Profiling methods reviewed

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There is a regular demand for fast inspection of structures like caverns, sewers and tunnels. The measurement of cross-sections provides selective information about these structures which can be used for various information gathering purposes. Often this process is called 'profiling'. A number of such techniques exists: some provide data at the time of measurement, others after subsequent processing. Each system has its own strengths and weaknesses.

It is often necessary to survey structures to detect changes in geometry or fabric. When assessing the structural condition and change in regularly spaced cross-sections, surveying is a proven technique as it cuts the quantity of information gathered to manageable proportions. Frequently this data is supplemented with information on the spatial position and orientation of the cross-sections. This information can be used to:

☐ estimate clearances;
☐ check alignments of ducts and lift guide rails;
☐ monitor changes which can indicate problems of deformation;
☐ compile inventories and 'as built' drawings;
☐ determine volumes of excavation or lining materials;
☐ indicate structural failure;
☐ collect information for refurbishment;
☐ check the driving of tunnels;
☐ monitor progress.

Many different methods and instruments have been used over the years to acquire profile data of structures such as tunnels, some more successfully than others. Tender document specifications often permit a range of systems to be considered. They vary in their speed, accuracy, range and cost. This review is limited by two factors. First, many contractors have developed their own systems and methods but have not published details. Second, it is not appropriate to make a full and critical analysis of each system here because of the wide range and diversity of equipment and uses.

Measurement of cross-sections of a structure such as a tube tunnel requires careful consideration. If too few points are measured, they will not adequately represent the shape of the tunnel. If the position of the cross-section that is measured is not referenced to some datum, level, or pre marks, then subsequent repeat measurements may be invalidated.

When cross-sections are used to monitor structural changes, it is essential that the same cross-section be measured repeatedly. This can be achieved by having visible permanent targets or marks in the plane of the cross-section. A minimum of three such targets will uniquely define a plane. Two methods can be used: fully and partially constrained.

With the first, three or more marks are used to define the plane of the cross-section and subsequent measurements must made in this same plane. In the partially constrained method, two marks may be used together with a spirit level to control verticality, or one mark and a spirit level plus controlled orientation of the plane of measurement i.e. alignment perpendicular to the structure.

The spatial position of the cross-section can be determined relative to its neighbours or to any datum by survey observations to the defining marks (Fig 1).

The number of points which should be measured on a surface is a function of the shape of the surface. A surface can be modelled from sampled spatial data provided that sufficient measurements are made. This is analogous to the signal processing situation where a signal must be sampled at least at twice its maximum frequency.

The surface character can be determined by preliminary tests to calculate the required frequency of point measurements. Shortages of time and money often limit the frequency. However, the sampling interval is important otherwise comparisons may be invalidated. The frequency with which complete cross-sections are measured also requires consideration if wriggle surveys are envisaged.

Past and present techniques

Methods currently employed to measure cross-sections may be divided into two groups: contact and non-contact. Contact methods take a number of forms and are generally used where access to more sophisticated and expensive equipment is limited or not allowed, or alternatively where a simple approach can yield quicker results.

With the probe and protractor system-measurements are taken from the centre of a tripod-mounted protractor to the surface being measured. The angular settings and distances give the appropriate information. Where clearances need to be measured, for example between a train body and tunnel structures, a rigid gauging frame can be set vertically and fitted with hinged or spring-loaded probes around its perimeter. The probes can be used to indicate clearances to the surrounding structure. Recording is generally done manually but optical encoders or potentiometers can be used.

The distances between permanent or temporary fittings attached to the inside lining of tunnels or pipes are measured with tapes fitted with extensometers. A repeatability was obtained by British Waterways of less than 0.5mm in a canal tunnel. This technique is often used to monitor changes in cross-section shape when deformations are expected but the accuracy of results can be affected by draughts and vibrations.

Contact methods have the advantage of providing a positive location even in the presence of soot or dirt. They are inexpensive and easy to use. Among their drawbacks are that they are labour intensive, require manual recording and access to all points of a structure may be difficult.

Non-contact methods of measurement fall into two categories: manual, where human involvement is required during the measurement process, and automatic, where limited supervision is required.

Theodolites measure angles and Electro-magnetic Distance Measurement (EDM) systems measure distances. These two operations are often performed by a single instrument, the electronic tacheometer or total station. Points on a structure which describe a cross-section, possibly illuminated by a rotating laser beam, are observed, recorded, processed and presented as X,Y,Z co-ordinates. The angular accuracy of these devices, possibly as good as one second of arc, is much higher than the distance measurement accuracy which, for close range applications, is relatively poor, with a specifications in the range of ±1-10mm. Further information can be found in books by Cooper and Burnside[1,2].

In their favour, these instruments enable data collection and processing to be performed in the field and the potential accuracy is high. But it is time consuming to make the ideal number of measurements point by point and usually a limited number of observations is made.

Optical tacheometers, such as the Zeiss Jena BRT 006, have been largely superseded but they can be used to measure cross-sections. The accuracy of tacheometric methods varies between 1:500 and 1:10 000 of their measurement range. The measured distance is read from a calibrated scale when the directly viewed image and an indirectly viewed image are brought into coincidence.

They are inexpensive, quick to use, robust on site and can be operated in hazardous environments. But they have limited accuracy and are labour intensive. In addition, the subject must be illuminated, and recording done manually.

Several instruments have been constructed which use the same principle as

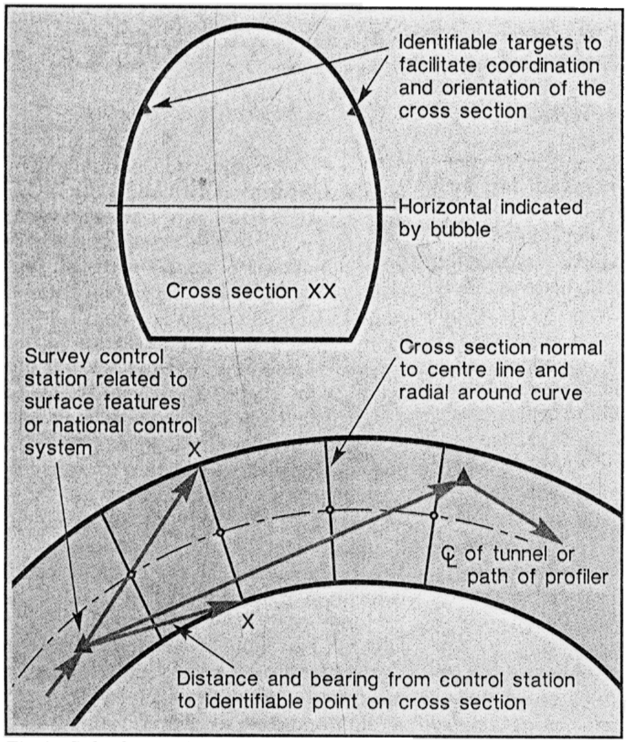

Fig 1. Calculating the number of measured points/cross-section.

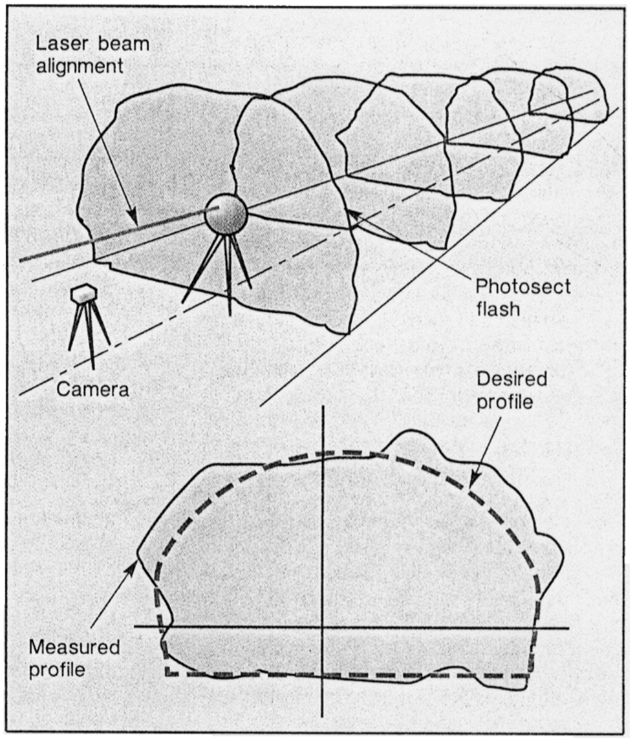

Fig 2. The Rockset system uses flash photography.

the optical tacheometer to perform profile measurement, such as the 'PROTA' tunnel profiler manufactured by R & A Rost of Austria. The measuring principle is described as: 'intersection by means of a laser beam via a right triangle with a variable base'. The laser reflection on the surface of the structure is imaged by a telephoto lens on to a ground glass plate. By changing the position of an adjustable mirror, the image can be made to coincide with a division mark and the distance read from an illuminated counter. The measuring range is 1.6-11.25m and the claimed accuracy is ±10mm. On the positive side, they are fast, easy to use, have acceptable accuracy for many applications and are relatively cheap. Against this, they require manual operation, are subject to laser safety restrictions and need manual recording.

Photogrammetry employs mono or stereo photography as a fast, non-contact recording system from which numerical information may be derived. Acquisition of the photograph with metric or non-metric cameras requires the minimum time on site, but a more lengthy period for processing and analysis in the laboratory.

Photogrammetry for tunnel profiling has been used from the early '60s. The second Mersey Tunnel was the subject of a photogrammetric wriggle survey in 1970[3]. In most early experiments when stereo photography was employed, the profile was marked by targets on or in the plane of desired cross section. The tunnel lining was illuminated, and the profile plotted using an analogue plotter.

The photographs provide a valuable and fast archive record which may be examined and remeasured at any time with high accuracy. However, analysis of the photographs requires skilled laboratory staff and some expensive equipment.

An important development in photography was the introduction of light sectioning. A light plane is projected by using a flashlight between two boards, or a rotating light source. This line can be photographed using a variety of cameras. Scale is established with surveyed targets or a measured bar. After processing, the photographs are measured on an analogue plotter or a mono or stereo comparator. The tunnels and caverns at the Dinorwig pumped storage station in Wales were measured using the light sectioning method[4]. The method has also been used successfully in railway tunnels by the contractor BKS Surveys.

A flash photography system is marketed by Rockset under the name Photosect 40. A flash unit and an anodised aluminium disk are used to project the shadow of the disk onto the wall. This silhouette is photographed and the cross section is then drawn from the negative. A non-metric camera is recommended with a 60 x 60 mm format film (Fig 2). The flash unit is positioned on a line described by a laser beam, scale is achieved with scale bars and level by spirit levelling. The accuracy claimed is 30mm and the profile photography acquisition measurement rate is 25-40/h.

City University in London used a photographic recording system with the profile defined by a rotating laser during the mid 1980s, the principles being briefly described by D Stirling in the book, 'Engineering Surveying Technology'. This system gives high accuracy, good identification of the cross-section and reasonable speed of measurement on site depending on system. It is also possible to use sequential measurement to determine deformation. But long exposure times are required for laser line methods necessitating skilled operators. Systems are still beig developed to automate the recording process using a computer-driven microscope table to view and measure identifiable points on the profile line and the fiducial marks.

Three manufacturers - Amberg, Fennel and MDL Profiler - have developed systems incorporating EDM for the task of profile measurement. The ability to use reflectorless EDM has given rise to equipment suitable for rapidly measuring cross-sections of frequently inaccessible surfaces. With older EDM systems which required a reflector, it was only possible to observe a few discrete points because of the difficulty in moving a prism from point to point.

A comparison of manual and automatic EDM methods of profile acquisition was made by Hagedorn in a paper on the use of the AMT. Profiler 2000. The EDM is automatically rotated to discrete positions when the angle and distance are stored on a portable computer. An interesting development has been the application of the Amberg Measurement Technique to the measurement of rail tunnels in Switzerland where the system is mounted on a train.

Reflectorless EDMs are simple to operate and suitable for use in tunnelling conditions, with reasonable measurement speed and automatic data recording. But, against that, they are expensive and not accurate enough for all applications.

A number of systems have been developed which utilise the accuracy of a theodolite to achieve an automated triangulation system. The Kern Space system is based on a number of motorised theodolites with telescopes and built-in CCD cameras. The system requires recognisable targets so that the theodolites can make positive identification and move from target to target. Automated theodolites have high accuracy and automatic operation. However, they are relatively slow, setting up is demanding, they are not ideally suited to tunnelling situations and are expensive.

The well documented technique of optical triangulation using CCD Linear sensors is similar in principle to that of the optical tacheometer, but, being electro-optic, is much faster, achieving greater than 100 measurements per second. It is reasonably accurate over the ranges encountered in tunnels. Tunnel Investigations was probably the first to pioneer this technique in 1983 and is documented by its patent application published in 1986. The accuracy claimed for this system is ±2mm. Another example, using a different configuration, is the pre-production device built at City University.

In its favour, optical triangulation is accurate, fast, robust, portable and automatically records. Against that, there are problems of occlusion and the need to follow laser safety regulations.

British Rail, with something in excess of 300km of tunnel to maintain, has developed a gauging train using a large number of cameras to check clearances in both tunnels and vicinity of the lineside structures. This system is designed to operate in conflicting lighting conditions and while moving. However, it is not a system for deformation monitoring. It provides a fast measurement rate but is highly application specific and expensive.

Future trends

There are two essential requirements for greater efficiency of profile measurement: faster speed of measurement and higher accuracy. Both are likely to be met in the near future with a high-speed, coaxial optical beam approach which will enable a great number of alternative uses for distance measurement which are not currently feasible. There appears to be a move towards further automation which is likely to gain momentum in the future. In some circumstances, especially where human access is difficult, intelligent, autonomous robotic solutions are likely to be developed.

In the short term, the development of a commercial optical triangulation measuring system could fill the accuracy and speed gap. This has already happened with very short-range devices where optical triangulation systems with a range of 50-100mm are regularly used in the manufacturing industry. This could ultimately be replaced by a short-range EDM.

Over the next few years there are likely to be further improvements in the close range measurement area with techniques from metrology, photogrammetry and machine vision merging to provide fast and accurate spatial data collection on a scale not yet contemplated. This will allow the 3-D mapping of structures and surfaces providing data for the next generation of computers to manipulate for a large variety of purposes. This close range information will complement that gathered by large scale surveying methods such as remote sensing, satellite positioning systems and traditional surveys. □

References

1. Cooper, M A R, 1987. Modern theodolites and levels. *BSP Professional Books, Great Britain, 2nd Ed, 258pp.*
2. Burnside, C D, 1991. Electromagnetic distance measurement. *BSP Professional Books, Great Britain, 3rd Ed, 278pp.*
3. Proctor, D W and Atkinson, K B, March 1972. Experimental photogrammetric wriggle survey in the Second Mersey Tunnel. *Tunnels & Tunnelling, pp115-118.*
4. Fellows, S, May 1976. Tunnel profiling by photography, *Tunnels & Tunnelling, pp70-73.*