Geotechnical Aspects of Underground Construction in Soft Ground, Mair & Taylor (eds)
© 1996 Balkema, Rotterdam. ISBN 90 5410 856 8

Monitoring of tunnels, surrounding ground and adjacent structures

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ABSTRACT: The authors have played leading roles in a number of large scale monitoring projects, and this paper briefly describes and examines the performance of the automatic ground and structural monitoring systems employed. The information from the monitoring systems has been used to control construction activities and ensure the safety of passenger trains travelling in tunnels within the zone of influence of the construction work.

Interpretation and presentation of the results are discussed, highlighting the basic features needed within the software to readily allow busy site engineers to fully interrogate the system and the data produced. The authors consider that the monitoring cannot be a 'black box' but must be under the control of the construction engineer.

The various types of transducers used by the authors in automatic monitoring systems are briefly described.

1. INTRODUCTION

Automatic Monitoring Systems (AMSs) are now commonly used on large construction projects and have become a standard feature of major tunnelling projects. The basic features of an AMS are sensors that can be automatically read, signal conditioning, data acquisition, data storage, data analysis and display. AMSs can be used to obtain frequent real time data from which any effects of tunnelling works can be easily identified. The information obtained can be used to give an immediate warning of parameters exceeding set limits so that remedial action can be taken before any damage is caused.

The uses of AMSs in tunnelling work range from measuring strains in critical components such as tunnel linings, to measuring the deflections caused in the surrounding ground, to the effects of the ground movements on buildings, structures and other tunnels founded in the zone of influence of the new works.

All the systems discussed were installed and in some cases designed by G Price and I F Wardle while working at The Building Research Establishment (BRE), or subsequently at Construction Monitoring Control Systems (CMCS).

The authors consider that wherever possible an AMS should be checked by a secondary independent measurement method. A precise surveying system usually forms an integral part of an AMS on structures, this can act as an independent checking system and is also used to tie the data from different locations back to a common datum. Most AMSs only record relative movement changes.

2. TYPES OF SENSORS

Any sensor that can be automatically read is suitable for an AMS. The sensors that have been most frequently used by the authors are briefly described below.

(i) Electro levels. BRE first brought ELs to the notice of the Construction Industry by using them on a series of pile tests in the late 1970s, (Cooke and Price 1973), (Cooke, Price & Tarr 1980). At the time ELs revolutionised the quality and quantity of data that could be obtained from the pile and the soil supporting the pile. Pile soil interaction was studied in the field and the data used to check new theoretical models such as p-y and Finite Element methods. The early use of the ELs was to monitor bending strains in piles and shear strains induced in the soil from a loaded pile. The work on piles was later extended to non-destructive testing of marine structures and subsequently to measuring ground and structural movements.

To monitor ground movements a number of discrete ELs are inserted in a tube installed in the ground either vertically or horizontally to work as fixed in place inclinometers. To monitor relative settlement of structures ELs are mounted on beams suspended from the structure on stainless steel pin brackets at each end, this permits the beam to move freely. Ideally the beams should be installed in sheltered positions so that the instruments are protected from sudden temperature changes, high winds and accidental damage.

Buildings are damaged at relative movements of 1 in 300 and are generally considered free of risk at less than 1 in 1500. Set at a resolution of one arc second an EL is able to monitor changes of 1 in 206,000 and is able to resolve relative movements well below critical levels.

The effect of temperature on instrumentation is a general cause of concern and since the EL is a comparatively new sensor the effects of temperature are of particular interest. Compared with other sensors the EL is inherently less affected by temperature because of its half bridge construction, ie, temperature effects on the two arms of the half bridge tend to balance out. Temperatures applied only to one arm of the EL half bridge can cause a problem, therefore ELs do not like even small differential temperatures along their axis, (Cooke & Price 1973). ELs are similar to many other instruments in this respect, ie, precise optical surveying is not possible with direct sunlight on one side only of the instrument. Because of the unpredictability of temperature gradients it is impossible to include the effects in any calibration, the solution is to avoid locations likely to be affected by differential temperatures or to make allowances for their effects at certain times of the day. Figure 1 shows the effects of temperature on two ELs. Temperature is plotted as the heavier continuous line, one of the ELs (A) is plotted as a heavy broken line and the other (B) as a thin continuous line. The change in temperature is about 22 degrees C, the change in reading of A and B respectively are about 7 and 35 arc seconds. Units on 'Y' scale = arc seconds or it can be seen that the effects of temperature on the two ELs are in opposite senses. The effects are complex and may be partially due to differential temperatures and the mechanical movement of the fixing plate to which the ELs were attached for this simple test. Twenty degrees is a significant proportion of the yearly temperature variation (UK) and except on a very few occasions far greater than the day to night change. The effects on the ELs in terms of rotation were: for A, 1 in 29,429 and for B 1 in 5,885, insufficient to prevent the system giving warning of short term critical rotations. The average EL would give a response somewhere between these limits. Movements of a building attributable to tunnelling (or other works) are difficult to evaluate, because of the complex normal structural movements caused, among other factors, by differential temperatures across a building as the sun moves in the sky and by seasonal temperature changes, the interpretation of the EL results is a small part of the whole picture.

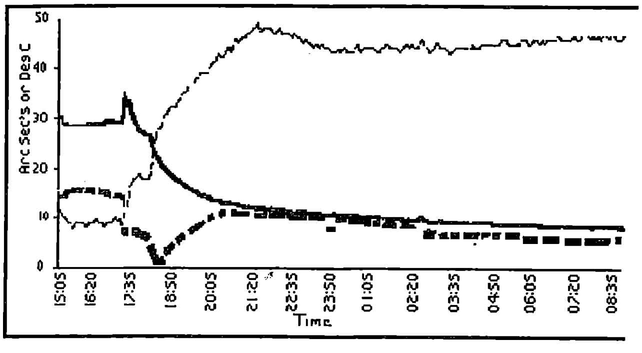

Figure 1. EL Temperature Plots

(ii) Linear Variable Differential Transformers. Extensometers are commonly used to monitor soil movements. Linear Variable Differential Transformers (LVDTs) movement transducers as the sensing element have extensometers. LVDTs have a continuous output, are more easily waterproofed, can be read to better than 0.01mm and are compatible with the logging system described below. LVDTs can also be used to monitor defects (cracks) in buildings as part of an AMS. The probe that carries the iron core through the centre of the LVDT can be completely free of the body and therefore no water seals are needed around the probe. The advantages over Vibrating Wire (VW) movement gauges are ruggedness, sensitivity and range.

(iii) Water Levels. To provide an automatic link to a datum or relative movement over long distances the authors have developed an automatic water levelling system using very sensitive pressure transducers. The transducers are capable of monitoring movements of up to 150 mm with a resolution of better than 0.1 mm. Use of any greater resolution would probably not give any greater accuracy of measurement due to surface tension and resistance to flow along the connecting tubes.

3. LOGGING AND DATA HANDLING SYSTEMS

(i) Hardware. A modular data logging system consisting of controllers, multiplexers and if required modems, linked back to a central computer for data analysis and presentation. The data is logged at one or more logging stations. A standard logging station consists of a controller and as many multiplexers as necessary for the number of sensors; each multiplexer accommodates up to 16 instruments. The data is logged and stored in the controller usually hourly but is scanned more frequently to trigger alarms and to allow access to current data at all times. Read stations can be linked together and back to a central control room using RS485 cables or read stations can be connected to a modem and data retrieved from the control room via a BT line.

(ii) Software. The quality of software plays a major part in making the data from an AMS useful. CMCS's philosophy is to provide the customer with a suite of programs that allow the end user to process the data and present it in a format that is easy to use.

Changing datum date easily, to look at short term changes, and the ability to carry out correlations with temperature are considered essential if engineers are to keep control of the construction process. For large projects the volume of data that is obtained means that data management becomes a major factor in the project, ie, at the present time a conservative estimate of the number of ELs active in AMSs in and around London is about 6,000, which if read every 2 minutes would generate more than 1.5 billion results in a year!

The types of data presentation CMCS have developed to cope with mass data are:

1. Diagrammatic - An overall picture of a system showing movements in mm.
2. Plots of movement along each run of instruments.
3. Plots of data from each instrument versus time to check stability and trends of movement.
4. Plots of each instrument versus temperature, or other instruments, to check for correlations.

4. MONITORING OF EXISTING TUNNELS

(i) The Second Severn Crossing. Four major AMSs were used in the 110 year old British Rail Severn tunnel during the construction of the Second Severn Crossing over the Bristol Channel. The line of the new bridge crosses the line of the tunnel at an angle so that the pile groups for the main pier on the English side straddle the tunnel. The two pile groups are spaced about 30 m apart either side of the tunnel, some 150 m off the coastline.

To monitor any distortion of the tunnel lining BRE inserted 36 ELs in the brick lining of the tunnel. Holes were cored in the lining into which short lengths of inclinometer tubing were cemented. ELs were then inserted into the tube and set to mid range. Six ELs were spaced around the lining, at the haunch, mid and shoulder level each side of the centre line of the tunnel. Three such sections were instrumented 6m apart at each of the locations where the pile groups were to straddle the tunnel.

The ELs had a resolution of one arc second, giving a resolution across the carriage on which they were mounted of 0.0005 mm. At this resolution the ELs could pick up the very small movements imposed on the lining (30 m below the sea) due to the 8 m tides see Figure 2. The 4 arc second peak on the trace represents 0.0025 mm of movement across the 100 mm carriage. The two year plot in Figure 2 shows the seasonal changes in the EL output (of the order of 100 arc seconds) and the overall stability of the system. The ELs were installed 18 months before work was to start on the new bridge and were to operate for a total of 5 years. After 12 months the warning levels were set to 0.15 mm for any EL, greater movements triggered a warning at the Control Room. The engineers involved in the project were not set the impossible task of checking all the data daily (over the five years of the project about 89,000,000 readings), that was left to the computer. The engineers looked at overall trends and reacted to disturbances or faults on the system, ie, failure due to power loss, damage to cables by third parties, etc. The following procedures were set up to deal with warnings.

(a) The computer analysed all the data and warned of limits being exceeded. The warning levels were set well below values considered likely to cause damage to the tunnel.

(b) The warning received at the Sudbrook Control room was forwarded to the Line Controller at Swindon who called on BR engineers and BRE to evaluate the cause of the warning.

(c) The data was interrogated by BR/BRE engineers using portable computers and modems. In this way

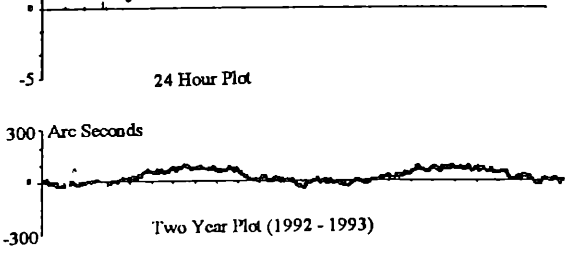

Figure 2. Long & Short Term EL Data

the probable cause of the warning could be quickly determined and if necessary a visual inspection of the tunnel arranged.

During the critical stage of the pile driving an engineer with specialist knowledge of the computer programs and hardware was on site continuously to deal with any problems. During the installation of the piles no significant movements were observed in the EL results.

The success of the system was due to: its installation, well in advance of any operation likely to cause disturbance to the lining, the level of confidence built up in the system during the period before work started, the clearly defined roles of all parties concerned and the free access to the data at all times.

(ii) The Angel. Eighteen tunnel distortions monitoring systems were installed in the 3.5 m diameter running tunnels during the formation of three major step plate junctions. A step plate is where a larger new tunnel captures an existing smaller running tunnel, the new tunnel completely surrounding the existing tunnel. As the existing tunnel is uncovered (and supported on formwork) stress changes in the lining could cause distortions that would reduce the clearance between the lining and the trains below allowable limits.

A series of beams shaped to fit the tunnel section were positioned continuously around the tunnel. Each beam was free to rotate at one end and free to extend or contract at the other. The beams were fitted with an EL to monitor rotation and an LVDT to monitor longitudinal movement between the mounting points. These two measurements allowed changes in the x, y co-ordinates of each of the reference points around the tunnel to be determined. Figure 3 is a photograph of a distortion monitor fitted in the tunnel.

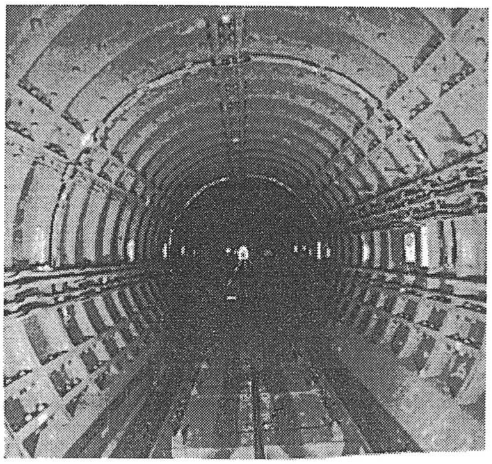

Figure 3. View of Distortion Monitors

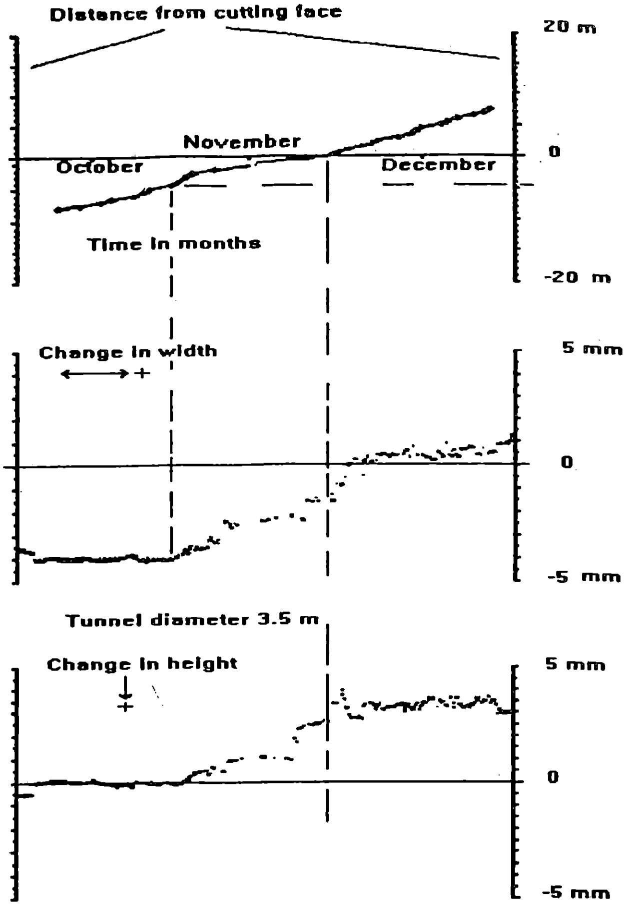

Figure 4. Lining Movements as Tunnel Advances

Figure 4 shows the movements of the lining as the cutting face approached one of the distortion monitors. It can be seen that significant x, y movements started when the cutting face was about 4 m from the section being monitored and that the width of the tunnel increased, while the roof moved down by a few mm.

To give more general information on the clearance envelope proximity sensors were fixed to the tunnel lining and set to detect the metal of any of the carriages entering the clearance envelope as the trains passed. The proximity sensors were considerably cheaper than the distortion monitors and could be spread out to cover a greater length of the tunnel. A high speed data acquisition system was used to record if carriages encroached on the clearance.

The system was set up to give automatic visual and audible alarms. Most of the alarms recorded were due to third party interference at night. Complaints from home owners close to the site who were woken up because of false alarms caused the contractor to have mixed feelings about the system. Technically the system worked very well.

(iii) Waterloo. Existing LUL tunnels were monitored during construction of a new escalator shaft. ELs and water levels were used to monitor settlement along the tunnels. Waterloo, (Harris et al 1994) was possibly the first example of how data from a modern AMS can be handled effectively.

The most pleasing aspect about the work was the co-operation between BRE, instrumentation consultants Geotechnical Consulting Group (GCG), main contractors Sir R McAlpine and BACHY. BRE maintained the system and brought the data back into the computer environment. When BACHY required to use the system to control grouting, BRE brought the data back from the local area where they were working interactively and allowed BACHY to control movements directly by talking to the grouting engineer, via an intercom system. While the operator was looking at the instruments in one specific area the loggers would be recording data from all other areas. The computer would periodically gather the data to make sure that no excess movements were occurring anywhere else in the system. The consultant from GCG could draw the data off the BRE computer at any time and carry out an independent analysis. GCG also made definitive movement profiles of the whole system on a day to day basis. If any third party caused any disturbance to the system it was logged and the processed data corrected for the disturbance.

5. MONITORING GROUND MOVEMENTS

Ground movements around new tunnelling works have conventionally been monitored using scanning inclinometers and manual extensometers. Where it is possible to install a tube in the right orientation more comprehensive data can be obtained using in place inclinometers and LVDT extensometers. The best data from in place inclinometers have been obtained by using discrete ELs, ie, ELs mounted on carriages that are not linked together.

Projects in which ground movements have been successfully monitored have been:

(a) During construction of the Docklands Light Railway (DLR) the first commercial manually read ground monitoring system using ELs was installed by BRE from one of the platform tunnels of the Northern Line at Bank underground station. This initial EL installation had been a natural extension of the pile test system developed by the authors, and was instigated by Dr Ward (formerly of BRE) consultant to Maunsel & Partners. At a later date five AMSs consisting of horizontal trains (a series of independent ELs on carriages) were installed in the ground around Bank Underground Station to monitor ground movements under and close to the Mansion House, (Price, Longworth & Sullivan 1994). All these trains showed the classic shape of settlement above a new tunnel. At other locations sets of extensometers were used to examine the vertical soil movements with depth.

(b) Waterloo. Two trains of ELs, one inclined (18 m long) above the inclined escalator shaft and the other 30 m long above the interconnecting passage from the bottom of the shaft, gave the order of magnitude of settlement caused by the new tunnel work. The information obtained gave an immediate indication if the mining techniques were working as well as predicted in terms of ground movements and the likely effect on the above ground structures. Extensometers installed between the tracks were used to examine the vertical soil movements beneath the existing tunnel.

(c) 104 Trial Jubilee Line Extension (JLE). Five deep trains of ELs from the access shaft and seven surface trains monitored the settlement troughs being generated above the NATM trial tunnels constructed at Redcross Way. These trials were used to decide on the acceptability of use of the NATM for the JLE under London.

This type of AMS allows the depth and extent of the trough of settlement transverse and/or longitudinally above tunnels to be determined.

6. MONITORING STRUCTURES

(i) Mansion House. The first major building above new tunnelling works to be monitored using an AMS was the Mansion House the official residence of the Lord Mayor of London. One of the platform tunnels for the Docklands Light Railway was constructed under the North East corner. There was concern that differential settlement could cause damage to this historic building. Mott MacDonald, Consultants, assessed the effect of the new tunnel on the Mansion House and recommended monitoring. The City of London engineers and advisers were aware of the limitations of conventional monitoring and a more sophisticated solution was sought. Mott MacDonald approached BRE who confirmed the suitability of the use of ELs. So that the system would record shear movements BRE mounted the ELs on a continuous series of beams, the beam system was installed in the basement of the MH to monitor differential settlement. To keep the runs of beams continuous holes had to be cored through massive brickwork walls and to pass doorway beams where beams were mounted on hangers and positioned in covered trenches.

The success of the system (still operational) was enhanced by the work done by Mott MacDonald in interpreting the data. The detailed information obtained showed the short term effects of the new tunnel work and also showed longer term trends of movement caused by an earlier passageway constructed 20 m below the Mansion House. The passageway rising was causing uplift to occur under the centre of the North East side wall.

(ii) Heathrow. Currently CMCS have 200 m long runs of 3 m long linked EL beam operating at Heathrow, some are positioned more than 8 m up on concrete structures. These are very long horizontal runs of EL beams installed in an extremely exposed position. Information from the system is at present commercial in confidence but CMCS are aware that the systems are giving useful data on profiles of movements imposed on the structures as the tunnel passes underneath.

(iii) The Jubilee Line Extension (JLE). AMSs were required to monitor the effects of ground treatment, stabilisation and settlement on existing structures and tunnels due to the JLE Project. AMSs were deemed to be necessary due to the extent of the tunnelling works involved and the importance of structures above the tunnels. CMCS are involved on two of the contracts JLE 104 and JLE 102. JLE 104 covers a highly complex tunnel system in a confined area at London Bridge Station and JLE 102 is one of the longest sections of tunnel works running under a series of historic and important buildings.

On JLE 104 the read stations were linked together and back to a central control room using RS485 cables while on JLE102 each read station was connected to a modem and data retrieved directly from the control room via the telephone network.

The AMS on JLE 104 consists of 850 instruments and 24 read stations. Data is retrieved and stored once an hour 24 hours/day which gives 20,400 readings/day that have to be processed and assessed.

Software being used on JLE 104 has been developed by CMCS, while on JLE 102 CMCS provided software to remotely interrogate the 2,500 ELs deployed (at hourly scans 60,000 readings/day) and store the data in a data base format, for further analysis by the Client, or his Consultant.

7. CONCLUDING COMMENTS

Automatic Monitoring Systems have been successfully used to safeguard tunnels, buildings and other structures during major new construction projects. The systems have worked very well where their advantages and limitations have been recognised.

The Severn Tunnel installation has demonstrated that they can operate at high sensitivity for long periods of time (5 years) and perform reliably in a tunnel environment.

Factors that have contributed to successful systems are:

1. Installation well in advance of operational requirement to establish normal variations in movements.
2. Clearly identified roles for the parties involved from the start of a project.
3. Realistic contract specifications, very high resolutions and stability can be obtained under specific conditions but these should not be expected to apply in the field. The performance of an AMS in situ should be checked by in-situ calibration, stability checks for a reasonable period of time before the start of construction and temperature correlation wherever possible. Very often contract specifications concentrate on parameters established in a laboratory but laboratory calibration and temperature checks cannot take into account the practicalities of physically mounting sensors or the varied environmental factors encountered in the field. For example it would be unreasonable to expect EL beams installed on old brickwork on the 4th floor of a building above windows to provide information on foundation movements to an accuracy of 0.1 mm.
4. Data handling and presentation that allows easy interpretation of the data by the engineer.
5. Freedom for all parties to examine the data independently and make their own interpretation.
6. Recognition that all monitoring systems can be seriously affected by some environmental conditions, ie precise surveying in high gusting winds.

8. ACKNOWLEDGEMENTS

The authors would like to thank their colleagues at BRE and CMCS and all the other Companies and people too numerous to mention here who worked on the projects outlined in this paper and without whom the systems would not have been successful.

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