Current aspects and future roles of geotechnical instrumentation in monitoring the performance of underground structures

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Abstract

Instrumentation used in geotechnical aspect is mainly to monitor the performances of engineered infrastructure earth slopes and the underground support structures. The main purpose is to verify the performance of the underground structures in long-term bases, control the construction procedures, giving adequate warning against any rock displacement or exceeding loads on a rock bolt supports and protection. The paper investigates the recent technologies adapted in instrumentation for monitoring geo technical underground structures and considers new changes in the ways of monitoring in the future and challenges faced in instrumentation and methods to overcome those challenges. The paper also summarizes based on the case studies in special projects on how and where to install instruments. Based on the Q value of the rock and other geotechnical data, the load on the rock bolts provided in these structures can be predicted and almost similar load can be observed in the Load cells. The movement of the rock mass can be predicted based on the joints pattern obtained from the face maps and instruments like Multipoint Bore Hole extensometers or Magnetic extensometers can be installed at required locations. The weak zones can be identified based on the geo- maps obtained and the Q value of the rock mass so that the maximum load over the underground structures and displacements which are predicted at a specific location can be measured precisely using the instruments installed and the same can be verified for the back analysis with the assumed design.

1. Introduction:

This paper will emphasize the various Geotechnical instruments that are used widely as a complementary tool in monitoring man-made structures and also the monitoring techniques employed in underground structures and the future of monitoring by using optical fiber cables (OFC). The transducers commonly used in geotechnical instrumentation are first introduced. This is followed by an introduction of the various types of instruments including their working principles and applications. The advantages and disadvantages of geotechnical instruments when compared with geodetic methods in structural monitoring are discussed.

In this paper the measurement of parameters and their influences on the structure will be discussed. The parameters like deformation, convergence, divergence, tunnel closure, load transfer on the support installed, pore-water pressure , stress field, surface settlement, horizontal displacement/ deformation, ground water level, blast vibration , redial & tangential support pressure and strain measurement. This paper also focused on the methods which make possible the determination of absolute displacement with the help of instruments like MPBX (Multipoint Borehole Extensometer)/ Magnetic

Extensometer with multiple points of measurements, Instrumented rock stress meter (IRB), Load cells, Pressure cells, Stain gauges, Vertical/ horizontal inclinometers and geodetic targets and crack meters for the deformed surface resulted cracks. As such field instrumentation for support and lining design is gaining popularity among both designers and construction engineers with little hesitation due to initial hindrance to construction progress. Of course, eventually the construction engineer did realize the net saving in the time of completion of tunnel resulting to the reduction in the number of tunneling hazards and cost overruns.

2. Rock mass evaluation :

The Q-value (rock mass quality) was originally developed to assist the design of tunnel and cavern reinforcement and support. In recent years, it has been used for other considerations in rock engineering. This paper explores the application of Q and its component parameters, for prediction, correlation and extrapolation of site investigation data. The general application of the Q value in rock engineering is for selecting suitable combinations of shotcrete and rock bolts for rock mass reinforcement and support.

The Q-value is estimated from the following expression:

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF}$$

The strength and deformation properties of a rock mass are governed by the existence of joints. These rock mass properties are also related to the quantity of rock mass. In general, a rock mass of good quality (strong rock, few joints and good joint surface quantity) will have higher strength and higher deformation modulus than that of a poor rock mass. There are three major types of sensors being used in the industry to measure the criteria's of geotechnical parameters.

3. Tunnel Mapping:

Tunnel mapping is mainly performed after excavation of the tunnel and is also performed once in every three blast to see if the rock is good enough or every blast if there is a necessity to support the rock mass after each blast. This face mapping gives the actual rock mass quality value that is going to be used to assess the rock support necessary to perform a safe excavation. In the below figure, an illustration of the parameters used to describe the discontinuity characteristics in the rock mass is presented.

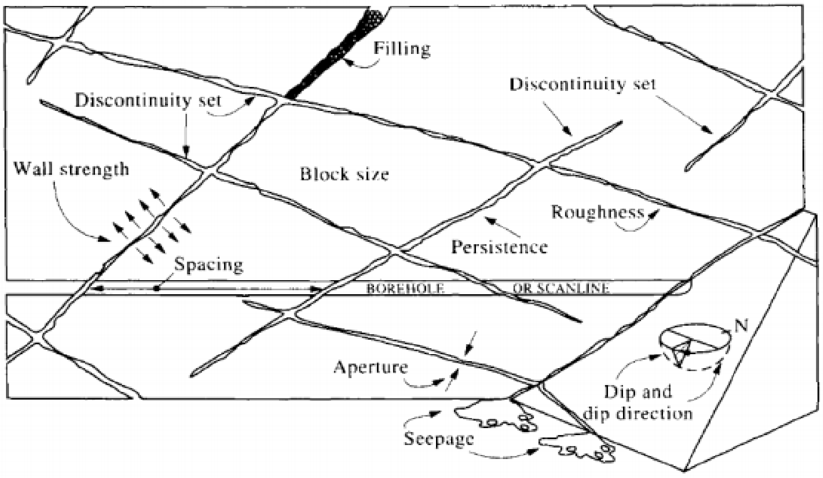

Figure 1 Schematic of the primary geometrical properties of discontinuities in rock

So from these Face maps and Q value the type of rock mass and the joints, shear zones can be predicted and based on these predictions, the instruments like Multi point bore hole extensometer, Piezometers, Magnetic extensometers and load cells can be installed.

4. Behavior of Rock Mass:

The rock squeezing behavior is represented plastically deformation of rock mass into the opening. The squeezing rate is time and stress dependent. Usually at initial stages, the rate is high several cm/day and then gradually reduces with time. These deformations are most likely to be captured by Bi- Reflective Targets.

5. Types of transducers used in Geotechnical Instrumentation:

5.1 Mechanical transducers:

Dial indicators and micrometers are the two most used transducers for mechanical measurements. The liner movement of a spring-loaded plunger is converted in to the movement of a pointer which rotates above a dial by a dial indicator. Displacements are measured by a micrometer by measuring the rotation of a finely threaded plunger when it travels in or out of housing.

5.2 Hydraulic Transducers:

The hydraulic transducers are used for measuring pressure and stress. There are two basic designs: the Bourdon tube pressure gages and manometers. A Bourdon tube is made by coiling a metal tube into a C-shaped configuration. The changes in curvature of the tube is measures the liquid pressure. A manometer uses a U tube where pressure on one side of the U-tube is balanced by an equal pressure on the other.

5.3 Electrical resistance transducers:

Electrical resistance transducers use the basic property that the resistance of the conductor is directly proportional to the change in the length of the conductor.

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} \times GF$$

Where,

$\frac{\Delta R}{R}$ is the relative resistance change,

$\frac{\Delta L}{L}$ is the relative change in length,

GF is the Gage Factor

Generally a Wheatstone bridge circuit is used to measure the output from electrical resistance gages.

5.4 Linearly Varying Displacement Transducers (LVDT):

A linear variable differential transformer consists of a movable magnetic core passing through one primary and two secondary coils (Fig. 4). When an excitation voltage is applied to the primary coil an AC voltage is induced in each secondary coil whose magnitude depends upon the relative position of the core magnets and secondary coil. The changes in the voltages of the secondary coil measure the displacement of magnetic core. Most LVDTs used in practice use this approach since it is often troublesome to get AC power supply in the field.

5.5 Potentiometer:

A potentiometer consists of a fixed resistance strip and a movable slider that makes electrical contact along the resistance strip. The measured resistance or voltage changes with the position of the contact point.

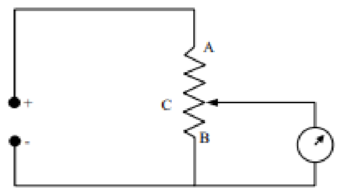

Figure 2 Circuit diagram of a potentiometer

5.6 Vibrating wire transducers:

A steel wire is clamped at its two ends. The frequency of vibration of the wire changes with its tension. Small displacements between the ends of the wire can therefore be measured by measuring the frequency changes. The frequency of vibration of a tensioned wire in terms of the wire stress is

$$f = \frac{1}{2L}\sqrt{\frac{\sigma g}{\rho}}$$

Where,

f is the natural frequency,
L is the length of the vibrating wire,
σ is the stress in the wire,
ρ is the density of the wire material,
g is the acceleration due to gravity

The electrical coil usually serves two purposes, plucking the wire and sensing the vibration of the wire in the same time. Some vibrating wire transducers can continuously carry out the measurement while the others measure only at discrete times

6 Instruments for Measurement of Deformations:

There are a many geotechnical instruments that have been developed for deformation measurements. These include extensometers (mechanical and electrical), inclinometers, tilt meters.

6.1 Extensometers:

Extensometer is used to measure the relative movements between anchors or points and movements across a crack, inside or on the surface of a slope. Based on the conditions of applications extensometers are made of materials such as steel tapes and wires, tensioned or un tensioned steel rods, and fiberglass. Extensometers usually use mechanical micrometers, electrical resistance and vibrating wire transducers. Most extensometers currently in use have a digital readout. Readings can be taken by site personnel, or can be stored in an electronic data logger and transferred to a computer afterwards. Measurement ranges of the available extensometers vary from a few centimeters (crack meters) up to around 180 m (tensioned rod extensometers). Most in-wall extensometers extend to about 30-40 m. Accuracies of better than ± 0.1 mm can be achieved, though the effects of temperature and wind can have adverse impact on the accuracy of an individual reading.

6.2 Inclinometers:

Subsurface lateral displacement of soil or rock is measured using Inclinometers. An electrical probe is lowered through a tube casing to the base of a vertical borehole. This probe is then pulled up and the inclination information of the tube is measured by the probes in two orthogonal planes which is registered at definite intervals. From this the, profiles of the borehole in the two planes can be derived and reviewed graphically. The lateral displacements of the borehole can be determined by comparing the measured profiles of the borehole obtained at different times. In practice it is usual to extend a borehole into stable ground in order to have a common reference point to compare borehole profiles for determining displacements. Servo-accelerometers are usually used as the sensors in an inclinometer probe which are also used as tilt meters. The inclinometer probes can achieve a sensitivity of ± 0.02 mm per 500 mm. Inclinometers are ideal to measure the lateral displacements occurring within a slope. However, it is difficult to fully automate the process of measurement with inclinometers.

6.3 Tilt meters and Electro levels:

The rotational deformation at specific locations on a structure can be measured by tilt meters. An electronic clinometers can give a resolutions of 1.75 - 0.01 micro radian (0.36 - 0.002 arc seconds). However, the high cost of these instruments mean that they are not widely adopted.

7 Instruments for Measurement of Load, Stress and Strain:

Instruments that measures load, stress and strain depends on the use of transducers to sense the small extensions or compressions caused by the load or by the deformation of the monitored object. Load cells, are installed in the tunnel structure in such a way that the structural forces pass through the cells. Based on the types of transducers in the load cells, there are mechanical load cells where dial gages are used, hydraulic type load cells, which has a pressure transducer connected to a liquid-filled chamber, electrical load cells which uses strain gages, vibrating wire load cells that use vibrating wire transducers. Most of the load cells have an accuracy of about 2-10% FS. Load cells are widely used to monitor loads in testing piles, rock bolts and drilled shafts.

Figure 3 Vibrating wire load cell

Strain gage type are often attached to the surface of a structure or embedded within the structure. There are also mechanical, vibrating wire and electrical resistance strain gages beside some other specially designed ones. There are five basic types of electrical resistance strain gages: bonded wire resistance strain gage, unbounded wire resistance strain gage, bonded foil resistance strain gage, semiconductor resistance strain gage, and the wieldable resistance strain gage. The measurement range, sensitivities and accuracies of the strain gages vary from one to another. Stress in rocks can be measured using pressure cells and stress meters that use vibrating wire transducers. It is also common to measure stresses directly by measuring deformations.

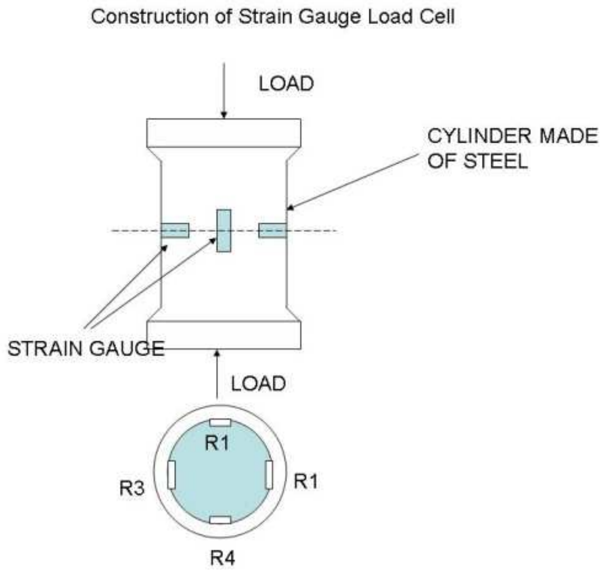

Figure 4 Strain Gauge type Load Cell

8 Instruments for Measurement of Ground Water Level and Pore Water Pressure:

Ground water level can be measured with a standpipe. Various instruments that are based on the use of mechanical, electrical, acoustic and pressure sensing gages can be used for this purpose. The mainly used ones include steel tape, dip meter, audio reader, and Piezometers. Piezometers are used to measure ground water pressures. They are used in an open standpipe, sealed in filled embankment, or driven into ground. The central part of a Piezometer is a pressure gage, with a mechanical or electrical or hydraulic or pneumatic transducer and based on the transducers used, there are vibrating wire Piezometers, twin-tube hydraulic Piezometers, electrical resistance Piezometers, Multipoint Piezometers can also be used to measure water pressures in different strata of the ground. Fig. 5 shows an example of such an arrangement. Piezometers are used in monitoring slopes, dams and underground constructions.

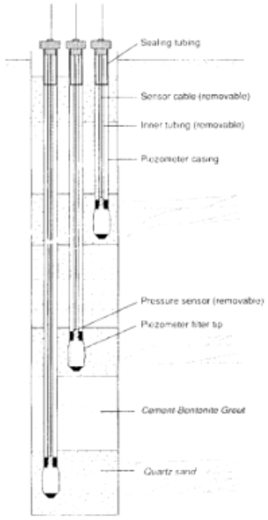

Figure 5 Multi-Point Piezometer

9 Comparison with Geodetic Methods:

On comparing with geodetic methods for structural monitoring, geotechnical instrumentation has the following advantages:

a) Geodetic methods are usually limited to deformation measurement, while geotechnical instruments can determine many other types of useful parameters such as load, stress and ground water pressure beside deformation measurement.
b) Geotechnical instruments make them very useful for applications as slope monitoring where information on the deformation inside a slope is often more important.
c) Most geotechnical instruments can output electrical signals and therefore be easily linked to an automatic monitoring system.
d) Very high measurement accuracy is possible using geotechnical instruments.

Geotechnical instruments also have their limitations:

a) Most deformation measurement instruments such as extensometers and inclinometers can only measure relative displacements within certain ranges.
b) Geotechnical instruments needs careful, complicated and expensive installations by experienced personnel before they can be used. The time delay in installation is also lengthy. When an instrument malfunctions, it's difficult be repaired or replaced.
c) If manual reading mode is used, the operator often needs to physically get to the site each time when data is collected.

10 Internetworking of Geotechnical Instruments:

Usually the geotechnical instruments that are installed in the carven or tunnels are standalone instruments, where the monitoring becomes a tedious task especially when the numbers of instruments installed are more. Generally, these instruments are all monitored

by personnel reaching each of the instruments location and measuring the deflections or deformations or loads by using data loggers. In addition, these values that are stored in the data logger are fed back into the system to get the desired results.
When considering four point MPBX (Multi point bore hole extensometer) of a vibrating wire type, they will generally have four wires from all the transducers for measuring the relative distance from the wall of the tunnel to the four anchors. Therefore, these four transducers are all having 4 different gage factors which are fed into the data loggers, and the vibrating wire frequency is captured into the data logger, which converts it to the respective displacement in mm based on the frequency. This data logger is then connected to a personal desktop where the data is fed from data logger and then the data is processed into information.

This process becomes very tedious when the numbers of instruments installed are in large quantity. Hence networking must become mandatory. Generally all the geotechnical instruments in practice are connected using hard wired 40 core cable. These 40 core cable are connected to a junction box, and from the junction box it is taken to the main server room where the data loggers are available and then it is transferred to the servers.

The major disadvantage of using 40 core cables is that when the number of instruments are more, then the quantity of 40 core cable increases.

From the conventional ways, there are other methods that can be employed for monitoring and networking of geotechnical instruments.

10.1 Wireless internetworking:

In wireless internetworking, the geotechnical instruments which are having a particular channel numbers are connected to a battery source that triggers electrical signals to strung the vibrating wire instruments and this obtained frequency is collected in a small storage memory card. This memory card collects the frequency of the vibrating wire instruments, then given to a GSM Module. This GSM module transfers the messages to the required sim which is connected to a data logger. GSM (Global System for Mobile communications) module is basically a modem which accepts a SIM card and works in the GSM network provided by the operator just like a mobile phone. The GSM module can be controlled by a computer or a microcontroller to do different tasks in the network such as calling, sending messages, accepting messages, sending FAX etc. The GSM module usually communicates with the parent hardware by means of serial communication. If the parent hard ware is a data logger then, the communication is usually done through the serial port (RS232) and if the parent system is microcontroller based, the communication is through the TTL pins Rx and Tx. This will directly get the readings at specified intervals of time. The Sim-cards can be programmed in such a way that the instruments that are near the face of the tunnels or the instruments that are crossing the limits can be monitored on daily bases so that the information from these instruments can be studied and can be used for analysis. Advanced GSM modules may even have Bluetooth or Wi-Fi connectivity.

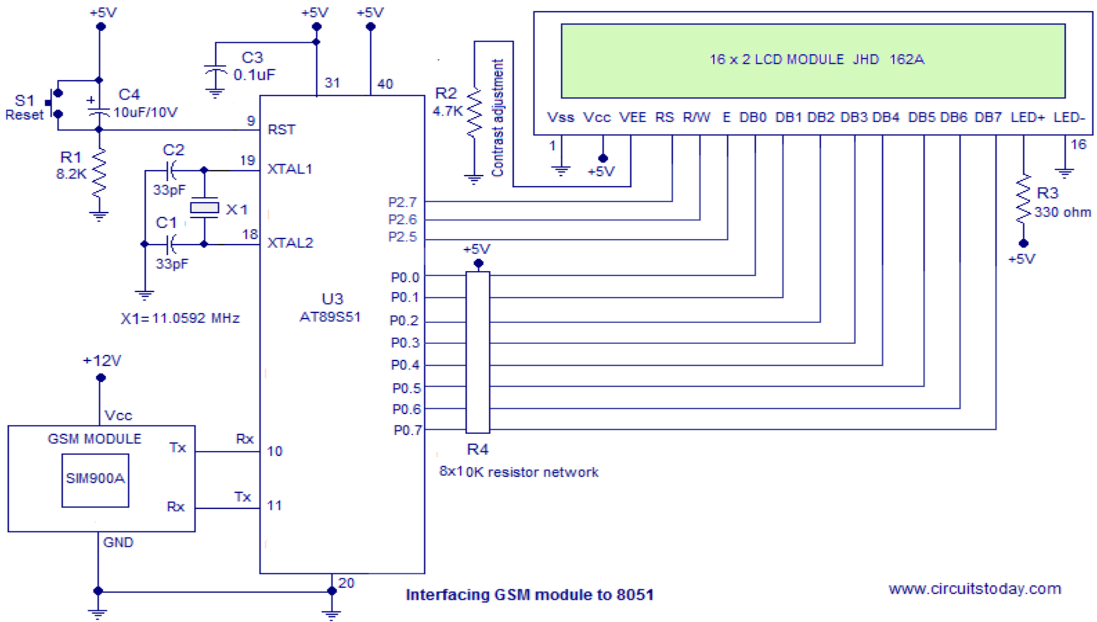

Figure 6 Circuit Diagram for interfacing GSM Module to 8051 Microcontroller

The circuit diagram for interfacing GSM module to 8051 microcontroller is shown above. Here the GSM module and the microcontroller communicate in between using serial communication. Rx pin of the 8051 is connected to Tx pin of the GSM module and Tx pin of the 8051 is connected to the Rx pin of the GSM module. The **LCD module** is involved to give an indication message when the SMS is sent. Switch S1, capacitor C4 and resistor R2 are associated with reset circuit of the microcontroller. Capacitor C1, C2 and crystal X1 are associated with clock circuit. C3 is just a noise by-pass capacitor. Resistor R2 is used to set the contrast of the LCD display. Resistor R3 limits the current through the back light LED.

10.2 About the Program:

1. Timer 1 of the 8051 is configured Mode 2 for serial communication.
2. Timer 0 of the 8051 is configured as Mode 1 timer for creating few delays used in the program.
3. The next part is controlling the GSM module for performing our task which is to send a predetermined message to a given mobile number. For this, first you need to send the command AT to the GSM module for checking the status.
4. Next you have to send the command AT+CMGF=1 to the GSM module for configuring the GSM module in the SMS mode.
5. Next you have to send the command AT+CMGS=”mobile number” to the GSM module for sending the target mobile number to the GSM module. The format is AT+CMGS=”mobile number”/r.
6. GSM module for configuring the GSM module in the SMS mode. The format is AT+CMGF=1/r.

7. Then you need to send the message text to the GSM module. This is done by sending the ASCII code of each letters in the text to the GSM module one after another.

10.3 Advantages of using GSM Modules:

The GSM modules available in the market comes with different supply voltages like 12V, 9V, 5V etc. The module I am using here operates on 12V. So give the power supply to the module according to your GSM modules datasheet.
The GSM module requires some time to get in to the network after it is switched ON. There will be an indicator LED on the GSM module for this purpose. In most GSM modules the network indicator LED starts blinking in a fixed rate when the GSM module is ready to use.

Make sure that your SIM card has enough cash balance and it matches with GSM module you are using.

11. Wired networking using Fiber optical cables:

A fiber optic cable is a network cable that contains strands of glass fibers inside an insulated casing. They're designed for long distance, very high-performance data networking, and telecommunications. Compared to wired cables, fiber optic cables provide higher bandwidth and can transmit data over longer distances. Fiber optic cables carry communication signals using pulses of light generated by small lasers or light-emitting diodes (LEDs). The cable consists of one or more strands of glass, each only slightly thicker than a human hair. The center of each strand is called the core, which provides the pathway for light to travel. The core is surrounded by a layer of glass called cladding that reflects light inward to avoid loss of signal and allow the light to pass through bends in the cable.

The two primary types of fiber cables are called single mode and multi-mode fiber. Single mode fiber uses very thin glass strands and a laser to generate light while multi-mode fibers use LEDs. Single mode fiber networks often use Wave Division Multiplexing (WDM) techniques to increase the amount of data traffic that can be sent across the strand. WDM allows light at multiple different wavelengths to be combined (multiplexed) and later separated (de-multiplexed), effectively transmitting multiple communication streams via a single light pulse.

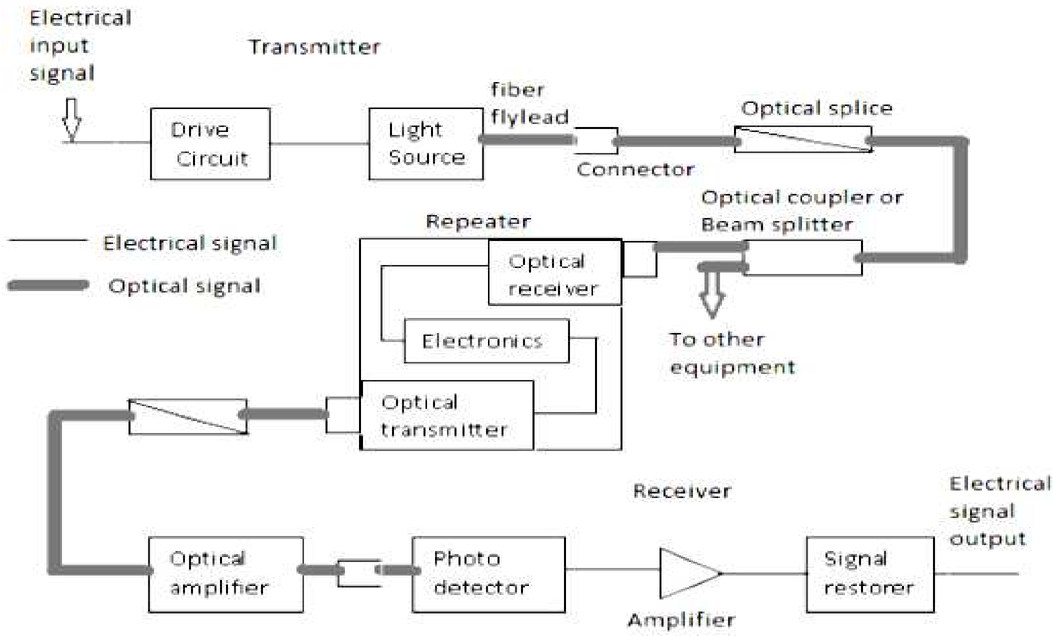

Figure 7 Circuit Diagram for optical networked instrumentation

Initially the electrical signal from the instrument is given to a drive circuit. This drive circuit is responsible for driving the light source. This drive circuit drives the light source very proportional to the electrical signals received. This Light source converts electrical signal to optical signal.

Fiber fly lead is used to connect optical signal to optical fiber.

Transmission channel: It consists of a cable that provides mechanical and environmental protection to the optical fibers contained inside. Each optical fiber acts as an individual channel.

Optical splice is used to permanently join two individual optical fibers.

Optical connector is for temporary non-fixed joints between two individual optical fibers.

Optical coupler or splitter provides signal to other devices.

Repeater converts the optical signal into electrical signal using optical receiver and passes it to electronic circuit where it is reshaped and amplified as it gets attenuated and distorted with increasing distance because of scattering, absorption and dispersion in waveguides, and this signal is then again converted into optical signal by the optical transmitter.
Receiver: Optical signal is applied to the optical receiver. It consists of photo detector, amplifier and signal restorer.

Photo detector converts the optical signal to electrical signal.

Signal restorers and amplifiers are used to improve signal to noise ratio of the signal as there are chances of noise to be introduced in the signal due to the use of photo detectors.

For short distance communication only main elements are required.
Source- LED
Fiber- Multimode step index fiber
Detector- PIN detector

For long distance communication along with the main elements there is need for couplers, beam splitters, repeaters, optical amplifiers.

Source- LASER diode
Fiber- single mode fiber
Detector- Avalanche photo diode (APD)

11 Conclusions:

By using these major networking techniques, the deformations in the tunnels can be monitored at a faster rate and the human errors can also be eliminated up to certain limit so that the exact data can be obtained which can be used to get the real information.

References:

1. Mandal A., Kumar C.,Usmani C. and Nanda A. (2014) " Geotechnical Monitoring to safe excavation of large rock cavern " International symposium on automation robotics in construction and mining (ISARC 2014)
2. Codes & standards: IS 14248-1985 Guidelines for instrumentation of barrage and weirs.
3. ASTM: 6230- Standard test method for monitoring ground movement using probe type inclinometer.
4. ASTM: 4403- Standard Practice for Extensometers used in Hard Rock.
5. Bieniawski, Z.T. 1989. Engineering rock mass classification. John Wiley & Sons. New York, 272 p.
6. Xiaoli Ding and Hui Qin "Geotechnical Instruments in Structural Monitoring"
7. Govind P. Agrawal. Fiber optic communication, Third Edition: Jhon Wiley & Sons. New York
8. Gordon L. Stüber. Principles of Mobile communication, Second edition: Kluwer Academic publishers New York