

Instrumentation and field measurements: The future

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Abstract—*This paper covers the recent advancements in field instrumentation for monitoring geotechnical and structural engineering parameters in various civil engineering projects. Adopting new technologies can increase accuracy of measurements with reduced costs and can monitor large topographical areas. The use of mobile phone as a data collection device can allow the field engineer to collect field data in a single compact palm held device. Wireless links eliminate the need to connect the installed sensors and the central host computer with cables. Adopting a web based data access service will allow all stake holders to have access to safety instrumentation network data and analysis in near real time from anywhere in the world. Laser scanning and automated monitoring system techniques can be utilized for real time monitoring of 3D displacements*

Keywords—*instrumentation; technology; advancement; wireless; automation*

I. INTRODUCTION

Instrumentation and field measurements used for optimised construction control and for safety monitoring, is getting more comprehensive and widespread. There is a need to design the instrumentation monitoring network system to be cost effective to reduce the cost of instrumentation and at the same time allow monitoring of more parameters within the same budgeted cost.

An essential feature of instrumentation is to make the collected data readily available in real or near real time to the stake holders wherever they may be sitting around the globe. The collected data needs to be presented in an easy to understand format such that not only the instantaneous value but the trend of variation over pre-defined interval of time is also available at the flick of a key. The data should be available in the form of charts or graphs. Going a step further, the safety monitoring network must identify imminent hazardous conditions well before a catastrophic failure takes place. To this end, they must alert personnel with authority to take remedial measures as early as possible. This is very important as affected communities, governments, project owners and stake holders are increasingly adopting a zero tolerance towards loss of human life even for projects undertaken under the most trying conditions.

Recent developments in technology have provided

opportunities and some of the finest equipment to make field instrumentation more precise, reliable, and cost effective. Some of these technologies for collecting information/data on structures and areas subject to geological hazards and monitoring them for safety have been discussed in this paper.

II. TOPOGRAPHY

Aerial mapping is fast replacing manual topographical survey, construction progress monitoring and preconstruction survey over large areas. Aerial mapping involves both visual inspection as well as inspection with spatial information. Visual inspection provides data, photos, orthophotos, videos that are very useful for the management team to visually follow the progress. In this way, the user of the service can document the progress, strengthen his claims, easily and impressively present his works to the government, client, owner, consultant and supervisor.

With spatial information, measuring values and accuracy to the data collected is added. Products such as mesh 3D models, volumetric calculations, texture 3D models, contour maps, slope maps and geo-referenced maps can be delivered to document the quantitative progress of the project as well. The accuracies that can be achieved correspond to a survey scale better than 1:500 for UAV (fixed wings) and 1:100 with drone (octocopter). In both cases, the benefits are plenty. A few salient advantages are listed below:

- Visits of personnel and visitors to site are minimized.
- Full information for the project area is collected and made available in a very short time.
- Quality of survey improves and cost reduces.
- It results in minimizing time and maximizing safety of personnel visiting for inspection/measurements in areas with landslides, high slopes or viaduct pillars etc.
- Data is collected very fast even from non-accessible areas.
- Virtual reality combination of design studies and actual environment

- Impressive and convincing way of presentation.

UAV with fixed wings such as Bramor rTk can be used at a height above ground level of 400 – 600m to give a Ground Sampling Distance of 8 – 12cm which is satisfactory for almost all earthworks and surface surveys. For survey of viaducts, bridges and/or other structures, flights can be undertaken with drones (octocopter) providing vertical and oblique images, from a close distance of maximum 50m.

A lot of international construction companies today are using aerial mapping for monitoring. Refer to Fig. 1.

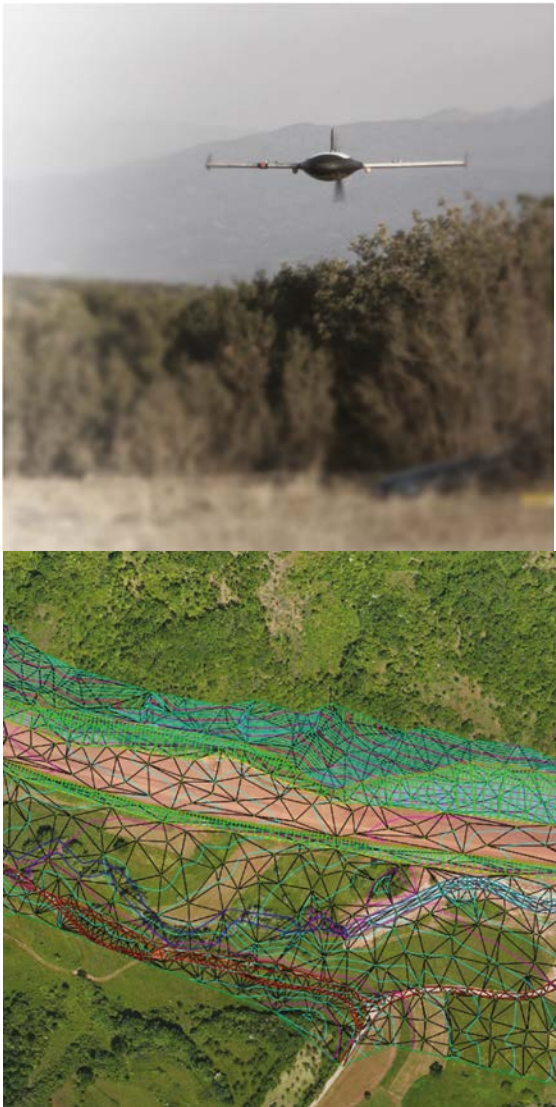


Fig. 1. Drone topographical survey

III. DIGITAL SENSORS

The basic element in monitoring is the sensor. Various types of sensors with different technologies like vibrating wire, resistance strain gauge, MEMS, electro-level, 4-20 mA output, frequency output etc. are available in the market manufactured by several manufacturers. Traditionally all sensors in a typical instrumentation network are connected

to a central data acquisition system (DAS) capable of accepting inputs from the various types of sensors. The outputs of sensors are measured by the DAS using multiplexers which connect the output from the individual sensors one by one to the DAS input. Most current generation DAS, after measuring the sensor output, mathematically compute the output in terms of suitable engineering units and store the result in its internal memory. The contents of the DAS internal memory is then retrieved by a PC which displays the measured values as a set of tables or graphs in a suitable format.

New digital sensors have changed it all! Many types of digital sensors based on different technologies are available. However, to illustrate the point, example of digital sensors and data acquisition system with SDI-12 serial interface is taken.

The beauty of the new system is that only a single 3 conductor cable is required to interconnect all the sensors and the data logger in a serial bus. SDI-12 is a multi-drop interface that can communicate with multi-parameter sensors. As the SDI-12 sensors are digital sensors the accuracy of the output (measured) value is not affected by the length of cable between the sensor and the DAS.

Most digital sensors store the calibration parameters inside the sensor and output the value of the measured parameters directly in terms of suitable engineering units which was not possible with analogue output sensors.

Sensors with SDI-12 bus interface have very low power requirement. Any commercially available economic data loggers compatible with SDI-12 interface sensors can be used to form a good sensor network for efficient monitoring. Technological advancements now enable to use just a single brick sized data logger for up to 180 sensors with SDI-12 interface. The data loggers can be powered by a couple of lithium batteries. If the data from the sensors need to be collected a few times a day and transmitted once daily to a cloud based data monitoring system, the batteries will last for more than two years. For lesser number of sensors a set of batteries can last as much as 5 to 7 years. A cellular service provider's data SIM card is all that is required to connect to the internet. The data logger generally spends its time sleeping, waking up at scheduled times of the day to collect data from the connected sensors and transmits the collected data to the cloud at programmed times. The location should, however, be covered by any cellular service network for this to be possible.

IV. USE OF MOBILE PHONE AS A MEANS OF DATA COLLECTION

Different types of analogue sensors require different types of hand held readout units for monitoring their output at site. Even when using central DAS for collecting and recording data it is essential that the data acquisition system has the necessary signal conditioners matching with the output of the sensors deployed in a project. The use of digital sensors allow the use of standard palm top computers to collect data from any digital sensor provided it meets certain communication standards.



Fig. 2. mobile phones as readout unit with graphic display

With the development of Bluetooth technology it is no longer necessary for the hand held computer to be connected to the sensor using a copper wire cable and the data from the sensor can be fetched wirelessly over the Bluetooth interface. Because of the low production volumes and proprietary nature of the operating system, palm top computers are quite expensive and the availability of software is severely limited. The palm top computer required the operator to go to a designated central location at the end of the day and transfer data to a host computer. It generally did not allow the operator to go through the earlier historical data for any sensor if the requirement arose

The mobile phone is changing all that. Today's mobile phones have evolved to become a very powerful computational platform. Most of the higher end mobile phones have a high resolution large colour graphics display, internal memory capacity that is specified in Gigabytes, Bluetooth wireless serial data link, cellular phone coverage nearly throughout the inhabited areas of the world, cameras with pretty high resolution and image quality, connectivity to internet, and in built GPS receivers that can tell the user his position anywhere in the world.

This new multifunctional device is now being used for field data collection in geotechnical or civil engineering safety instrumentation networks.

While installing sensors for the first time, especially in the open, it is required that the sensor location be determined using surveying techniques. Traditionally a qualified surveyor with optical surveying instruments was

required to determine the geographical coordinates of the sensor location. This process took some time and required additional surveying resources.

With the in-built GPS receiver of a higher end mobile phone the operator can determine the sensor location without requiring help of a surveyor.

desired. The video clip can serve as a record of the actual method followed to install the sensor, or can serve as a training video for other installation personnel.

For installation of very sophisticated sensors or sensors requiring strict adherence to laid down procedures, the operator can use the video clip playback facility of the mobile phone to see an instructional video for installing that sensor at the site itself. Similarly, the internet browsers of the mobile phone allows the operator to access such training videos uploaded to video sharing portals like YouTube at the sensor installation site itself.

If a project uses many different types of digital sensors or distributed DAS with Bluetooth interface a mobile phone loaded with different application software would be able to download and visualize data from all such devices. Thus the mobile phone can save the cost of many different readouts/dataloggers required to read the different types of sensors in a conventional instrumentation network.

Use of mobile phones with standard operating system like Android allows the users to choose from a wide variety of phones from many different manufacturers around the world. Earlier if a proprietary readout unit developed a fault

the unit had to be returned to the manufacturer for repairs that took a lot of time.

With mobile phones the user only needs to get another mobile phone and load the application software supplied by the sensor manufacturer. The memory card from the old phone can simply be transferred to the new phone and all the earlier data would be available to the user again.

Thus the mobile phone of today equips the field engineer simultaneously with a phone, camera, location fixing, personal computer, web browser, video recorder and player, training manuals on demand and a host of sensor readouts and data loggers in a small compact and economical palm top unit.

V. WIRELESS LINKS

Wireless links are becoming very popular for connecting sensors to the central DAS or host computer. Wireless links as the name implies eliminates all cabling between the individual sensors and the central DAS. There are many different types of wireless links but no one type of link is suitable for all situations found in the field. A knowledge of the advantages, disadvantages and limitations of each type of wireless link is essential for designing an economical and reliable wireless sensor instrumentation network.

The use of radio frequency spectrum for establishing a wireless link is tightly controlled by respective national governments and generally requires a license from the national radio frequency regulatory body. However, in general the 2.4 GHz and 5 GHz bands are free for unlicensed use in most countries. In some countries the use of certain frequencies in the 800 to 900 MHz range is also allowed without requiring a license.

Sensors and Data collection units that operate at 2.4 or 5 GHz require a near line of sight access between the two communicating devices. Except for small obstructions any significant obstruction that comes between the two communicating devices can render the wireless link unusable.

Wireless links operating at 800 to 900 MHz band are more tolerant towards in line obstructions and the radio signals between the two communicating devices can to some extent travel around the obstruction provided it is not very large.

A Bluetooth standard wireless link operates at 2.4 GHz and is generally used for very short distance communication of up to 10 meters but the link can be used for distances up to 100 meters using higher power. This low power link is generally used for communication between a digital sensor or datalogger and a hand held or a portable data collection unit. For example connection between the cable reel of a digital traversing type inclinometer to the hand held readout unit is nowadays done through a wireless link avoiding the use of cables and problematic slip rings to make the connection to the rotating reel.

The higher power Bluetooth link is used for link distance above 10 metres. For example the data from a difficult to

reach borehole extensometer/anchor bolt load cell combination installed at the crown of a large tunnel or underground chamber can be accessed from the base or floor wirelessly using Bluetooth wireless link.

Large instrumentation project sites generally have a large number of sensors spread over a wide area that need to be connected to a central DAS. Connecting all the sensors to the central DAS using copper cables may not be a viable solution due to many factors. However, the distance between most of sensors and the DAS may often be beyond the range of low power wireless links or near line of sight location may not be possible for all sensor locations. A similar situation is also found in tunnel instrumentation as the sensors are spread out over a large linear distance from the face of the tunnel. A curved tunnel section introduces more problems in using low power point to point wireless links.

Digital sensors equipped with ZigBee RF modems allow what is known as mesh networking. The ZigBee modems allow each sensor to get data from its neighbour farther away from the DAS and relay them to another neighbour that is more nearer to the central DAS. The communication links established between the sensors themselves make up what is commonly known as a mesh network. Mesh networks are only suitable for low data transfer rates and the ZigBee modems are increasingly being designed for lower power consumption. This makes the ZigBee mesh networking a good candidate for use in civil engineering instrumentation projects.

For covering very long distances or wide areas, GSM/GPRS modems are used either with individual digital sensors or more commonly with a small DAS that caters to a cluster of sensors deployed at the same location. GSM/GPRS modems leverage commercial cellular phone service provider's network and the internet to relay sensor data to a central DAS or host computer connected to the internet. For using the GSM/GPRS modems it is essential that the sensor location is covered by a cellular service network provider. Using GSM/GPRS modems sensor data can be transmitted to a DAS or host computer even at the other end of the world.

VI. DISTRIBUTION OF PROCESSED DATA OVER INTERNET: WEB BASED DATA MONITORING SERVICE (WDMS)

A civil engineering project during construction phase will have many stake holders who would be interested in the safety status of the project. Typical stake holders would be the project owners, designers or consultants, contractors and site engineering and safety monitoring personnel. For large projects the stake holder's empowered personnel may have offices located hundreds of kilometers away from the actual project site. Consequently there is a need to provide all the stake holders with near real time access to data from safety monitoring instrumentation network irrespective of their actual location.

An important function of safety instrumentation network is providing means for alerting authorized personnel about development of potential hazardous development in near

real time so that remedial actions can be started without delay.

Proprietary software is now available that can be hosted on servers connected to the internet. Softwares like DRISHTI, VDV, TERRAMOVE and TUNNELCAD are capable of collecting data from the various sensors and dataloggers deployed in a project over conventional copper cables, optical fibre cables, or various types of RF links according to a preset schedule. The collected data is added to a database. The software presents the collected data as a set of meaningful graphs or tables in a format appropriate to the parameter or parameters being monitored on demand by the various users from different locations around the world over the internet.

The database management software fetches the historical (including the most current) data from the database, performs the required calculations on the data and presents it to the end users, on demand, in a suitable graphical or tabular format as a web page using a web server. The end user has a lot of flexibility in choosing how and over what period the data is to be displayed.

If different alarm thresholds are defined for the logged parameters, the software can also issue an alert to authorized personnel through e-mail or SMS (Short Messaging Service)

about any parameter or a set of parameters exceeding the preset alarm thresholds. Most software will allow setting up of up to 2 alarm levels corresponding to a general alert that the parameter has exceeded a preset alert level that demands immediate remedial action or the parameter has exceed the safe limits specified by the designer and further work should be stopped.

Cloud based web data monitoring service (WDMS) allows users to monitor project instrumentation data remotely from an internet connected computer located anywhere in the world. It also allows multiple authorized users at different locations to view any data or report from the same project site simultaneously.

An important feature of the WDMS system is the use of GSM/GPRS cellular services to transmit data from the individual data loggers wirelessly to the remote monitoring computer (host). As long as a reliable GSM/GPRS cellular service is available at the data logger site, the data loggers can be located virtually anywhere in the world. WDMS can support multiple data loggers per project site and the individual data loggers can be spread out over a wide geographical area. The database management system also supports data uploaded manually incase manual method of data collection are used.



Fig. 3. Different sensors connected through sdi-12 bus cable to a data logger with web based data monitoring

VII. SOME EXAMPLES OF SITE INSTALLATIONS WITH WEB BASED DATA MONITORING



Fig. 4. Shows typical low power sensors deployed for monitoring civil engineering structures. Picture a sensitive biaxial tilt sensor monitoring a bridge pier suspected of developing a tilt. Black box near the base contains a battery powered data logger with cellular network connectivity. This is an example of a user monitoring isolated problem areas spread over a large area with a few autonomous sensors together with cloud services. Picture b –strain gauge for monitoring stress on a structure. Picture c –water level/piezometric pressure sensors to monitor water level in a river or piezometric pressure in the ground. Picture d –crack meter monitoring a crack in a structure that has started showing signs of movement.

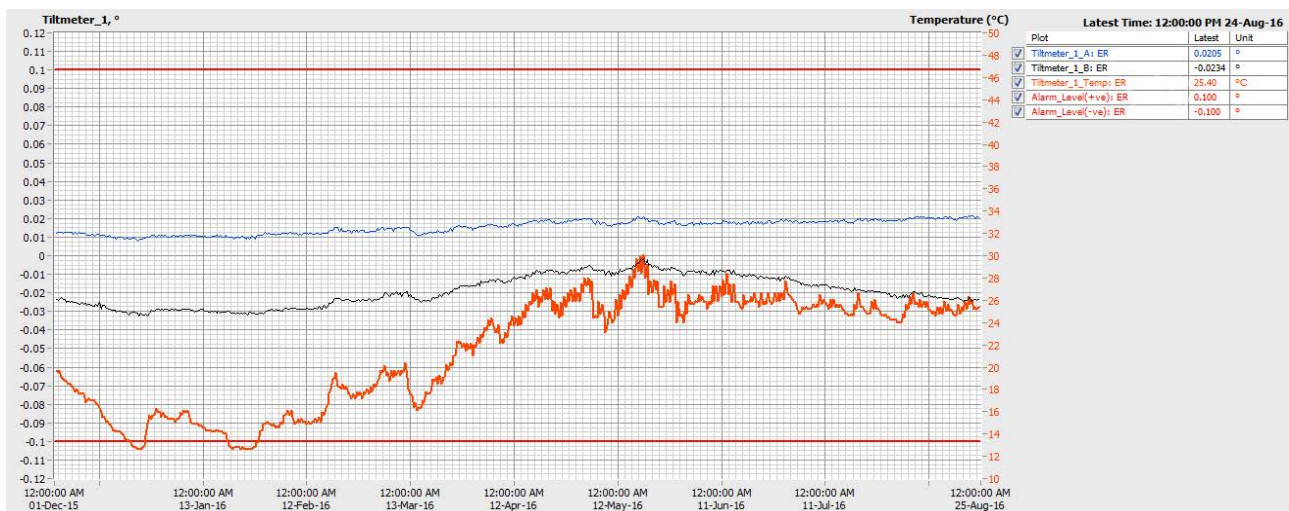


Fig. 5: Screen shot of graph presented by a cloud based data monitoring service showing eight months data of a biaxial tilt sensor sampled once a day at a fixed time. The trace in red showing larger variation is of ambient temperature variation. The other two traces are magnitude of tilt in degrees along two orthogonal axes. The difference between the maximum and minimum value of tilt registered is approximately 0.02 degrees. The two red lines at the top and bottom are alarm limits set for the biaxial tilt sensor.

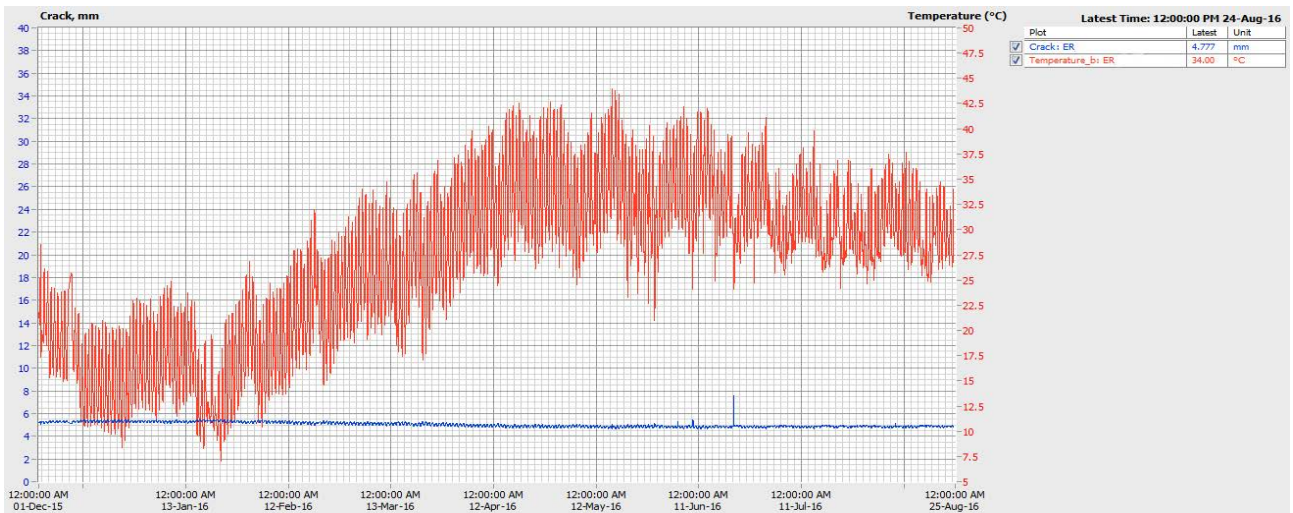


Fig. 6. Shows eight months data of crack meter set at 6 mm to register both closing and opening of crack with time. Band like trace is ambient temperature. As sensor is being sampled every 30 minutes it is tracking variation in ambient temperature over whole day unlike figure5 in which sensor is sampled once a day.

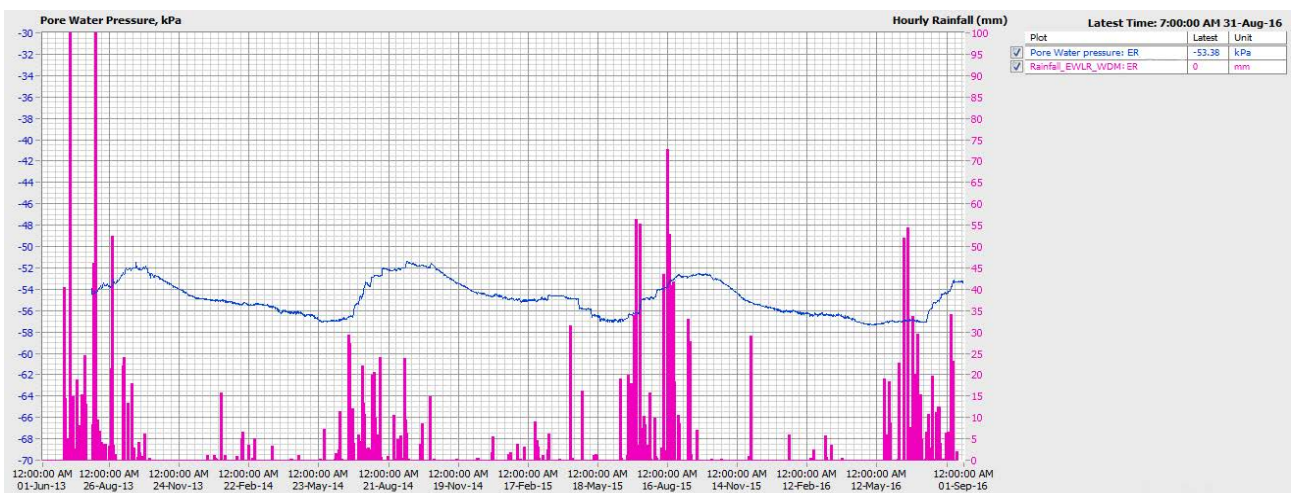


Fig 7. Shows three year's data of changes in ground water table and rainfall. Ground water level is logged four times a day. Rainfall is logged continuously. Data is transmitted once a day to cloud server. Co-relation of variation in ground water level with rainfall can be seen on the graph. Similar instrumentation is used for online automatic monitoring of river water level and rainfall with time.

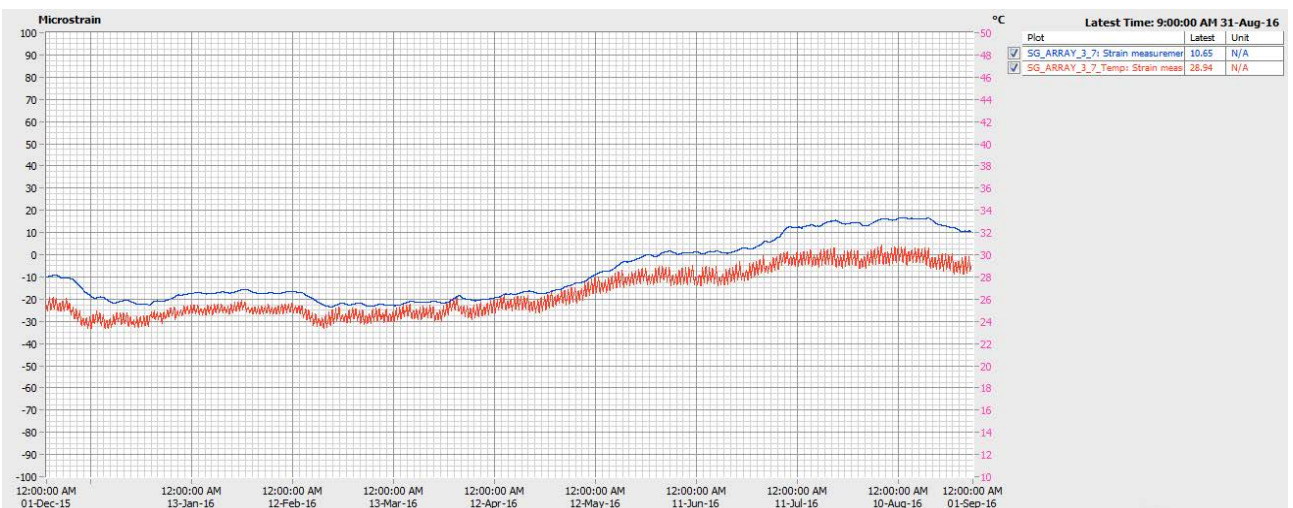


Fig. 8. Shows eight months' data of variation in strain on a structure. It gives important information on changes in strain/stress in the structure with time at that point. The strain values are affected by changes in temperature; so the temperature variation is also plotted for correlation on the graph.

end users do not have to install any special software on their device. the end user can use any device like a laptop, tablet, smart phone with any type of operating system running on their system. as long as the device has a standard web browser the end user can access the site data as well as perform many administrative tasks provided he/she has the necessary privileges to access the site data

VIII. LASER SCANNING

Laser scanning is a new mapping method for geometric documentation of buildings, architectural and archaeological monuments, construction projects (such as tunnels, bridges, dams, etc.) or any other construction which requires a high degree of analysis, is inaccessible or difficult to access or must not be touched. It is based on a very dense three-dimensional coordinate map of the surface areas to be mapped in fast output of several thousand to one million points per second.

The creation of clouds of reference points is the first in a series of other derivatives that someone may derive from laser scans with further processing. Depending on the situation and on the user's needs, horizontal, perpendicular or diagonal sections, views, images, videos, orthophotographs, elevations images, contour equivalents, three-dimensional digital models, designated distortions and a plethora of other analyses can be derived from the scanner in the invisible spectrum.

Laser Scanning is a measuring method where a surface is scanned using laser technology. It analyzes all kinds of objects and collect data on its shape and possibly its appearance (e.g. colour). The collected data can then be used to construct digital, two-dimensional drawings or three-dimensional models useful for a wide variety of applications. Three dimensional laser scanners can measure the same quantities as a total station (horizontal and vertical angles and distances). Instead of providing these polar coordinates for targets selected by the instrument's operator, the laser scanner's measuring head turns to angles by predefined angle steps measuring distance to the object point lying in that direction. Modern laser scanners have very small angle steps resulting therefore in extremely high spatial resolutions. This feature is a huge advantage because of the fact that it can record huge numbers of points with high accuracy in a relatively short period of time

Advantages of laser scanning method

- Non-contact measurement
- Higher accuracy when compared with other known methods
- Faster and more reliable method
- Long range
- Fast data acquisition
- 3D surveying

Deliverables:

- Mapping existing conditions and those "under construction"
- Geometric documentation of the construction

- Quantitative calculation and Volumetric analyses for excavation
- Inspection of open area for passage – designation of obstacle points
- Creation of 2D and 3D products (sections, views, 3D models, TINetc.)
- Ortho photographs
- Tour videos
- Creation of virtual reality
- Creation of high-quality 3D copies
- Databases regarding excavations that shall be refilled
- Creation of models for the building of degraded monuments, statues, devices etc.
- Geometric documentation in association with theoretical models
- Reverse Engineering
- Structural Design
- Contour equivalents
- Graded surface elevations
- Monitoring phenomenal developments with a quantitative designation
- Monitoring the project's progress

IX. AUTOMATED MONITORING SYSTEM (AMS) OF REAL TIME TOTAL DISPLACEMENTS (3D)

An automated measuring system for the total displacements (3D) in real time in zones where the TBM tunneling or other tunnel/station/shaft works might give rise to settlements to sensitive buildings and other structures is described.

The system consists of a series of networked robotic total stations and prisms located along the Project's alignment. This system ensures valuable and timely monitoring of the displacements, providing high measurements density, simultaneous wireless transmission and entry of the results into the database system to ensure minimal time between their reading and their evaluation. The measurements are taken with a series of automatic electronic total stations of high precision, which will record the displacement of reflecting prisms on the ground surface and on buildings.

The robotic total stations are capable of carrying out automatic measurements, both at predetermined sequences and at any arbitrary time and the maximum measurement range is in accordance with the environmental conditions.

The total stations are remotely controlled by software and are capable of:

- Following a pre-programmed operation
- Allowing changes in the measurement regime to be implemented, including the measurement cycle
- Providing continuous data for one point or several points simultaneously.



Fig 9. Laser scanning of a tunnel



Fig. 10. Monitoring by automatic total station (ats)

The system allows the above changes to be made remotely via modems and telecommunication lines. The instruments are capable of self-seeking a point which has moved by up to 30 mm, without affecting the monitoring regime/data return time adversely

X. TUNNEL SEISMIC PREDICTION (TSP)

Seismic methods of predicting rock conditions up to 150 m ahead of the tunnel face have developed and improved significantly in recent times. Predictive range is around three times that can be achieved by probe drilling on the face of the tunnel. Moreover, TSP does not interfere with the tunneling process as the TBM need not to be stopped during the test process. Installing seismic receivers and loading and detonating around 30g explosive charges takes about one hour and can be scheduled during maintenance intervals or short breaks. Boreholes to house explosive charges and receivers are drilled into the side of the tunnel behind the TBM by using ordinary handheld rock drills and without causing disruption to the excavation schedule.

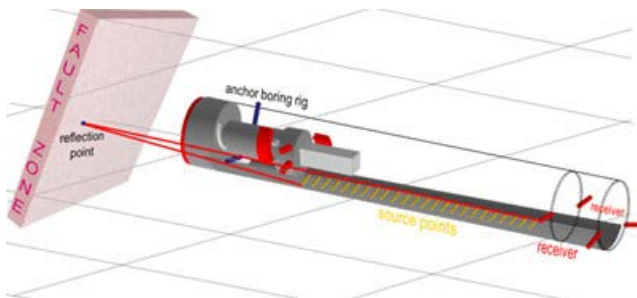


Fig 11. Standard tsp layout in a tbm heading. Acoustic waves are reflected from a geological discontinuity and picked up by receivers

Explosives in adjacent successive holes are fired at fixed intervals and reflection of elastic body waves created as a consequence are evaluated. Body waves travel as compression or shear waves through the ground and are reflected at interfaces with different properties, density or elasticity. Seismic echo signals reflected from changes in the elastic rock characteristics normally associated with discontinuities in rock mass are evaluated. Accurate spatial information concerning the geology and rock mechanical properties in front of and in the vicinity of the face is obtained. It is possible to evaluate data thus obtained in predicting rock conditions including mechanical properties of the ground in front and around the tunnel in the suspected risk zone. In addition, site geologists continually map the tunnel sidewalls to describe precisely the geological features encountered and to classify the rock mass for determination of the rock support.

Some benefits of Tunnel Seismic Prediction are as follows:

- Continuous prediction ahead of the face.
- Spatial positioning of fault zones and potentially water-bearing areas
- Gain time for construction and logistical counter-measures
- Minimise the downtime risk of expensive tunnelling equipment

- Improve safety
- Can be used in both TBM and conventional tunnelling operations
- Profit from shorter construction times and cost savings

XI. FIBRE OPTIC SOLUTIONS

Use of optical fibres is increasing since the past few years to monitor structural health and geotechnical conditions of infrastructure projects within the Mining, Civil Engineering and Geotechnical field of activities. The technology is being innovatively used for monitoring change in strain and temperature using a single optical fibre cable over large lengths and areas at a number of locations in the World.

The sensing cables are specially made. In the fiber Bragg grating (FBG) system a type of distributed Bragg reflector is constructed in short segments of the optical fiber that reflects particular wavelengths of light and transmits all others. This is achieved by creating a periodic variation in the refractive index of the fiber core using an intense ultraviolet (UV) source such as a UV laser, which generates wavelength specific dielectric mirrors. A fiber Bragg grating can therefore be used as an inline optical filter to block certain wavelengths, or as a wavelength specific reflector and translate the phenomena to be measured, e.g. strain or temperature, into a proportional change of the reflected light.

Main components of the systems are the sensor comprising of a specially grating cable, an interrogator unit, a computer, a multiplexer and appropriate software to monitor several sensors at the same time. Most suppliers provide online web based cloud services for evaluating and reporting the data.

Features are:

- Fast installation: Arrays with multiple measuring sections (gauges) in one-cable-design or long-gauge sensors together with simple cable topology reduces installation efforts.
- Intrinsic safety: Together with harsh-environment tolerance and EMI immunity, the intrinsic safety represents the key advantages of the FBG technology.
- Simple set-up: Final monitoring system can be fully tailored to the characteristics of each individual project.
- Integrated software provides automation functions with real-time access via web hosted database. Sensors can be easily customized.

XII. CONCLUSION

This paper highlights the recent trends and advancements in the areas of topographical surveys, sensor technology, laser scanning, surveying using automatic total stations, tunnel seismic prediction, fibre optic solutions, data

transmission, data recording and presentation in field instrumentation employed for monitoring of geotechnical and structural engineering parameters in various civil engineering projects.

Keeping a watch and adopting new technologies can increase accuracy of measurements with reduced costs. Using digital sensors allows many benefits like calibrated outputs, non-degrading accuracy and easy transmission of data over long distances to a remote host computer.

The use of mobile phone as a data collection device can allow the field engineer to carry the equivalent of a phone, camera, location tracking, web browser, training and user manuals, video recorder and playback, and a host of readout units in a single compact palm held device.

Wireless links eliminate the need to connect the installed sensors and the central host computer with cables. In some situations wireless links would be the only solution as laying of cables may not be feasible. An understanding of advantages and limitations of different wireless links will help in choosing the most optimum solution for a particular project.

Adopting a web based data access service will allow all stake holders to have access to safety instrumentation network data and analysis in near real time from anywhere in the world. The system will also allow authorized personnel with authority to initiate suitable remedial action to be alerted to potentially hazardous developments that can give rise to a catastrophe over time. Timely alerts can prevent loss of human lifetime and money due to catastrophic failures.