Emerging Technologies in Instrumentation and Monitoring of Tunnels & Underground Caverns

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Introduction

It is of utmost importance to monitor safety of tunnels and underground caverns as their design and construction deals with naturally occurring heterogeneous materials, engineering properties of which are not exactly known. It necessitates monitoring of geotechnical parameter using filed instrumentation as the construction progresses. The design judgments may be evaluated with the observed data and changes made, if required.

Field instrumentation used for safety monitoring during construction of tunnels and underground caverns has become highly sophisticated and advanced over time. As adoption of safety monitoring is getting more comprehensive and widespread, there is a need to design the safety monitoring network system to be cost effective to either reduce the cost of instrumentation or to allow monitoring of more parameters within the same budgeted cost.

Stake holders today also expect the safety monitoring network to identify potential hazardous conditions or developments well before a catastrophic failure takes place and alert personnel with authority to take remedial measures as early as possible. Therefore, another essential feature of safety monitoring network is to make the collected data readily available in real or near real time to the different stake holders, who may be located in any part of the world. The collected data needs to be presented in an easy to understand format like suitable charts or graphs including historical data of the parameters at that location.

1. Instrumentation for monitoring system for tunnels and underground caverns

It is necessary to have a combination of instruments across different sensing technologies to give complete information about potential deformations in tunnels and underground cavities. Ease and practicality of installation/replacement of the instruments and communication setup are equally important, apart from proven sensor types and core-technologies to achieve an effective and long-term tunnel monitoring system. Various building blocks of the system are described in the following paragraphs.

1.1 Field instruments

Some surface and subsurface sensors that may be used for monitoring tunnel and underground caverns are mentioned below:

- Borehole/rod extensometer to measure deformations of rock mass
- Load cell to measure load in rock bolts
- Load cell to measure stress in ribs and struts
- Strain gage to measure strain in ribs and struts
- Strain gage to measure strain in shotcrete
- Shotcrete-concrete stress cell to measure stress in shotcrete (Fig.1)
- Pore pressure meter to measure pore water pressure around tunnel and underground caverns
- Convergence measurement by mechanical methods-Tape Extensometer
- Convergence measurement by optical methods- Bireflex and Prism Targets
- Inclinometer and magnetic settlement devices

- Measuring Anchor to measure distribution of load exerted on grouted rock bolts

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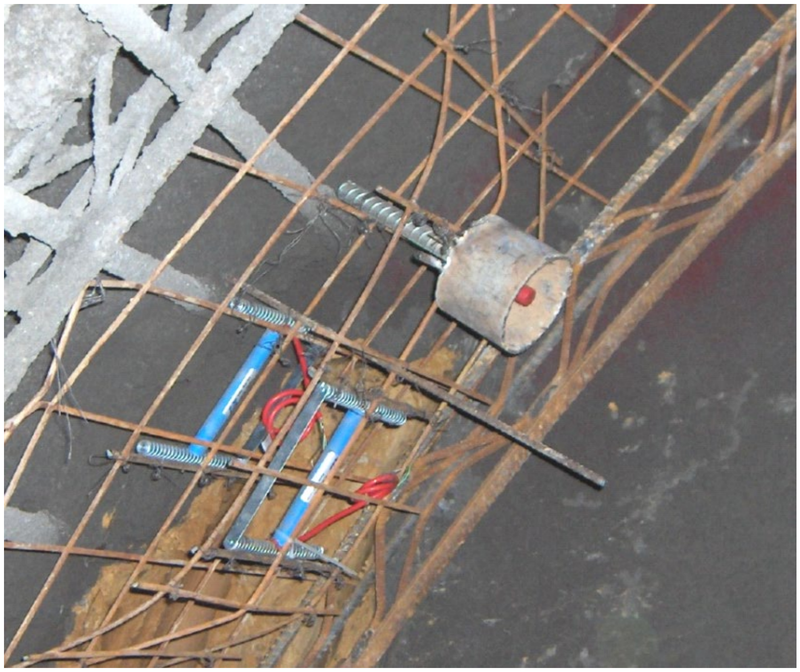

Fig. 1. A pair of shotcrete strain gages and convergence bolt of an optical target installed before shotcreting of an NATM tunnel

1.2 Typical monitoring schemes for underground structures

Any point on the surface of a rock mass is subjected to stresses in two directions, the stress in a direction perpendicular to the surface being zero. Any point inside the rock mass, if not next to a void or cavity, is subjected to stresses from all the directions. Excavation of any cavity inside a rock mass, like making of an underground power house or boring of a tunnel, results in the release and readjustment of these three dimensional stresses around the cavity. Readjustment and release of stresses results in displacements. These displacement are also time dependent. The forces of gravity acting on the excavated surface and the stresses released behind the surface, result in instability which requires the supporting of the tunnel/cavity. There are many methods by which the roof and side walls of excavated cavities can be supported. One of the methods by which the roof of excavated cavities can be supported is by providing arched ribs made of heavy duty steel sections. Another method called the New Austrian Tunnelling Method (NATM) is by applying a thick layer of shotcrete around the excavated area that quickly solidifies and supports the excavation. The instrumentation for underground cavities varies widely with the type of construction methodology used, the nature of rock obtained, the size (width) of the underground cavity, the height of over burden etc. Typical schemes from actual instrumentation done at different project sites are described below:

- <u>Power house & transformer hall cavern instrumentation</u>

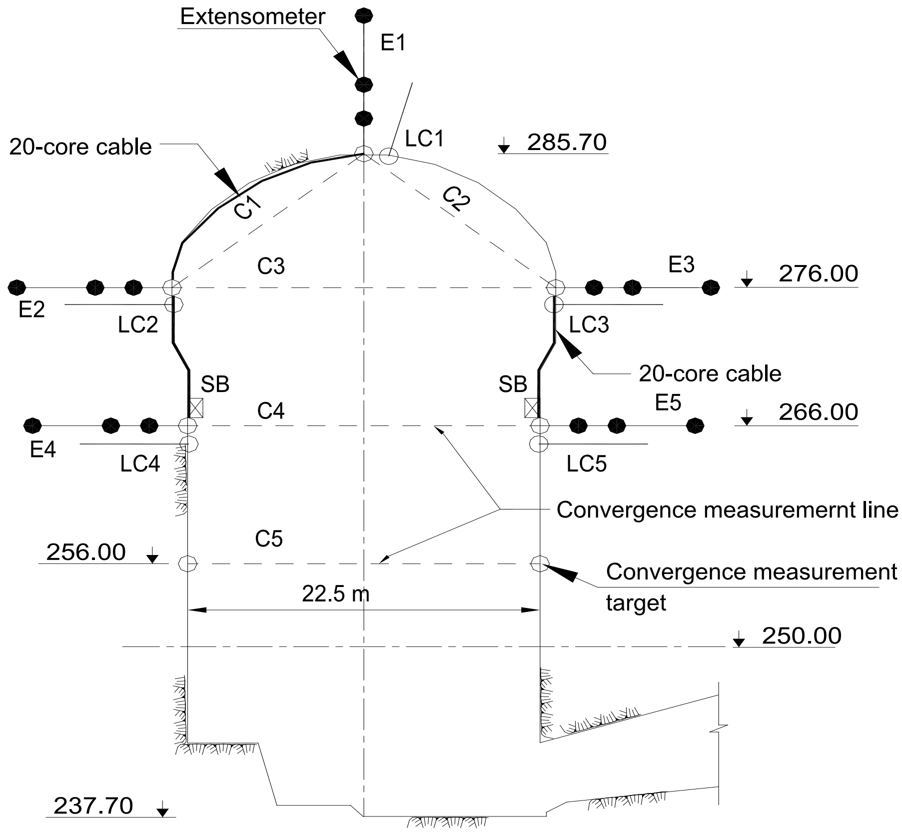

Fig. 2. The instrumentation scheme shown above was repeated every about 20 m at this site

Figure 2 shows instrumentation for only one section. It consists of three point electronic borehole extensometers, electronic centre hole load cells for rock anchors and tape convergence points. Piezometers may be mounted if required.

- Penstock instrumentation

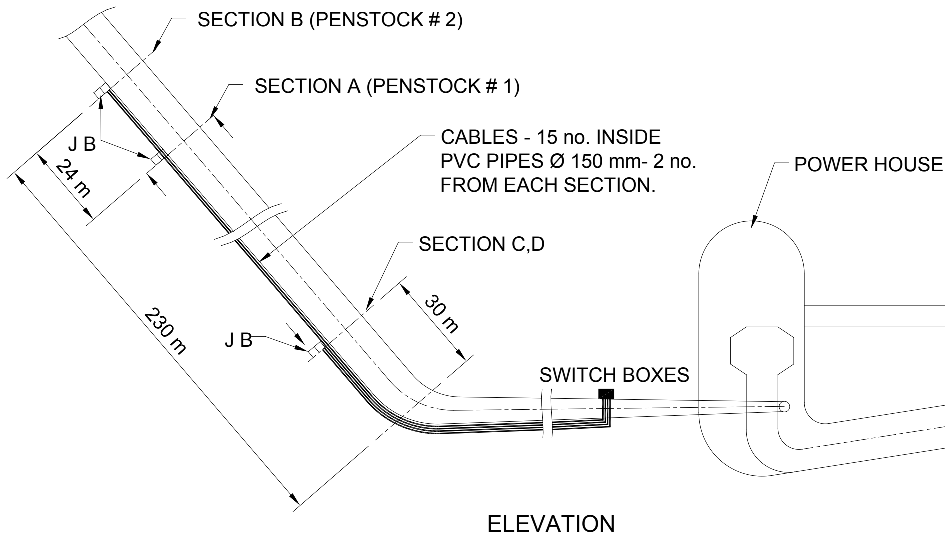

Fig. 3.In the particular project, instrumentation was done in three sections (about 7 m dia) spread over a distance of 230 m

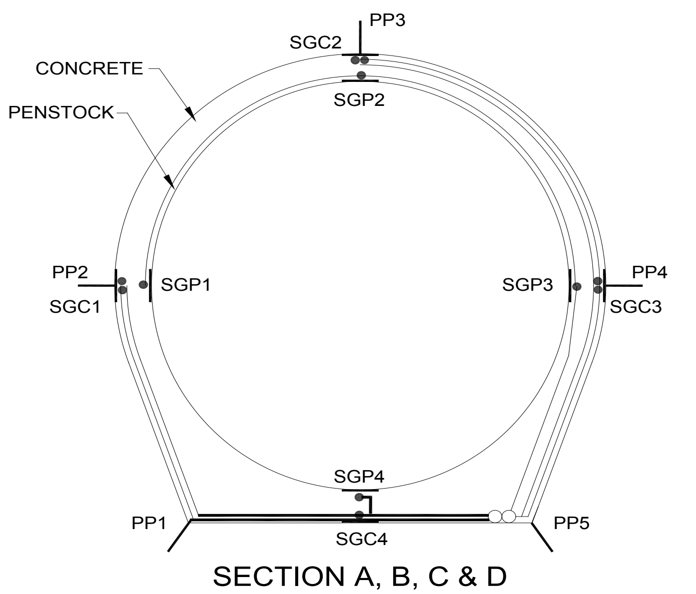

Fig. 4. Each section had pore pressure meters, embedment strain gages and strain gages

- Road/rail tunnel instrumentation

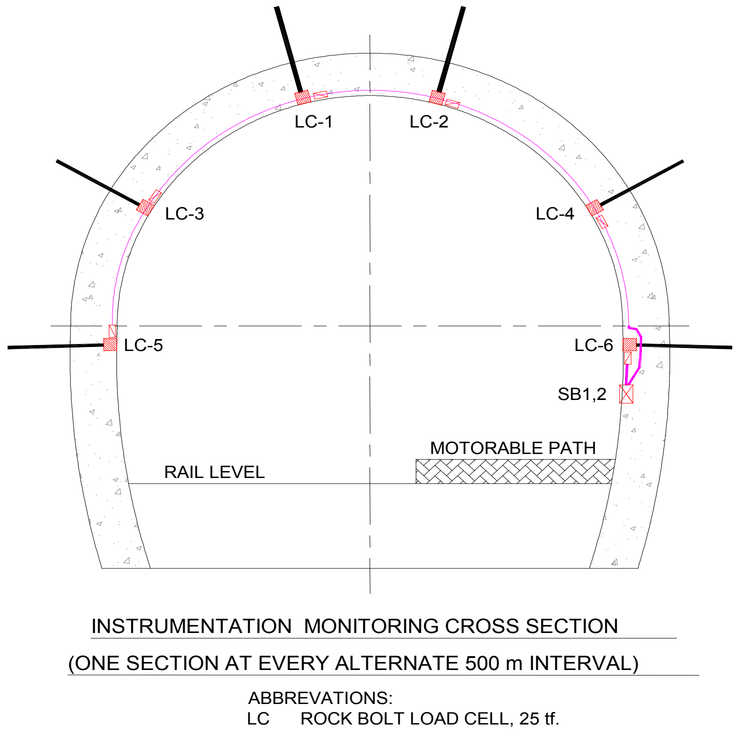

Fig. 5. In this particular project, to monitor tension in the rock bolts, five centre hole load cells of 250 kN capacity are used. This section is repeated at every 500 m.

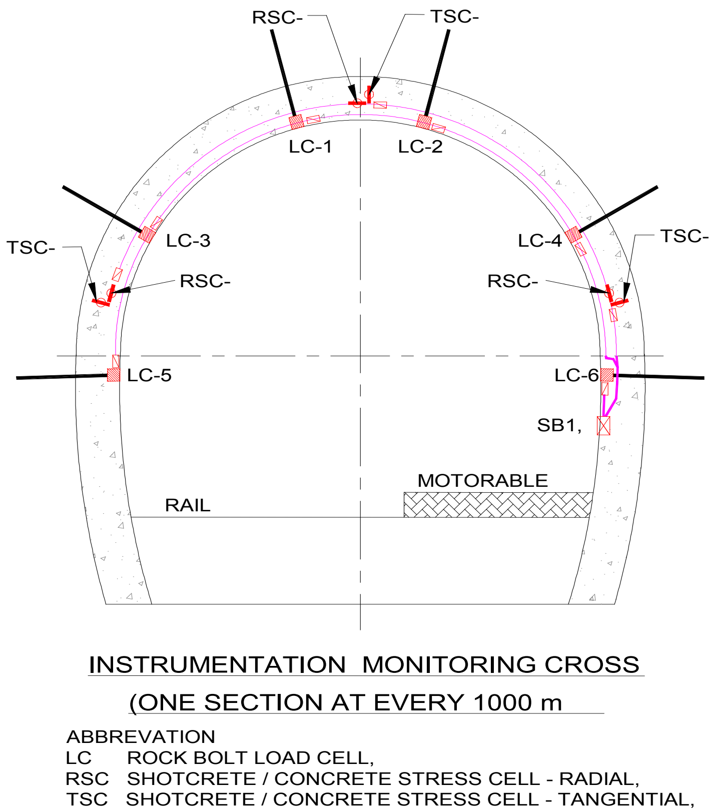

Fig. 6. In this particular project, to monitor shotcrete stress, three pairs of shotcrete cells are used. Each pair has one 5 MPa cell for measuring radial and one 20 MPa cell for measuring tangential stress.

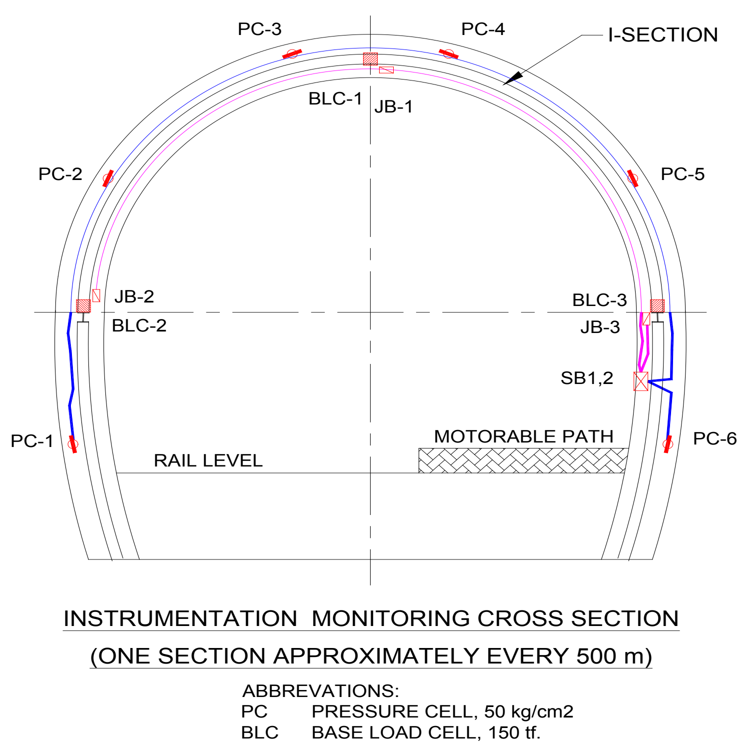

Fig. 7. The section shown above, repeated every 500 m, has three compression (base) load cells of 1500 kN capacity in the I beam and six pressure cells of 5 MPa capacity in the concrete.

1.3 Automatic 3-D Deformation Monitoring System (ATDMS)

The ATDMS measures movements of targets fixed at the final lining or supporting members of the tunnel and underground caverns in three dimensions (x, y & z). It comprises of the following major components:

- 3D prism targets
- Automatic total stations (ATS)
- Control box
- Monitoring database

Fig. 8. Prism target components

Fig. 10. Monitoring sections of a tunnel with prism targets (left) and ATS mounted on the tunnel wall

One or more high precision servo driven, computer controlled ATS is installed at a suitable location on concrete/steel pillars with enclosures or on the wall itself (Fig. 9) to automatically sight the 3D prism targets sequentially and record the data. Reference prism targets at stable locations make the system complete.

The ATS is controlled by a control box (Fig. 9) which is essentially rugged field computer. It is powered by 220 V, 50 Hz AC mains and in turn power up the ATS. Solar panels can be used where mains power supply is not available. The control box features GSM/GPRS modem with dual SIM slots for data transmission. Data is collected by the public cloud-based web data monitoring service described in section 2. Alarms can also be programmed in the

Fig. 9 ATS control box

database resulting in sending SMS/e-mail alerts automatically to the concerned personnel, in case deformation of any point breaches a trigger value. Typical data presentation of prism targets on WDMS is shown in figure 11 below.

PRISM TARGET – RPN 194

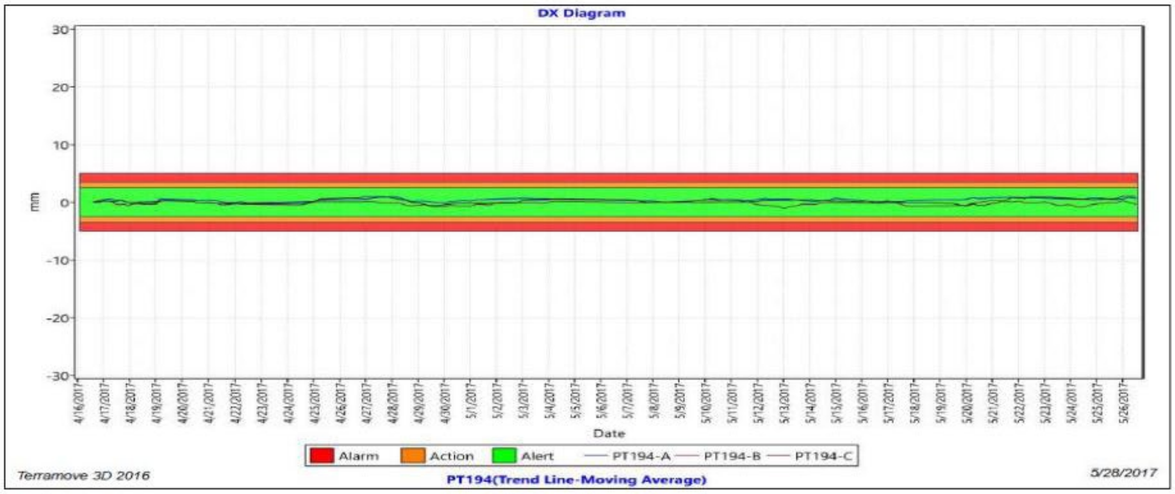

Fig. 11. Typical data presentation of a prism target

1.4 Deformation monitoring through laser scanning

Laser scanning is a rapid and reliable surveying method, collecting data in static, stop & go or kinematic mode. This method of deformation monitoring based on exceptionally dense mapping of three-dimensional coordinates of the points on the surface to be monitored (Fig 12). From the point clod produced, the exported section profiles can be used to monitor deformations in tunnels and underground cavities.

Fig. 12. Laser scanner for tunnel deformation monitoring

1.5 Sensor communication & data transmission

- Monitoring system with SDI-12 Interface sensors

The SDI-12 system is a bus communication system in which a wide array of tunnel monitoring sensors can be connected to a single 3-core cable. This is a great advantage and is possible as the electrical interface for the protocol involves three lines: a serial data line, a 12 V power line, and a ground line. The datalogger, featuring GSM/GPRS modem transmits the logged data over the internet to the web-based data monitoring service described in section 3. Refer to figure 13 for a block diagram of tunnel monitoring instruments network built on an SDI-12 bus.

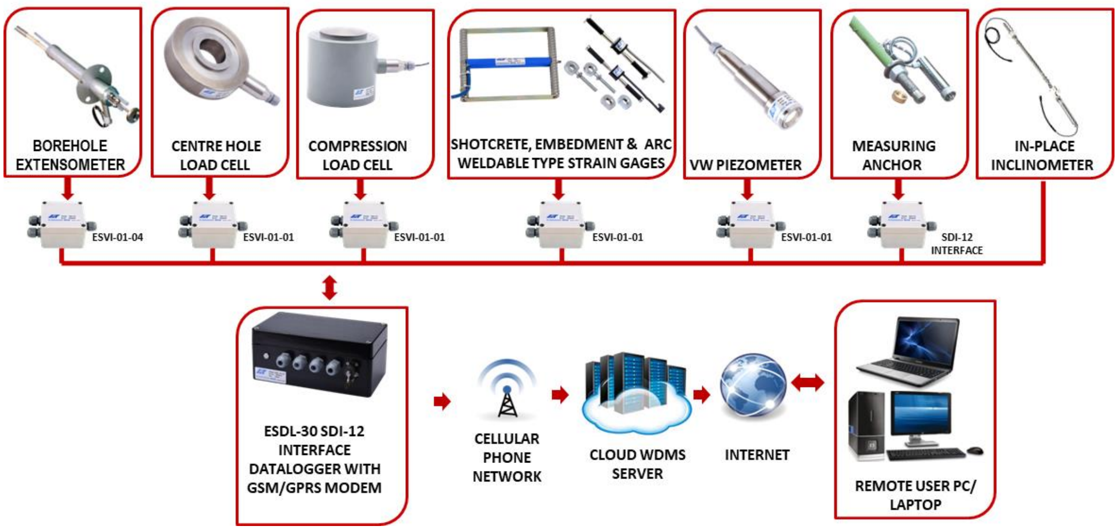

Fig. 13 Tunnel/cavern instruments on an SDI-12 network

- Wireless monitoring system using radio frequency (RF)

Tunnel/cavern monitoring sensors network with radio frequency (RF) communication does not require any cabling. It essentially comprises of sensors connected to RF dataloggers and gateways and features long-range communication on ISM frequency range of permitted in the country of use, of up to 15 km in open field conditions. The low power consumption of the system results in datalogger batteries lasting up to 5 years. Refer to figures 14 & 15 for general arrangement of RF field sensor network and block diagram of tunnel/cavern monitoring instruments network built on this communication technology, respectively.

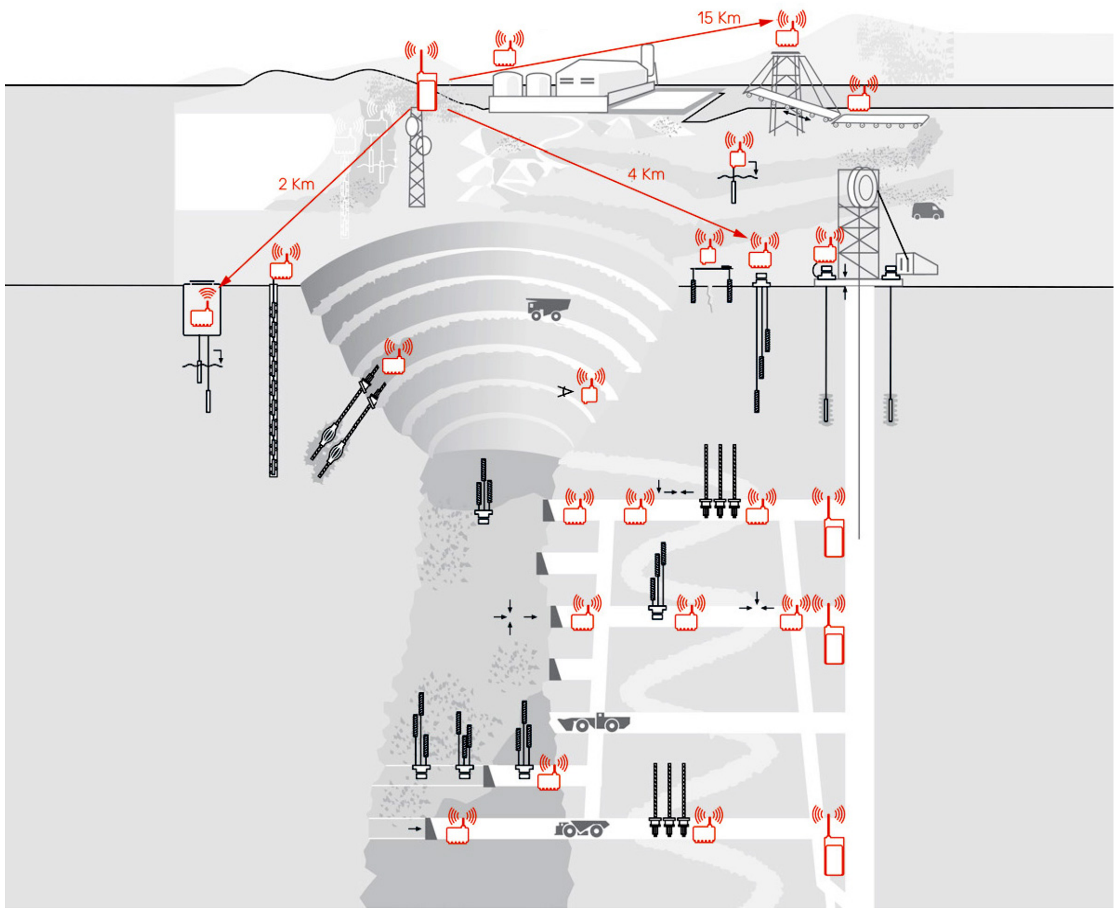

Fig. 14Typical RF sensor network at field

The RF dataloggers, often called the ‘nodes’ of the wireless network, can be easily configured in the field using the smartphone Android app provided. These are available in single and multichannel configurations suitable for receiving the vibrating wire and analogue inputs and automatically collect, store and transmit data from the connected sensors. The RF gateway (Fig. 16) controls the network and is the aggregator of all data collected by the nodes. It has an integrated 3G modem with antenna supporting HSDPA, EDGE & GPRS, and a high sensitivity GPS-GNSS module. The gateways transmit the data over the internet to web data monitoring service described in section 2.

The system offer benefits by means of hassle-free installation- as cable runs-often long and tedious at the tunnel construction sites are not involved, cost & time savings, remote monitoring of hard to access locations, easy expansion of the system, if required in future, and easy maintenance.

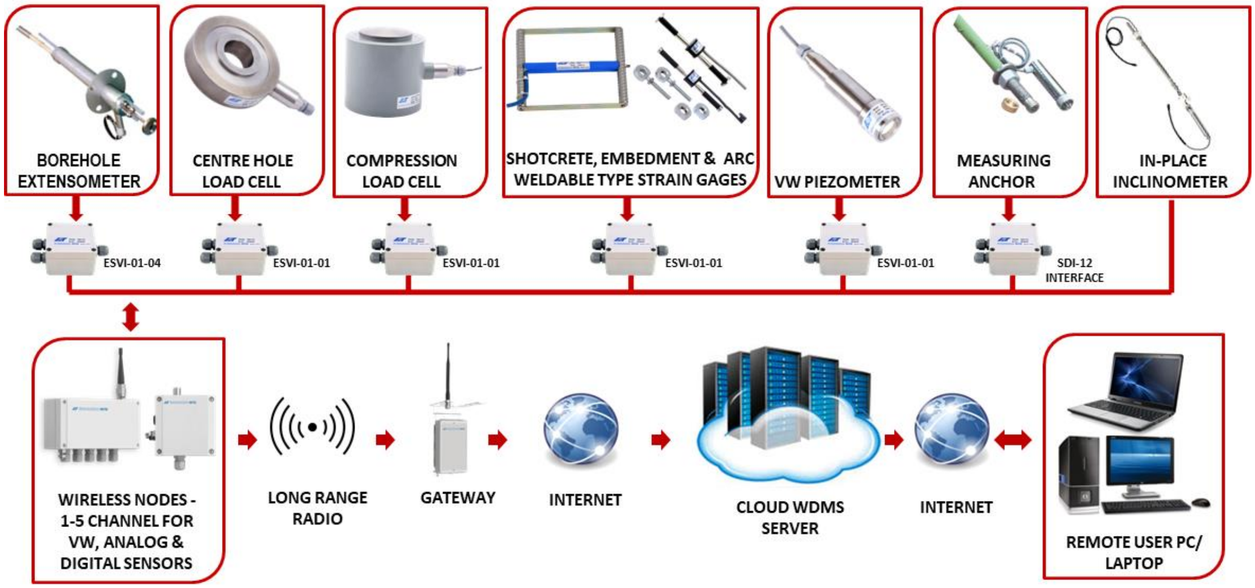

Fig. 15. Tunnel/cavern *m monitoring sensors connected to an RF network*

Fig. 16. RF gateway

2. Web based database management system

Cloud-based web data monitoring service is available with major geotechnical instrumentation service providers for retrieving data from the dataloggers, archiving retrieved data in a SQL database, processing data and presenting the processed data in tabular and most suitable graphical forms (Fig. 17) for easy interpretation of logged data. This is a highly flexible online monitoring system that can combine data from structural, geodetic and environmental sensors.

Cloud-based WDMS usually work on a rental model. The user has to pay a small setup fee for the first time and then a monthly rental has to be paid for accessing the data over the cloud as long as required.

Web data monitoring service's database management software acts as a data collection agent, a database server and a web server and is hosted on a high-reliability server computer. Choice of the software depends on the measurement technologies deployed.

A master plan of the project is incorporated into the database with locations of each monitoring sensor. From this master plan, the user can get data in the graphical form of any sensor with just a mouse click.

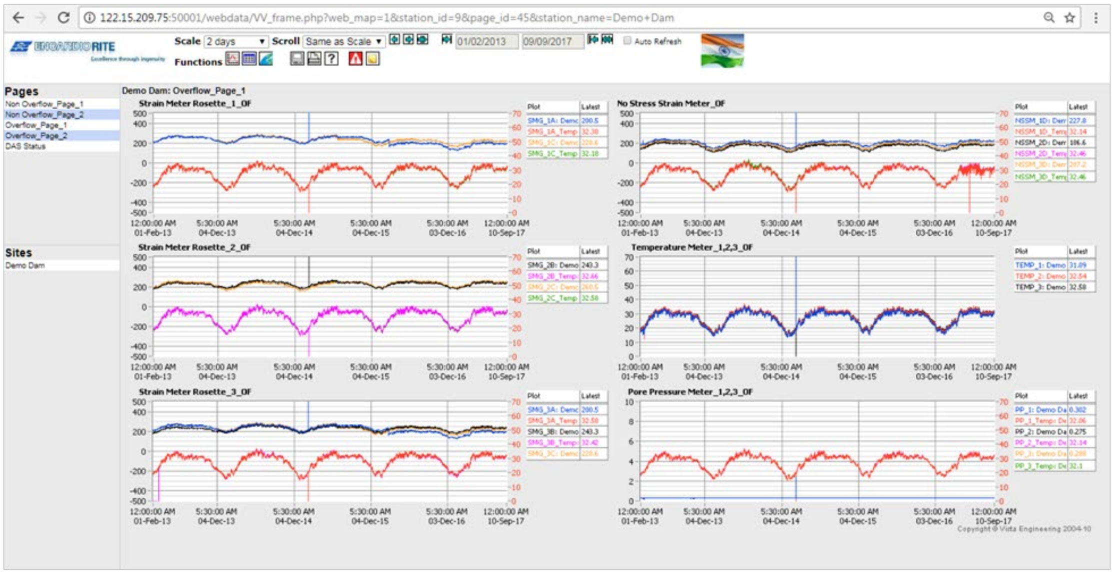

Fig. 17. Graphical data presentation on WDMS

Multiple authorized users at different locations assigned with an individual password are allowed to view any data or report from the structure simultaneously. Graphs & reports can be viewed using popular web browsers like Microsoft internet explorer or Mozilla Firefox amongst others.

Details like sensor identification tag, last recorded sensor reading and values of programmed alert levels can generally be viewed on the master plan of the project. If any of the alarm levels of any sensor exceeds, the colour of the marker representing the sensor location changes. Clicking the pop-up table brings up an associated data window where the sensor data can be seen either as a table or as a graph.

Site administrators can set alarm limits, which are generally considered as "alert level" and "evacuate level". WDMS can also be programmed to send SMS alert messages or e-mail to selected users as soon as any sensor data crosses its predefined alarm levels, either while going above or going below the alarm level.

Features of the data management software can be summarized as follows:

- Data from multiple sensor types are converted into meaningful information in graphical as well as numerical format
- Results available on a wide variety of fixed and mobile devices
- Access to all sensors on one screen
- Instant alerts via SMS or e-mail to authorized personnel
- Combined charts in one report
- Create graphs from any combination of parameters and time period
- Variety of visualization and analysis tools to identify potential failure scenarios
- No special software required for accessing the user sites as information can be viewed using most standard and popular web browsers

3. Human factor in success of an instrumentation programme

Human factor plays an important role in success of an instrumentation programme. Even a slightest of a human error has the potential to jeopardise proper functioning of an advanced monitoring sensor. A lot of patience and perseverance are required to make an instrumentation system function properly. It has been noted in one of the projects that shotcrete pressure cells were not giving any data as pinching was not done after curing of shotcrete.

For verification of readings from electronic displacement transducer(s) of MPBX it is essential that a set of initial reading is also taken from depth micro meter. Proper initialization of instruments is also vital for quality data suitable for further interpretation. Above small but essential details if omitted by the installation/monitoring personnel can be detrimental on the long run.

Also the monitoring personnel have to be very alert and be well aware of the ongoing construction activities. Field notes prepared by the monitoring personnel go a long way in meaningful data interpretation.

4. Case Study

Multipoint borehole extensometers (MPBX) were installed at the crown and sidewalls at various chainages of an underground chamber in one of the projects instrumented and monitored by the author's organization. The designed dimensions of the cavern were 60 m high x 19.8 m wide and it was a major component of a powerhouse complex with a designed capacity in excess of 1000 MW. Anchor depth of the electronic MPBX at the crown was 25 m, 20 m, 15 m, 10 m and 5 m. During the routine monitoring of an MPBX at a particular chainage, an abrupt change in the reading was recorded in 15 m, 10 m and 5 m anchors as shown in the chart shown in figure 18 below:

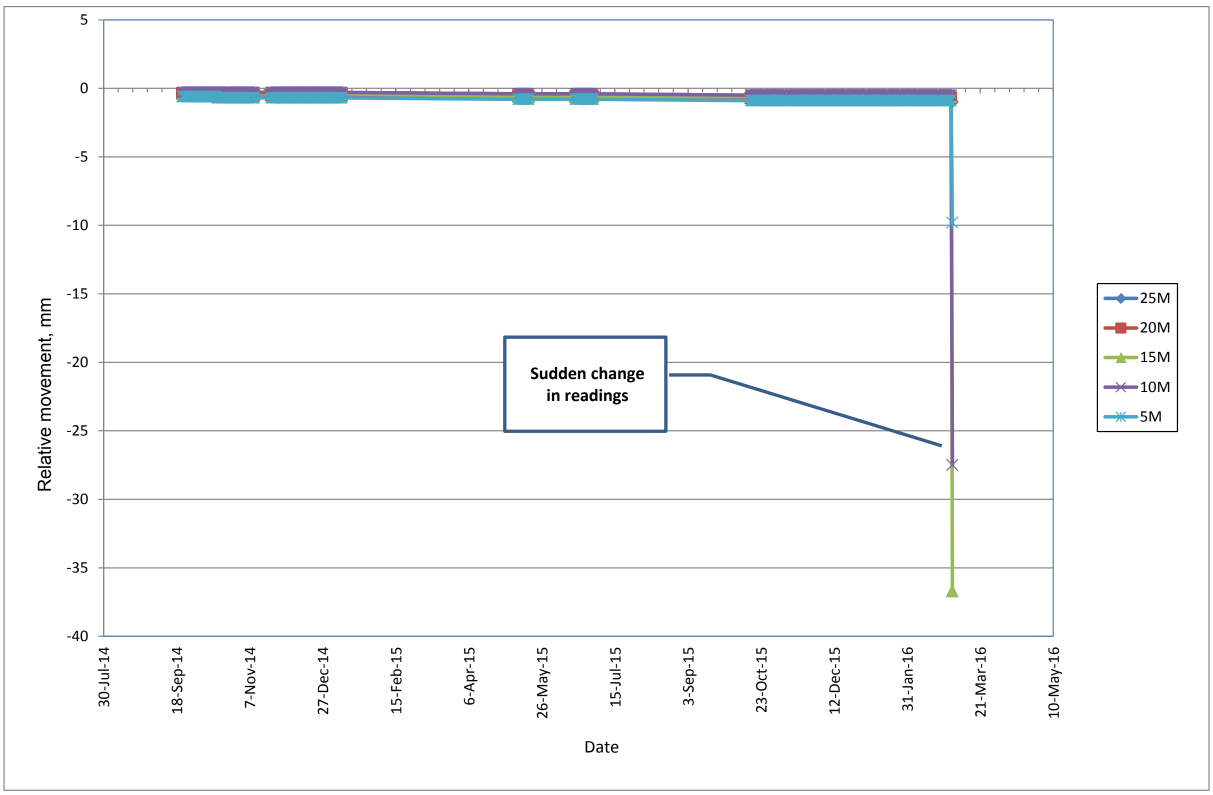

Fig. 18. MPBX data showing abrupt change before the collapse

Excavation depth was 23 m at the monitored chainage. The readings were retaken few hours later for verification purpose. Representative of the client also witnessed the same and the exercise confirmed the readings observed in earlier. The abrupt change was informed to the higher project authorities without losing any time.

Unfortunately, the roof collapsed 45 ahead of the monitoring section resulting in sad demise of six men (Fig. 19). Excavation depth at the chainage of collapse was 29 m.

Construction work was stopped in the chamber after the incidence. Upon further investigation with crosshole tomography, a cavity with dimensions 91 m x 82 m x 30 m was discovered above the chamber.

Fig. 19. Picture of the collapse (locations of the instruments are also indicated)

As a remedial measure, strengthening of the chamber was undertaken along with two more underground chambers next to it, as a precautionary measure. The chambers had to be refilled by up to 20 m to undertake the reinforcement with rock bolts and steel plates.

5. Conclusions

Instrumentation and monitoring plays an important role in reducing the risk of underground tunnelling/cavern project as engineering properties of the ground are not always known accurately. By monitoring an underground tunnel/cavern, action may become possible earlier than the occurrence of any failure. Human factor plays an important role in the successful execution of a monitoring programme. Proper installation of geotechnical instruments is as important as the quality of instrument itself since once embedded, the instrument cannot be accessed. The solution for setting up a safety instrumentation & on-line monitoring system is not expensive with the advent of new technologies in this field like SDI-12 bus and RF communication, ATS, laser scanning and cloud based WDMS. Considering holistically, the cost of instrumentation and monitoring is a small fraction of what is spent later on in repair and rehabilitation operations.

The Author

Mr. Prateek Mehrotra has done MSc. in Engineering from Moscow Power Engineering Institute (Technical University), Moscow, Russia in 1997. He had joined Encardio-rite Electronics (P) Ltd. in March-2000 and is presently working as Vice President-Technical. During the span of 17 years with Encardio-rite, he has been involved in successful execution of I&M programs at several large scale civil engineering projects including tunnels and underground caverns in India and the Middle East.