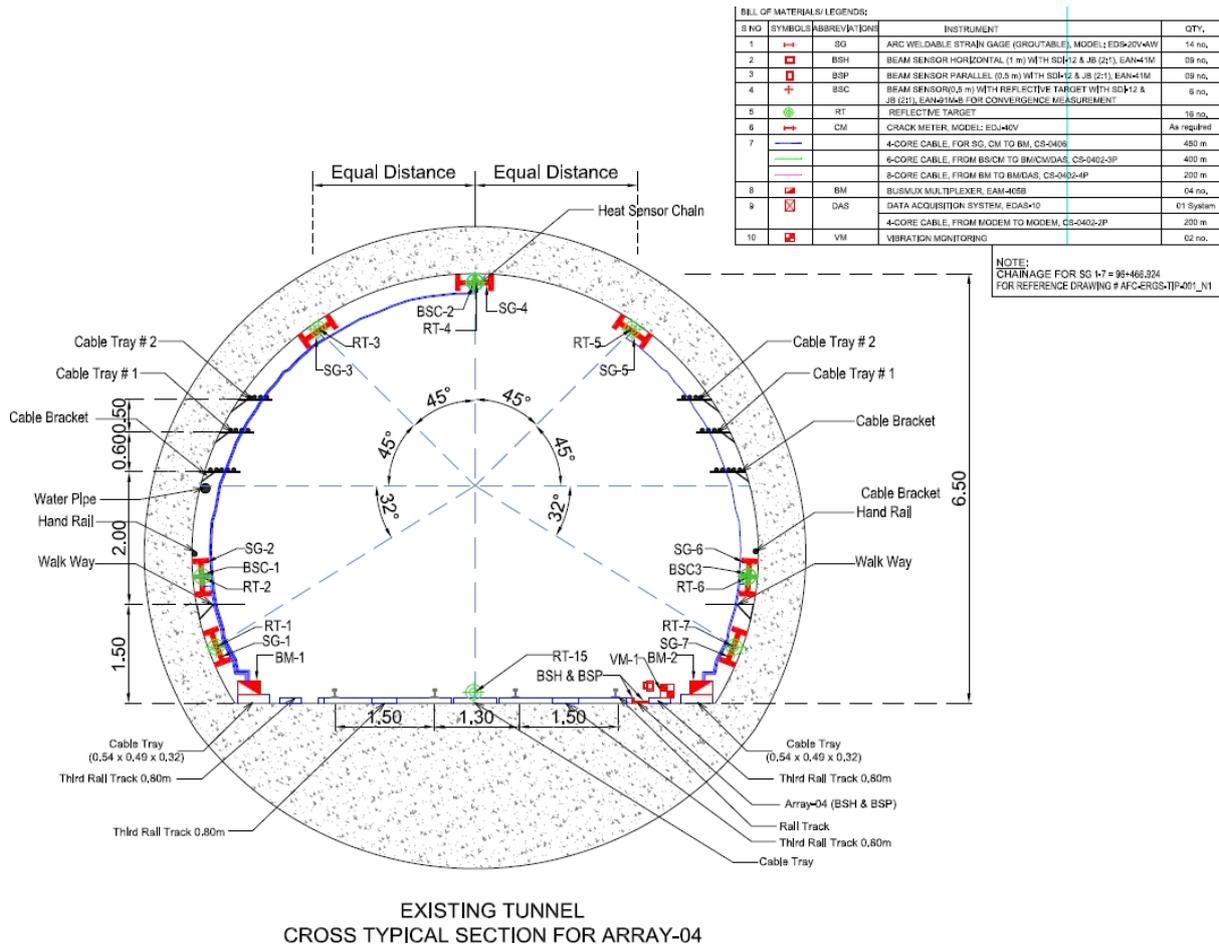


Figure 2. Instrumentation section of the road tunnel



Figure 3. Instrumentation plan for the metro tunnel



**Figure 4.** Instrumentation section of the metro tunnel

The monitoring trigger values and minimum recommended monitoring frequencies for the instruments mentioned in table 1 above were also provided under the risk assessment cum I&M plan.

### 3. INSTRUMENTATION & MONITORING PLAN IMPLEMENTED

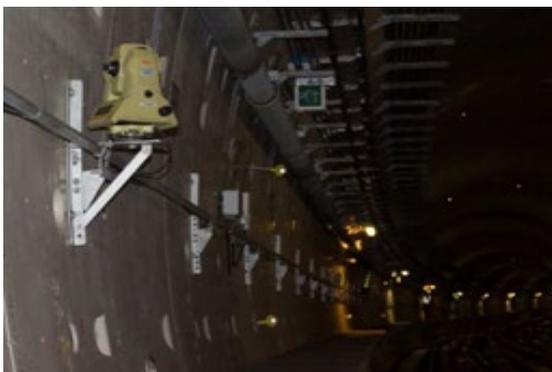
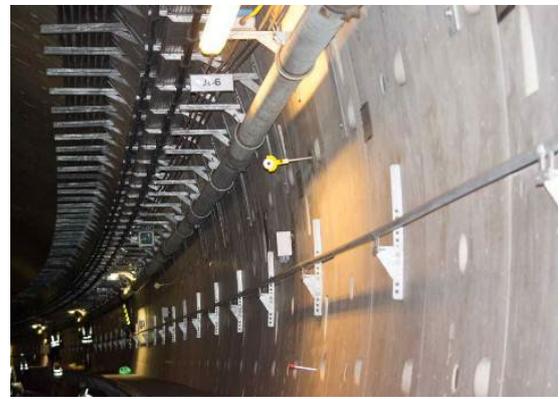
The author's organization was entrusted by the shoring contractor to perform the following tasks:

- Supply and Installation of geotechnical and geodetic instruments
- Weekly monitoring to establish a firm set of initial readings prior to construction
- Automatic as well as manual monitoring of geotechnical instruments and surveying
- Online data availability of critical parameters with continual live updates
- Daily & weekly reporting with evaluation & interpretations
- Pre-construction condition monitoring of both tunnels

In the following figures 5 & 6, instruments installed in the ground and inside the tunnels are shown. It is followed by the representative graphical data presentation of key instruments in figure 7.

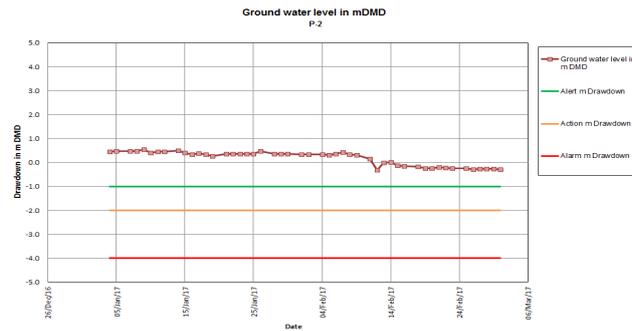


**Figure 5.** Site pictures showing existing road tunnel instrumentation

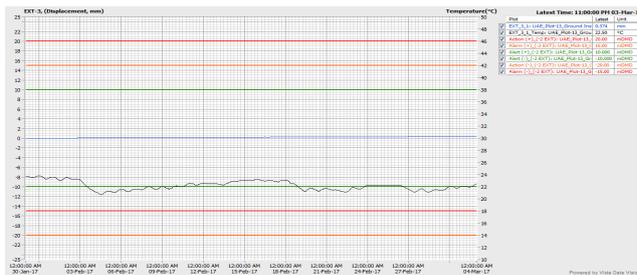


**Figure 6.** Site pictures showing existing metro tunnel instrumentation

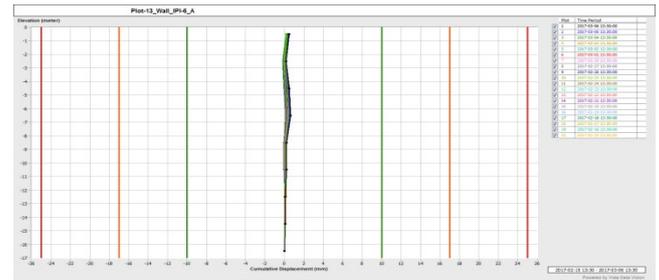




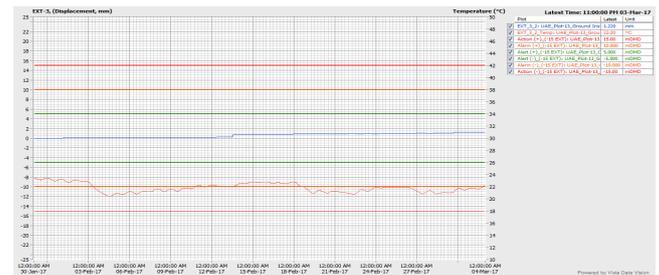
Standpipe piezometer



Extensometer (EL -2 m)



Inclinometer



Extensometer (EL -15 m)

Figure 7. Monitoring data presentation

#### 4. CHALLENGES FACED AND LESSONS LEARNT

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

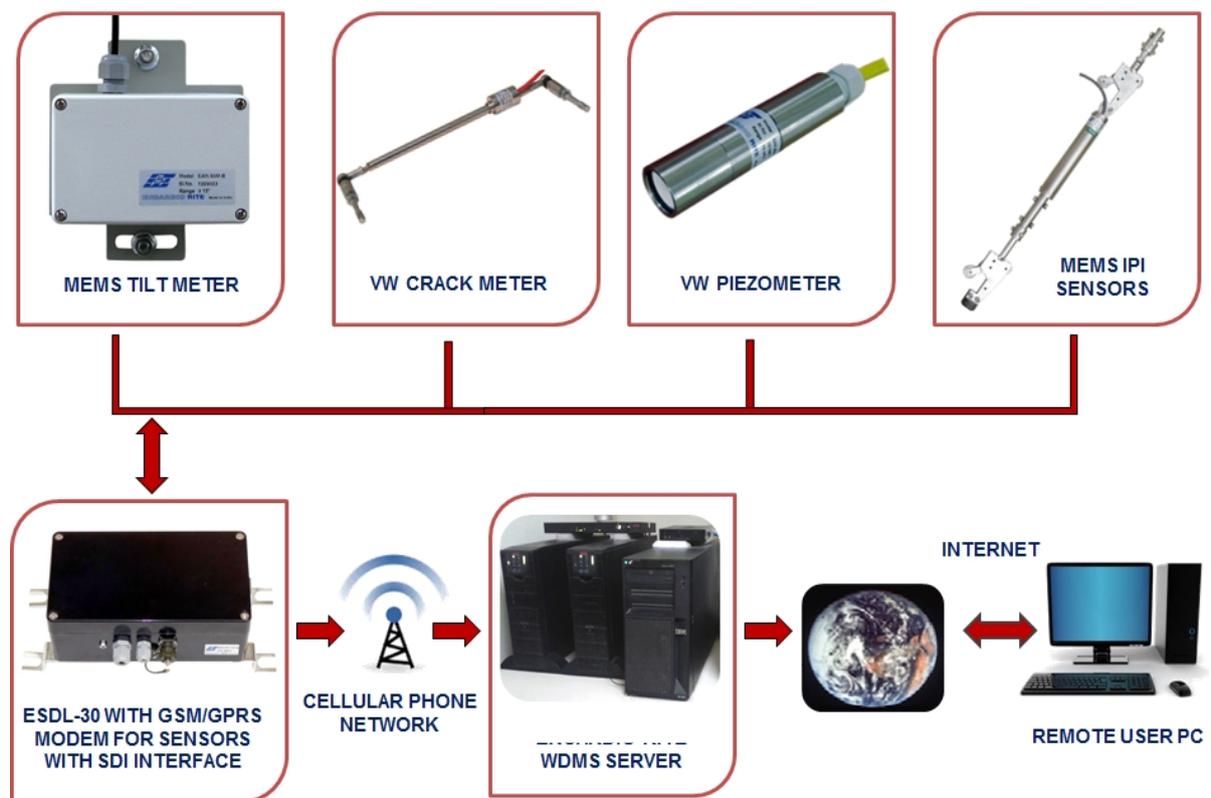
- Installation of sensors in the existing metro tunnel was very critical, as the running metro trains allowed a window of just 2 hours around the midnight for the installation works.
- Drilling on the lining segments of the metro tunnel was not allowed.
- Due to the above condition, a special frame was designed by the site team to suit 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” was applied smoothen out fluctuations for better presentation of graphs.
- Tagging/ID assigning work for all instruments must be done well before the installation schedule.
- While using JB's/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.
- GSM data SIM cards must be recharged before schedule to ensure no data is lost during the monitoring.
- Vibrating wire to SDI-12 interfaces installed at the ground with ESDL-30 must be properly sealed to avoid shorting/data loss.

- Strain gages should be protected with boxes made out of insulating material to minimize effects due to fluctuations in ambient temperature
- Mounting of vibration sensors should be attached to the structure properly to avoid fluctuations in the readings.

## 5. DATA REPORTING

Monitored data was available on-line through the public cloud-based web data management service (WDMS) to the Contractor, Client 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 8.** Data flow diagram for WDMS

The WDMS retrieved data from the SDI-12 sensors and ATS control boxes fitted with data SIMs over the internet, archives the retrieved data in a SQL database, processes data and presents it in tabular and most suitable graphical forms (refer to figure 9 ) 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. From this 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
- Generated settlement and piezometric contour
- 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

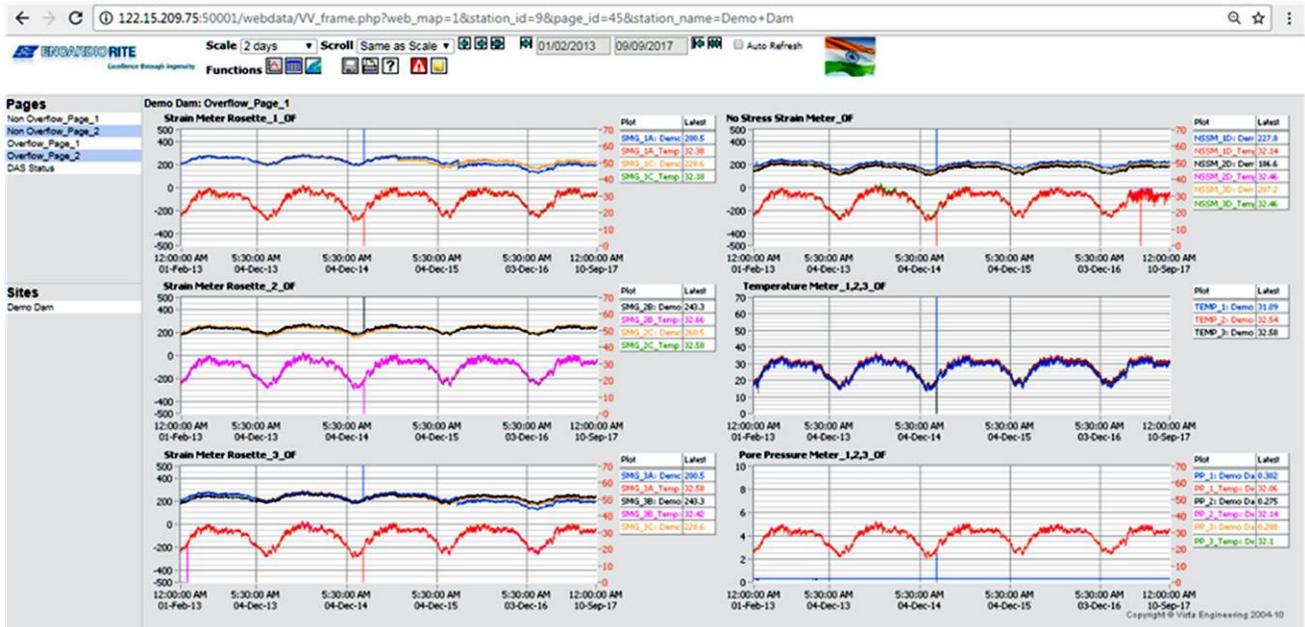


Figure 9. A sample screenshot of the historical data window of WDMs

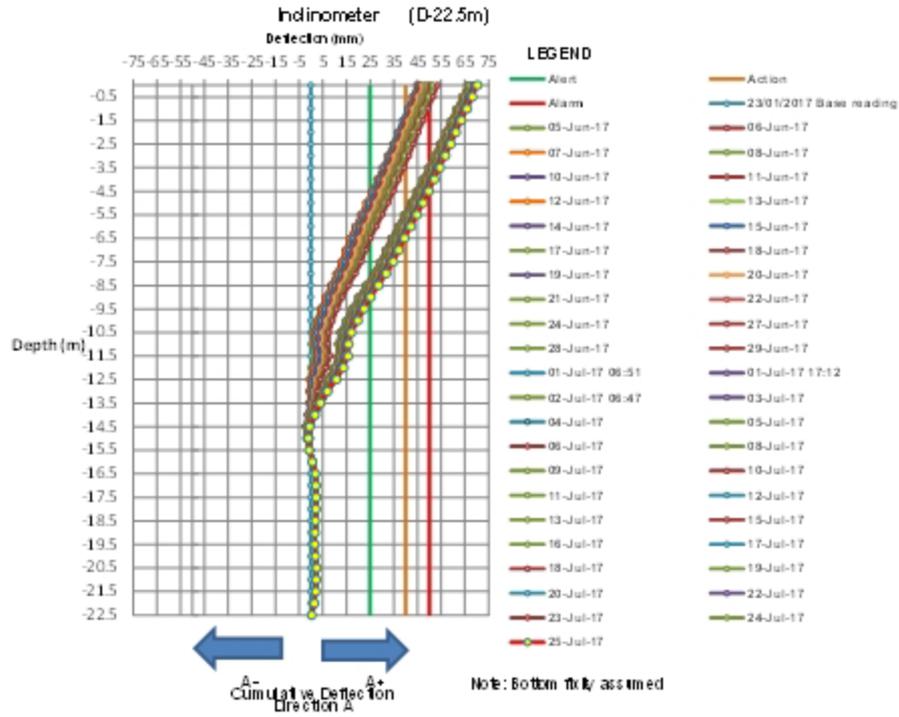
Monitoring reports were also submitted with a summary of the monitoring data on a daily and weekly basis. These reports comprised of basic interpretation of the results, correlating these with the construction activities in their vicinity.

### 5.1. Discussion on the inclinometer data

Progressive movements were noted in one of the in-place inclinometers (IPI) installed in the shoring wall in the vicinity of the existing road tunnel (refer to 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 IPI behaviour to a great extent. 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 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 untoward incidence. 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.