A REVIEW OF TUNNEL PROFILING METHODS[1]

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It is often necessary to survey structures to detect changes in geometry or fabric. Observations to collect data appertaining to regularly spaced cross sections is a well known and proven technique to assist the assessment of structural condition and change because of the reduction in the quantity of information gathered to manageable proportions. Frequently these data are supplemented with additional information concerning the spatial position and orientation of the cross sections. This type of information can be used for:

(i) estimation of clearances,
(ii) checking alignments of ducts and lift guide rails,
(iii) monitoring changes which can indicate problems of deformation,
(iv) compilation of inventories and "as built" drawings,
(v) determination of volumes of excavation or lining materials,
(vi) indication of structural failure,
(vii) collection of information for refurbishment,
(viii) checking the driving of tunnels, and
(ix) monitoring progress of projects.

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 are often written to permit a range of systems to be considered. These will have differing: speed, accuracy, range, and costs of operation.

CONTACT METHODS

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 where a simple approach can provide quicker results. Three methods are briefly described.

> *Probe and protractor.* Measurements are taken from the centre of a tripod mounted protractor to the surface being measured, the angular settings and distances giving the appropriate information.
>
> *Finger probes.* 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 manual but optical encoders or potentiometers can be used.
>
> *Tape extensometers.* 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[2]. This technique is often used to monitor changes in cross section shape when

deformations are expected. The accuracy of results can be affected by draughts and vibrations.

For: positive location even in the presence of soot or dirt, inexpensive, and easy to use.

Against: labour intensive, manual recording, difficulty of access to all points of a structure.

NON-CONTACT METHODS

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

Manual.

Theodolite, EDM or Electronic Tacheometer. 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 plus or minus 1-10mm. Further information can be found in books by Cooper[3], Burnside[4], and RUeger[5].

For: data collection and processing can be performed in the field, and the potential accuracy is high.

Against: it is time consuming to make the ideal number of measurements point by point, and usually a limited number of observations are made.

Optical tacheometer. 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 - 1:10,000 of their measurement range[6]. The measured distance is read from a calibrated scale when the directly viewed image and an indirectly viewed image are brought into coincidence.

For: inexpensive, quick to use, robust on site, and the equipment can be used in hazardous environments.

Against: limited accuracy, labour intensive, the subject must be illuminated, and manual recording.

Laser tacheometer. Several instruments have been constructed which use the same principle as 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"[7]. The laser reflection on the surface of the structure is imaged by a telephoto lens onto 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 can be read from an illuminated counter The claimed accuracy is +/-10 mm, the measuring range 1.6 - 11.25 metres. A number of similar systems exist.

For: fast, easy to use, acceptable accuracy for many applications, and low cost.

Against: manual operation, subject to laser safety restrictions, and manual recording.

Photogrammetry. 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.

Stereo. Photogrammetry for tunnel profiling has been used from the early 1960s, the second Mersey tunnel was the subject of a photogrammetric wriggle survey in 1970[8]. 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.

For: the photographs provide a valuable archive record which may be examined and remeasured at any time, high accuracy, and rapid acquisition of photography.

Against: analysis of the photographs requires skilled laboratory staff and some expensive equipment, on site powerful uniform illumination is necessary, and expensive metric cameras with built in illuminated fiducial marks are required.

Light sectioning. An important development in photographic was the introduction of light sectioning. A light plane is projected by using a flash light 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 Dinorwic pumped storage station were measured using the light sectioning method[9]. The method has also been used successfully in railway tunnels by the contractors, BKS Surveys Ltd[10]. A flash photography system is marketed by ROCKSET under the name Photosect 40[11]. A flash unit and a 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 (Figure 1).

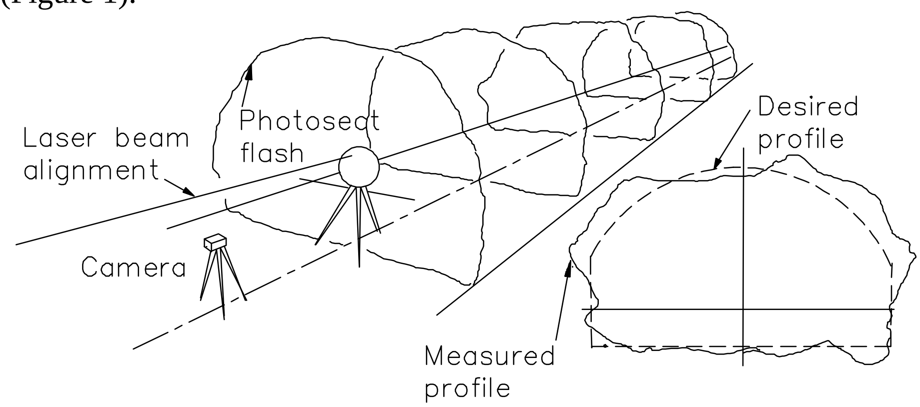

Figure 1. The Rockset system in use.

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 per hour. Tunnels and Tunnelling reported the successful use of Photosect in 1984 for measurement of the CERN nuclear laboratory project in Geneva[12]. City University used a photographic recording system with the profile defined by a rotating laser during the mid 1980s, the principles are briefly described by D. Stirling in the book Engineering Surveying Technology[13].

For: High accuracy, good identification of the cross section, reasonable speed of measurement on site depending on system, sequential measurement to determine deformation is possible.

Against: long exposure times for laser line methods, skilled operators are necessary. Efforts 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 have been made14, but are still being developed.

Automatic.

Reflectorless EDM. Several manufacturers have developed systems incorporating EDM for the task of profile measurement[15,16,17]. The ability to use reflectorless EDM has given rise to equipment suitable for rapidly measuring cross sections to what are frequently inaccessible surfaces. With older EDM, 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[18], 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 example of the data that can be collected using this system is shown in Figure 2.

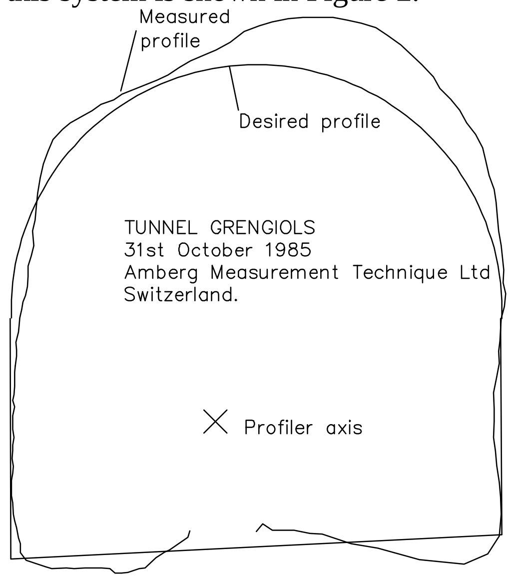

Figure 2. Data collected by AMT Profiler.

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[19].

For: simple operation, reasonable measurement speed, automatic data recording, and suitability for use in tunnelling conditions.

Against: expensive, and not accurate enough for all applications.

Automated theodolites. A number of systems have been developed which utilise the accuracy of a theodolite to achieve an automated triangulation system. The KERN Space system[20,21] is based on a number of motorised theodolites having telescopes with built in CCD cameras. The system requires recognisable targets in order that the theodolites can make positive identification and move from target to target. Kyle states `In the field of applications, surface form is an important requirement. Here Kern is developing a general "Profiling" package based on a scanning laser spot.'.

For: High accuracy, and automatic operation.

Against: Relatively slow speed of operation, setting up is demanding, not ideally suitable for tunnelling situations, and expensive.

Optical Triangulation. The well known 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. A description of this technique can be found elsewhere[22]. Tunnel Investigations Ltd[23] were probably the first to pioneer this technique from as early as 1983 which is documented by their patent application published in 1986[24]. The accuracy claimed for this system is +/- 2mm. Another example, using a different configuration, is the pre-production device built at City University[25], see Figure 3.

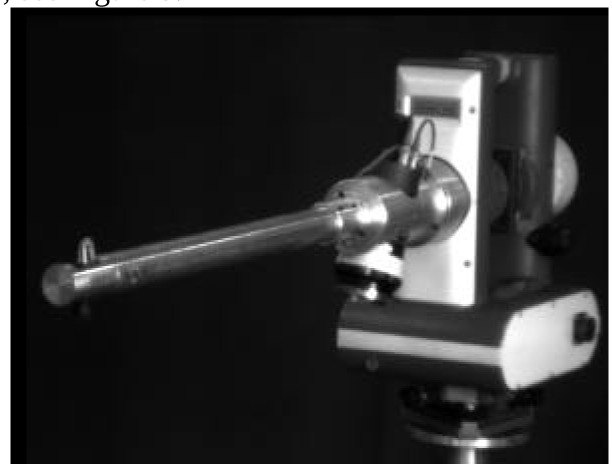

Figure 3. Pre-production lab testing prototype profiler.

For: accuracy, speed of measurement, automatic recording, robust, and portable.

Against: problems of occlusion, must be used in accordance with laser safety regulations.

Railway gauging train. 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[26]. This system is designed to operate in the presence of conflicting lighting conditions and to operate while moving, it is not a system for deformation monitoring.

For: fast measurement rate.

Against: highly application specific and expensive.

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PAPER REFERENCE

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