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Development of Software for Real-Time Instrumentation, Monitoring and Interpretation of Tunnels and Other Civil Engineering Structures

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Abstract. Tunnels and other civil engineering structures are multi-purposes structures fulfilling several needs of the society. These are capital intensive structures and their failure can be catastrophic. Instrumentation for monitoring behaviour of these structures both during construction and in operation is crucial from its safety point of view and is considered an important activity integral to the Project. Though the necessity of instrumentation is well understood at all the levels right from stake owners to implementing agencies, the level of implementation is generally confined to the instrumentation during construction stage only; that also limited to fundamental requirements. With the advancement of technology and realizing criticality of real-time monitoring and interpretation of data, the need for development and implementation of advanced monitoring and presentation tools is realized. This paper presents the development of real-time monitoring techniques and discusses its various features that highlight certain additional specific features that have been addressed. The features developed in the software include continual monitoring during design life to ensure functionality in light of the inevitable ageing and degradation resulting from operational environments; providing warning against impending failures; mitigation aids like triggering warning alarms at different levels; real-time visualization of sensor data and location; integration of data from all sensors including geodetic sensors, geotechnical sensors, seismic sensors, etc. The paper also specifies certain parameters, which if monitored can provide warning against any impending failure. The paper also discusses the importance of planning and discusses various steps involved in designing any successful monitoring scheme for Tunnels.

Keywords: Tunnels; Dams; Instrumentation and Monitoring.

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1 Instrumentation of Tunnels

1.1 Introduction

It is very important that a proper structural monitoring scheme is implemented in each tunnel and the interpretation of data be done meticulously as soon as it starts becoming available.

Monitoring involves collecting observations from various sensors planted at different locations on various components of the structure. This activity is carried out over a specified period, or in the case where any other activity may affect the behaviour of tunnels. Periodically sampled response measurements from an array of sensors installed at various locations in the tunnel are used to extract damage sensitive information which is subsequently followed by its analysis to determine the current state of structure health and to ensure the ability of the structure to perform its intended function.

The prime motive behind any monitoring system is safety and economy. However, there are several other reasons why instrumentation is provided in large civil engineering structures such as tunnels. One of the biggest advantages of implementing a successful monitoring system is to have a warning against an impending failure so that adequate remedial methods could be undertaken, and the problem can be fixed well in advance. Other advantages include evaluating critical design assumptions, control construction and operation procedures, prevent possible damages to adjacent structures, enhanced understanding of the behaviour of tunnel under design loading conditions, optimizing design, etc.

One of the emerging reasons for providing instrumentation is due to the increase in litigation cases. Even though this aspect and the importance of the instrumentation and monitoring was understood at a very early stage and Terzaghi and Peck highlighted the same by adding a new chapter in the second edition of their book "Soil Mechanics in Engineering Practice", 1967 and the chapter was called "Performance Observations". They were the first people to point out that the documentation of the monitoring soil and structural performance during construction work could be used to provide evidence in lawsuits. It was stated that a fair decision could be expected only if the causes and the nature of the mishap were known. If the contractor or owner could prove that he had anticipated the undesirable condition, has observed its progress during construction, and had done everything possible to avoid it, he would be in a much more favourable position than if the condition had taken him by surprise. The element of surprise not only injures his professional reputation, but it may also injure his financial standing. This aspect of doing 'everything possible' is termed as applying 'due diligence' in the jargon of the insurance world.

1.2 Instrumentation of tunnels

Underground excavations tend to close under the in-situ stresses of the surrounding rock mass and, depending on the ground characteristics, this may lead to either reduction of the excavated area or collapse, either of which is not desirable. Therefore, a basic requirement for the success of the excavation of an underground opening is to monitor its deformation during excavation and to control it before it reaches the limits of instability. Modern methods of underground excavations are based on the principle of controlled deformation rather than no deformation or too much deformation. This is achieved by establishing a detailed monitoring system which not only records the deformations during excavations but also indicates the need for additional supports if the convergence exceeds certain limits. Incidentally, it also tells us about the adequacy of the support system being deployed for the reach which depends upon several factors such as in situ stresses, rock mass characteristics, method of excavation etc.

The monitoring requirements of any structure depends on a large number of Technical, Practical and Commercial considerations and a lot of instrument find their requirements in various applications related to the construction of tunnels. The objective of a monitoring scheme is to select the most sensitive parameters that will change significantly before any failure. This can provide early warning of many conditions that could contribute to tunnel failures and incidents. Accordingly, some of the parameters that are usually monitored in tunnels are Convergence of Tunnel, Deformation of Rock Mass, Load on a support system, Stresses & Strains, Porewater Pressure etc. Typical monitoring section of tunnels is presented in Figures 1 to 3.

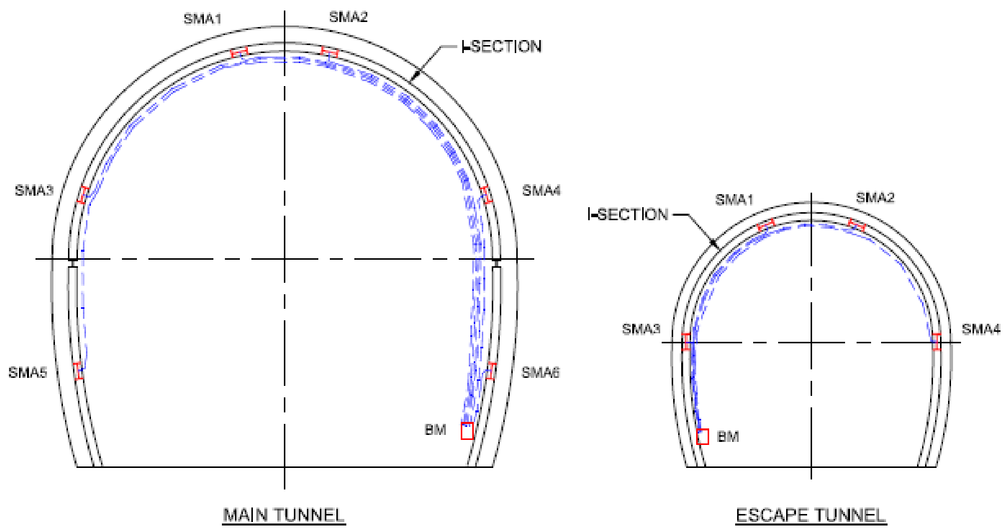

Fig. 1. Typical Monitoring section for installation of Arc Wieldable Strain Gauges on Tunnel Support.

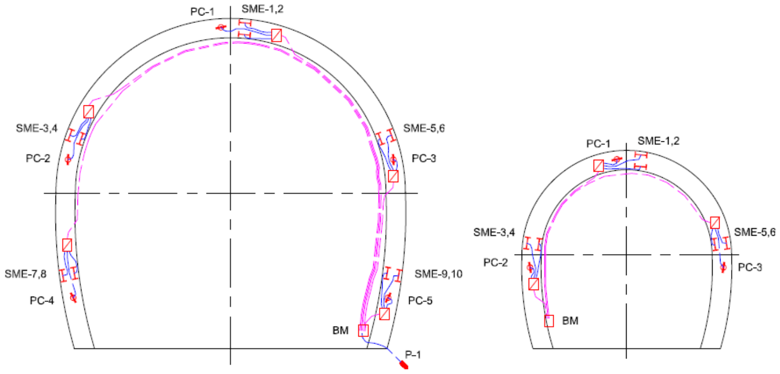

Fig. 2. Typical Monitoring section for installation of Embedment Strain Gauges, pressure cells in tunnel lining and piezometer in surrounding rock mass.

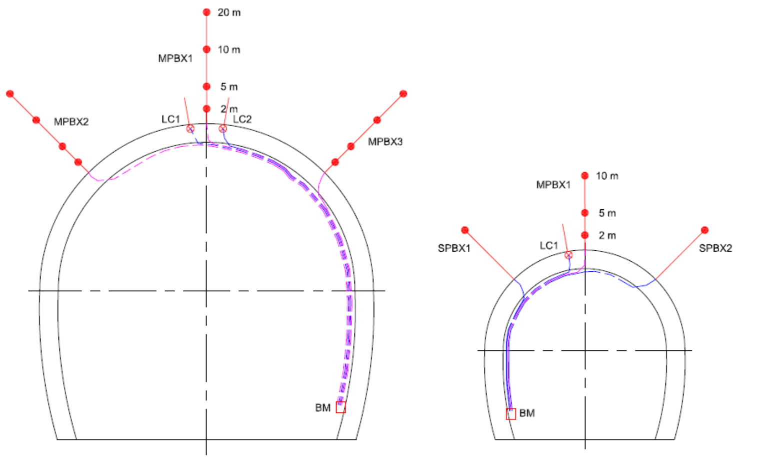

Fig. 3. Typical Monitoring section for installation of Multi-Point Bore Hole Extensometers in surrounding rock mass.

2 Development of Software

2.1 Current practices of monitoring

The current practice of instrumentation scheme adopted for tunnels is generally in line with the project technical requirements and adequate instruments are being installed at critical locations of the tunnel; however, there is a big lag in the time of recording and the time of analysis of records (of the order of more than 15 days in many cases).

Such a big time lag renders the analysis ineffective and in absence of effective analysis of data, the instrumentation records correspond to a data-rich and knowledge-poor environment, with streams of data from multiple sensors at multiple locations throughout the structure that are recorded at discrete, although not necessarily uniform, time intervals.

2.2 Need for improvement

The instrumentation and monitoring scheme being adopted for monitoring of most of the tunnels in India satisfies the fundamental requirements of reading the sensors, processing the recorded values, and distributing the results amongst all concerned. Answer to the fundamental requirements is relatively easy and involves installing sensors at specified locations, deciding for taking readings manually and recording the response of sensors. However, in addition to these fundamental requirements, there is a specific requirement of reading the sensors real-time and providing daily reports and at the same time keeping the costs in defined budgets. The current scheme does not cater to these specific requirements. The instruments installed and the readings obtained are essentially useless until they are processed, presented graphically, and distributed; and this is where the real challenge is. The real benefit of any monitoring system lies in analyzing the readings well in time and distributing the results to all concerned so that necessary actions may be taken.

Field monitoring of civil infrastructures demands the integration of several levels of legacy hardware and software within the realm of structural health monitoring. It is required to ensure that the data is relevant and must answer specific questions relating to the site. The system must be capable to establish in real-time that the data being recorded is accurate and reliable. The schematic configuration for automatic monitoring system is presented in Figure 4.

Fig. 4. ARMS Software

In the current system being developed; all the sensors are installed in the field and are connected to a data logger through cables which are programmed to record the readings at a specified interval of time. The number of data logger units depends on the number of sensors installed, their respective locations and distances, availability of an adequate number of cables and cable protection systems etc. The signal conditioning can be performed either in centrally at observation room (Figure 5) wherein data logger and multiplexers are placed and all the sensors are connected to observation rooms by 40 core cables; or the conditioning can be performed locally (Figure 6) by installing 5/10 channel bus multiplexers, data from which is further transmitted to observation room through a single 8 core cable.

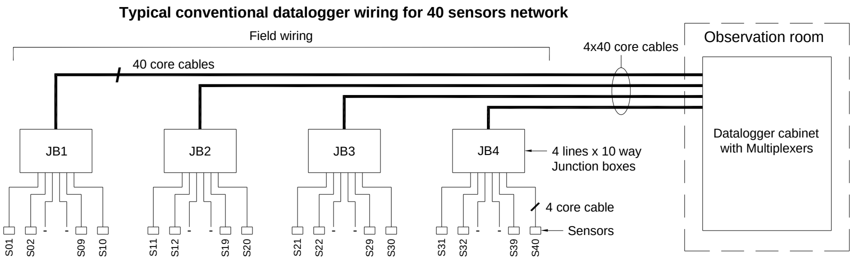

Fig. 5. Typical conventional data logger wiring for 40 sensors network

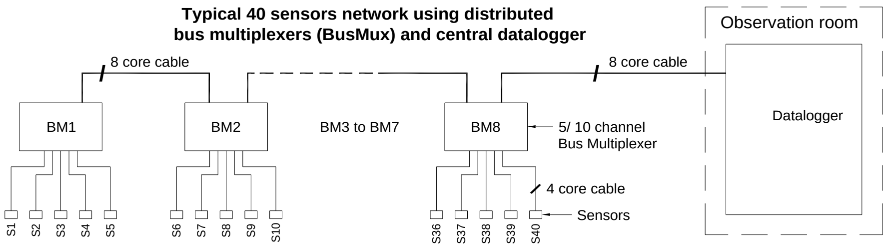

Fig. 6. Typical 40 sensors network using distributed bus multiplexers and central data logger

2.3 Advantages of Real-Time monitoring

Some of the advantages that are derived by installing the new system capable of monitoring the structure in real-time are listed hereunder:

Data will be available real-time to all concerned. In Current System reports are prepared & submitted in several copies by the contractor once a week/once a month which is then forwarded to the consultants for their expert opinion and advice. By that time the construction work progresses further because of which swift decision for implementation/correction if required cannot be taken With new Automatic Data Acquisition System (DAS); all data will be made available real-time to all stakeholders.

Limitations of spreadsheets. The data thus forwarded to consultants who mostly analyses them using in-house developed spreadsheets. Though these spreadsheets can analyze the structure; processing data is not as easy and cost-effective as it looks like.

They are swamped with data and have file management problems. Some other limitations associated with spreadsheets include

Processing time lag. There is usually a time lag from the time of recording the readings to the time when the concerned have ready information on their interpretation.

Expensive to set up and operate. A lot of manpower is required for recording the data and input it in the spreadsheets, analyzing the results and preparing word/PDF reports.

Limited Data Capacity. They have got limited data capacity and no of sheets in a spreadsheet and spreadsheets go on increasing with the progress of readings.

Alarms not possible. The spreadsheets cannot be programmed to send alarms in situations where the recorded values cross their design values
It is not possible to prepare PDF reports in spreadsheets and distributing the same to all concerned.

Non-Working sensors identification. In case of new automatic data acquisition system; the non-working sensors can be detected immediately. This will create situational awareness and tactical methods could be deployed to make up for the lost sensor.

Less manpower. Manpower not required for collecting the reading manually using the read-out unit.

Elimination of human errors. In case of manual monitoring, even if we adopt the best of our people and equipment; the possibility of manual error cannot be ruled out. However, the same is not a concern about adopting automatic monitoring.

Possible monitoring after tunnel completion. It is observed that in case of manual monitoring; the sensors are not being monitored after the tunnel has been lined. This is underutilization of a lot of resources that are embedded in a tunnel in the form of sensors. This issue can be overcome by adopting new automatic data acquisition systems. In that case, the tunnel can be monitored indefinitely even after the tunnel is opened to traffic at a very minimal cost.

Increased monitoring frequency The monitoring frequency is kept as once a day during initial stages, which reduces to once a month with the progress of works. Although the readings of most of the instruments get stabilized with the progress of works and there is no change with time, but this is true only till there is no accident or till all the materials behave as predicted. By adopting automatic monitoring the frequency of readings can be kept constant throughout the project duration and for any time even after completion of the project. Not only that, but the frequency of the readings can also be increased from once a day to say once every hour. No doubt the data generated in that case will be enormous, but commercial software is available for handling the same.

Triggering alarms. It is possible to set 3/4 alarm levels in this commercially available software so that the system automatically generates SMS/email message to the concerned persons in case any instrument reads a value which exceeds the pre-specified value of that parameter due to normal or extreme loading conditions. This may prevent many accidents and there are can also prove to be a lifesaver in adverse situations.

Data analysis. Advanced commercially available software can receive the latest data from your installation, remotely download it from the data logger to a PC, thereby reducing downtime and improving efficiency. Not only that, but it can also be programmed to remotely check signal strength.

The new system being developed shall eliminate possible malpractice of manipulations in readings/readings being reported even from dead sensors.

Statistical and history/trend analysis possible as the data is in digital format. It can be used as an input for other analysis software.

2.4 Need for State of Art monitoring software

It is high time for the industry to cater to the specific needs and deploy real-time monitoring systems for the monitoring of upcoming tunnels. The objective can only partially be achieved by installations of automatic data loggers which are capable of automatically recording readings, but have certain inherent limitations that can be overcome only by controlling data through some state of the art software. Only Data Loggers are not sufficient as these loggers can only record thousands of readings at the frequency they have been programmed for. Sample output from these data loggers is shown in Figure 7.

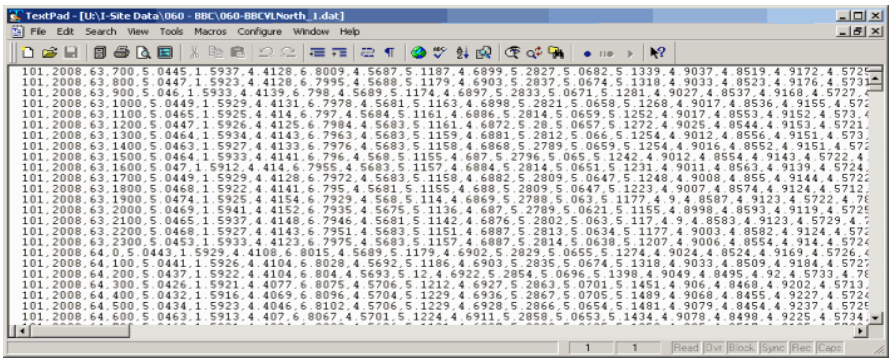

Fig. 7. Sample output of data loggers

These readings are essentially useless until they are processed, presented graphically, and distributed; and this is where the real challenge is. The most difficult part of any monitoring system is to analyze the readings well in time and distribute the results to all concerned so that necessary actions may be taken well in time.

Data analyzing software. With the advancement of technology in the field of instrumentation and monitoring, a number of commercially available web-based monitoring software have been developed to provide monitoring engineers with a web-based, data-management, calculation and presentation tool and since then they have been used on numerous projects around the world. These are server-based software and can be accessed anywhere in the world. Users interact with the software using their web-browser. All the processing takes place on the server. It is platform-independent and can be accomplished from the local network or, when connected to the Internet, from any location in the world. It is always on-line and is a true multi-tasking data management and presentation tool. The schematic diagram showing data flow in case of a web-based monitoring system is shown in Figure 8.

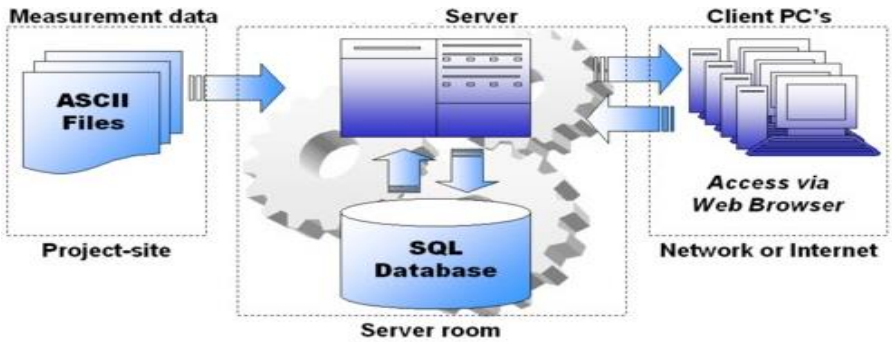

Fig. 8. Data flow in a web-based monitoring system

Common features associated with this software include:

Control levels. All the users have an individual login name and password, giving them access to all sites within the database that they have access rights to. Users can select the language they wish to use from a list of available languages. The architecture of the software generally provides 3 control levels: administrator, user and guest.

The administrator of the project has been wrested with all the powers and options concerning the project. For each project, the administrator can add users and guests, and control the level of access each has. The user has limited configuration ability whereas guest has got only viewing rights.

For instance, if five tunnels are being constructed and monitored by a specific department of a state; the Chief Engineer will have the right and control over all the five tunnels and would be assigned "administrator" for the project. He can view and control data of all the five bridges.

The Dy. Chief Engineers and Executive Engineers of all those tunnels will be given the “user” privileges of their respective tunnels. Further, there may be two Section Engineers involved in each project responsible for different portals. All those will also be given “user” privileges for the sensors located in their respective portal. Each of these users can access the information related to their specific location but none can see the information of any other. The level of control which “user” has (for example permitting manual data entry or not) will be decided by the “administrator”.

All others who may have a significant interest in monitoring results but could not be given the control shall be assigned as “guest”

Plan views and project photos. The software provides with the facility to upload project plan views and project photos and mark sensor locations onto them (Figure 9). The main window of the project displays overall project view along with sensor locations whereas any number of additional plan views/photos along with respective sensor locations can be configured. These views/photos are very useful in visualizing the location of sensors at the site, their current readings, and their alarm status. The background graphic of the plan view is created from a CAD file or a photograph. Thus it is possible to have plan views, section views, and photo views.

Fig. 9. Senor locations mapped in software

Customize sensors. ARMS permits a lot of information to be stored for each sensor thereby enabling each sensor to be fully customizable. Some of the information that is stored for each sensor includes the name of the sensor and its short name which will be displayed on the display photos/maps, serial number, date of installation/re-installation of the sensor, date when the sensor was removed or replaced, information on the location of sensor – text information along with coordinates, calibration factors, engineer relations to convert raw data into respective engineering units, date of base reading and remarks. Also, the administrator is empowered to change any of this information at any stage during the monitoring of the project.

Controlling sampling rate and storing data. The software automatically talks to the data loggers and control their sampling rate as per administrator instructions. It further stores the data from the field in MySQL database and can be readily accessed and analyzed.

Performing required calculations. The software performs real-time calculations and converts the data to respective meaningful engineering units. Calculations are performed for each sensor depending on the formulae being keyed in by the administrator.

On-site visualization Construction of tunnels in week Himalayan Geology is becoming complicated as the tunnels alignments are required to pass through various thrust/fault zones. This is both designs as well as construction challenge and hence; monitoring becomes even more critical. The requirements are very stringent and call for absolute zero tolerance in terms of exceeding deformations and vibrations beyond prescribed safe limits. Monitoring requirements in such cases call for the implementation of On-Site visualization of changes of parameters being monitored. In its original concept; on-site visualization is a system wherein 3 numbers of LEDs are installed with every sensor that is installed at the site to display the following parameters:

- Green: Readings are normal and are in line with predicted values
- Yellow: Reading are approaching borderline and there is a need to pay attention to all concerned.
- Red: The readings have crossed their ALARM Levels and site is required to be vacated immediately.

Presentation of results. The software presents the results real-time in graphical and numerical format. It also generates trend plots including time plots, profile plots, and combination plots (Figure 10). Plots can be generated reflecting the change in any particular value over last 1 day, 1 week, 1 month, 1 year, since inception and so on. Plots can be printed or saved and used in reports. These plots are set up in advance by an administrator and then made available through pull-down lists shown in the control panel.

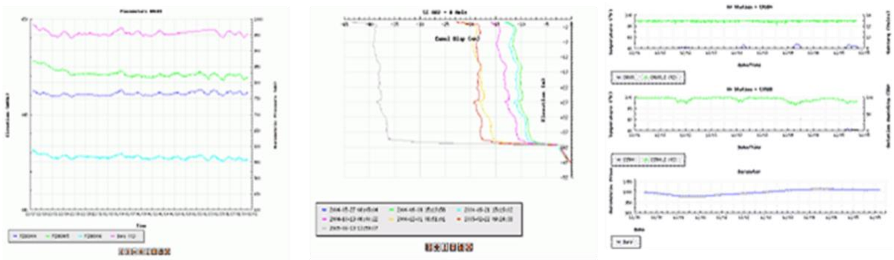

Fig. 10. Graphical outputs of the ARMS software

Triggering alarm messages. Administrator of the project can generate 3/4 trigger levels and specify the persons to whom alarm message will be automatically triggered once the field values cross alarm values. The software checks for alarm conditions when it receives data files. It provides a number of algorithms for calculating the alarms (thresholds, rate of change, etc) and mostly four levels of alarms (Blue, Amber, Red & Black). Alarms are not only displayed on the screen (Figure 11) but also distributed by email and SMS messages.

Fig. 10. Alam display in ARMS software

Creating automated PDF reports. The software generates PDF reports on a daily, weekly, or monthly schedule and distributes the reports automatically to selected users.

Manual data entry. The software provides a central collection point for readings that are obtained manually. It can also be used to record information such as excavation levels. A spreadsheet containing the readings could also be entered.

Data downloads. The software provides data downloads for those who need to analyze data further. The data is exported typically as a CSV file.

3 Conclusions

In Rock Engineering, one deals with several uncertainties. Since the properties of rock mass matter the most, attempts are made to get them from direct and indirect methods. The tunnels in India are generally designed for a design life of 100-120 years. This doesn't necessarily mean that the structure will no longer be fit for its purpose at the end of that period. Various loads and load combinations are accounted for in design procedures to ensure this requirement. Nevertheless to mention the loading conditions in the real environment are always much more complicated than what engineers consider. As the structures are designed for a long service period; inevitably, they are constantly subjected to environmental corrosion, destructive effects of material ageing, long term loading and fatigue effects, etc. therefore, there is significant interest in securing the investment with two fronts; first the safe operation and maintenance to ensure long service life and second ensuring safety and efficiency of modern design practices. Both of these intentions may benefit from instrumentation and monitoring of these structures.

Real-time web-based monitoring offers enormous advantages over the conventional practice of installation and subsequent manual monitoring of instruments; the benefits are not limited to only stakeholders but are also to various associated implementing agencies and consulting engineers. The solution not only offers better data management and risk identification system during the tunnel construction; the advantages may continue to be availed during the lifetime of tunnels at considerably minimal additional costs and efforts.

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