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Overbreak and underbreak in underground openings Part 1: measurement using the light sectioning method and digital image processing

N.H. MAERZ[*], J.A. IBARRA[†] and J.A. FRANKLIN[‡]

[*]*N.H. Geo Consulting Limited, Kitchener, Ontario, Canada*
[†]*Excavaciones Soporte Y Tecnologia, Zapopan, Jal., Mexico*
[‡]*Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, Canada*

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Summary

Quick, simple, reliable, and inexpensive measurements of overbreak and underbreak are needed for proper evaluation of tunnelling by the drill and blast method. Problems causing rock damage can be identified and remedied while the work is still in progress. The measurements are also useful in identifying causes of overbreak and overbreak, and in helping to settle contractual disputes relating to payment for replacement concrete and secondary blasting of 'tights' (zones of underbreak). A newly developed method to measure underbreak and overbreak is presented here. The light sectioning method (LSM) uses a radial sheet of light to define the tunnel profile. An image of the final tunnel profile is acquired and digitized, using digital image analysis. This profile is superimposed over the design profile, and from this zones of overbreak and underbreak are identified, quantified, and presented graphically.

Keywords: overbreak, underbreak, digital image processing, tunnelling, blasting assessment, tunnel profiling

Introduction

Excavation of tunnels in rock by blasting inevitably results in a tunnel perimeter that is in some places larger and in others smaller than called for in the tunnel design. This is called, respectively, overbreak and underbreak. A classic example of overbreak is shown in Fig. 1. Overbreak and underbreak are both undesirable, costing money and time to remedy. In tunnels that are to be lined, underbreak needs to be removed, and overbreak requires extra concrete to replace missing rock. In addition, overbreak is usually accompanied by rock damage and loosening. In unlined hydraulic tunnels, the combination of underbreak and overbreak creates a rough longitudinal profile, resulting in greater resistance to flow.

Overbreak and underbreak are caused by geological conditions or blasting factors, or a combination. Typically, blasting factors can be adjusted to reduce either underbreak

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Fig. 1. An example of massive overbreak in the Aqua Milpa tunnel, Mexico

or overbreak, although reducing overbreak tends to increase the incidence of underbreak and viçe versa. Geological conditions cannot be changed, but the excavation method, and sometimes the size, shape, or alignment of the excavation can be adjusted to improve the tunnel profile.

Making adjustments to the excavation method along a tunnel, including varying blasting parameters, requires a quantitative real-time analysis of overbreak and underbreak as the tunnelling progresses. Until now, a simple, inexpensive, portable, efficient, and reliable method to measure underbreak and overbreak has not been available. The light sectioning method (LSM), first presented by Franklin *et al.* (1989) and Ibarra (1991), is capable of meeting these requirements and is more fully described in this paper. The image-processing techniques used for this analysis were first developed for analysis of jointing (Franklin and Maerz, 1987), fragmentation (Maerz *et al.*, 1990), and roughness (Maerz *et al.*, 1987).

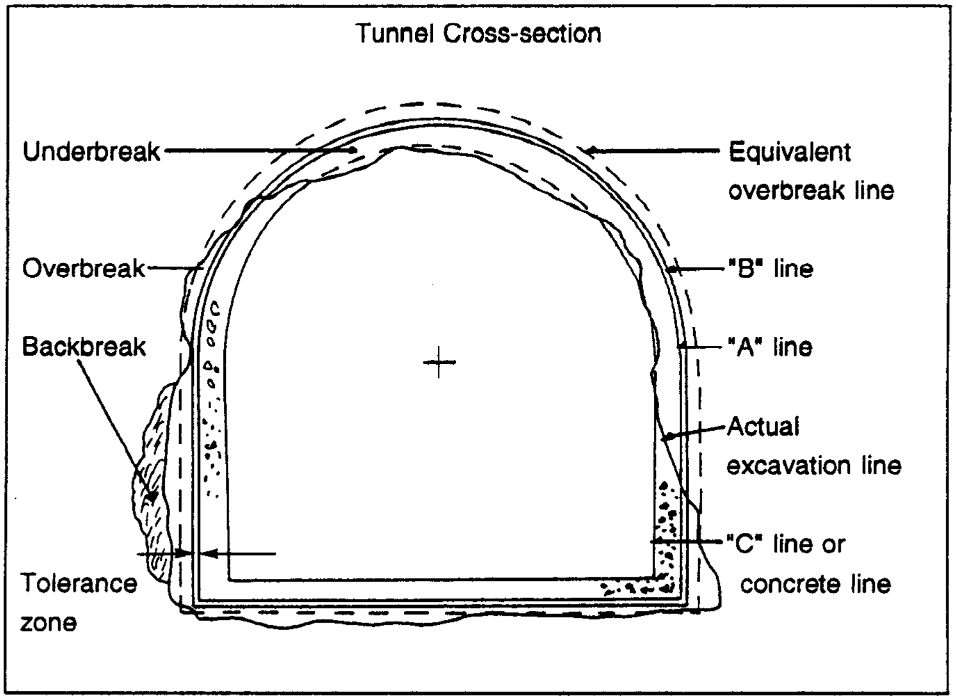

Fig. 2. A tunnel cross-section showing the design lines and zones of underbreak and overbreak

Definitions of blast damage and geometry in tunneling

The following definitions describe the main geometrical concepts relating to tunnel cross-sections, and are shown in Fig. 2. The 'A line' is the ideal or minimum perimeter of the excavation. No rock may project inside this perimeter. 'Underbreak' is the rock left inside the A line. This requires secondary excavation. Zones of underbreak are sometimes referred to as 'tights'. The 'concrete line' or 'C line' is the finished perimeter of a concrete-lined tunnel, and is the A line minus the thickness of concrete. The 'B line' is the maximum design perimeter, which usually is also the 'excavation payment line'. Concrete needed to replace rock removed beyond this line is usually at the contractor's expense. 'Overbreak' is rock excavated beyond the 'B line'. This is also a measure of 'rock damage'. It is expressed as the volume of rock per unit length of tunnel (m^3/m). As well as requiring extra concrete, overbreak can result in decreased stability of the openings. The 'Tolerance zone' is the theoretical space between the 'A line' and the 'B line'. This is to allow the contractor enough space for normal blasthole deviation during the drilling operation. Usually the tolerance is uniform around the perimeter of the excavation, but in some designs larger tolerances are permitted in the arch of the tunnel and smaller tolerances in the wall below the springline. Tolerance zones are typically about 200 mm. The 'Equivalent overbreak line' is a theoretical line that represents the average overbreak i.e. the amount of overbreak evenly distributed around the perimeter of the opening. 'Backbreak' refers to a special case of overbreak, where excavation beyond the B line is attributed to the release of blocks along geological structures, rather than as a result of blast damage.

Need for damage measurements

There are two basic reasons why overbreak and underbreak need to be measured. The first is to enable evaluation of the drilling and blasting techniques, and to adjust the method to minimize overbreak and rock wall damage or underbreak. The second is to quantify overbreak, underbreak and excavated volumes for payment or litigation purposes.

Operational aspects

An improved understanding of blast damage, overbreak and underbreak, can lead to improved techniques of controlled contour blasting. Realistic and timely assessment of the results of a round of blasting can be used to make changes in the next round, to improve tunnelling results.

In addition to the obvious savings in avoiding remedial work as a result of a more precise profile, better blasting techniques can lead to a reduction in the damage to tunnel walls. This in turn reduces rock reinforcement and support, decreases rock falls and consequently increases safety (Proctor and White, 1946; Müller, 1959; Kanoh and Ohtsuka, 1983).

Measurements of overbreak and underbreak can result in blasting strategies that reduce overbreak and rock damage to a minimum, while at the same time avoiding underbreak. Minimizing the impact of blasting will give a thinner relaxed or plastic zone (Holmberg, 1979; Sakurai *et al.*, 1985); reduced hydraulic conductivity in the fractured zone (Kelsall *et al.*, 1984); a significant increase in rates of advance and a reduction in cost for explosives and drilling (Hamrin, 1974; Hagan, 1984; Hulkkonen, 1987).

Contractual and litigation aspects

Accurate measurement of profiles is necessary for control of payment for excavation and concrete emplacement, and to resolve contractual disputes and litigation.

Tunnelling contracts typically pay per metre advance along the tunnel, but require the contractor to pay for the volume of rock excavated beyond the 'B' line, and to remove rock inside the 'A' line. Without an accurate measure, the quantities of overbreak and underbreak are frequently the source of disputes. Because of the uncertainty of measuring the profiles, the tolerance between 'A' and 'B' lines in the contract specifications for a tunnel construction may not be well thought out. In some places the specified tolerance is 200 mm regardless of tunnel size or geological conditions. With the possibility of accurate measurement, more realistic tolerances, specific to each tunnel design, can be specified.

The two main causes of blast-related rock damage, inferior rock quality and deficient blasting methods, are an important source of disputes. Discussions as to which of these is the cause of overbreak in a specific tunnel are common, leading to claims for excess costs incurred by the tunnelling contractor as a result of 'unforeseen adverse ground conditions', and to counter-claims by the owner that the contractor failed to achieve a suitable blast design, and/or was negligent in putting his plans into practice.

Often these claims and counter-claims are difficult to substantiate because of a lack of quantitative data. In addition, this kind of conflict leads to lengthy and expensive legal and technical investigations. Three types of data are needed to resolve such a dispute: tunnel profile (overbreak/underbreak) measurements, rock-quality measurements, and quantitative statistics on the blast. This paper deals with overbreak/underbreak measurement.

Measurement criteria

The following are the criteria needed for tunnel profile measurements:

(1) Speed: the underground measurement must be done without interfering with tunnelling operations. Analytical results must be available from one round of blasting even before drilling begins on the next round;

(2) Accuracy and precision: measurements must be reproducible, and of sufficient accuracy;

(3) Simplicity: the method must be easy to implement by the personnel available in the project;

(4) Low cost: purchase, operation, and maintenance of the equipment must be within the budget of typical operations;

(5) Reliability: the equipment must function under a large range of conditions, including high temperature, humidity and levels of dust;

(6) Versatility: the method must be operational for different shapes and sizes of tunnels, shafts and inclines;

(7) Clarity of results: the output data must be immediately usable. In practice this means both graphical and numerical output.

The light sectioning method was developed with these criteria in mind.

State of the art in profile measurement

Overbreak and underbreak often are not measured in tunnels or underground mines, because existing methods are too complicated, expensive, inaccurate, or time consuming. There are currently three methods of actually measuring profiles: surveying techniques – manual or laser based – and photographic light sectioning methods. Predictive methods are also used.

Manual surveying

Manual methods rely on physically measuring the distance to the tunnel from a central control point, using a tape–measure or telescoping measuring rod (e.g. Sunflower Cross-sectioner: Durham, 1913). Measurements are made around the perimeter of the tunnel profile, usually at fixed angular intervals such as 10 to 15°. These methods however are neither reliable nor quick. Typically, to decrease the time needed for measurement, intervals of 5 to 10 m along the tunnel axis are not uncommon. These widely separated measurements are scarcely sufficient for perimeter control or payment purposes. Measurements need to be processed and evaluated manually, although computer processing is possible. The results of this method are frequently in dispute. Manual survey methods are usually slow (the measurement of tunnel profiles normally hinders the construction work), labour intensive and costly, and the results are inaccurate. In addition, they are not capable of measuring large cross-sections, and the results are rarely available in time for the net blast design.

Laser surveying

More recently, electronic, computerized laser equipment has been available to measure tunnel profiles. Field data are recorded in a digital form and then transferred to a computer for evaluation. Triangulating lasers, however, require reflectors to be mounted on the tunnel walls for greatest accuracy, a time-consuming operation. Pulse lasers require no target, relying rather on the reflectance of the rock. These measurements can be affected by dust and humidity in the air, dust and oil on the rock surface, low rock reflectance, and in practice can be used only in tunnels with a radius of 5 m or greater (Hon *et al.*, 1985; Breytenbach, 1985). Although the method is faster and more accurate than manual ones, the instrumentation is very expensive and complex, and also requires the assistance of a theodolite for positioning in the field.

Photographic sectioning methods

Various tunnellers have used a photographic method in which a thin sheet of light is projected radially on to the walls of the tunnel, and overbreak or underbreak is calculated by manual measurements on the photographs (Koppenwallner, 1959; Fellows, 1976; Thompson *et al.*, 1979; Legge and Alocco, 1981). Although field procedures are fast and do not interfere significantly with tunnelling operations, the subsequent manual analysis takes more time, and the results are rarely available before the next round of blasting.

This light sectioning principle is the basis for the research presented in this paper.

Predictive methods

Methods exist to predict overbreak and underbreak from blasting and geological parameters. Bjarnholt *et al.* (1988) predicts the depth of overbreak and underbreak from the spacing of perimeter blastholes. Thidemann (1976) predicted overbreak under two empirical relationships, one between tunnel orientation and joint direction, and the another based on the tunnel's cross-sectional area as a function of the blasthole length. These methods are however predictors and not measurements, and results may therefore, have no validity.

The light sectioning method

Principle

The principle of the light sectioning method (LSM) is quite simple. When a thin sheet of light is projected radially onto the perimeter of a tunnel, the intersection of the sheet of light and the tunnel wall is the cross-sectional profile of the tunnel at that point. If the image of that profile can be recorded from a position orthogonal to the profile (along the tunnel axis), it can be processed and analysed either manually or digitally.

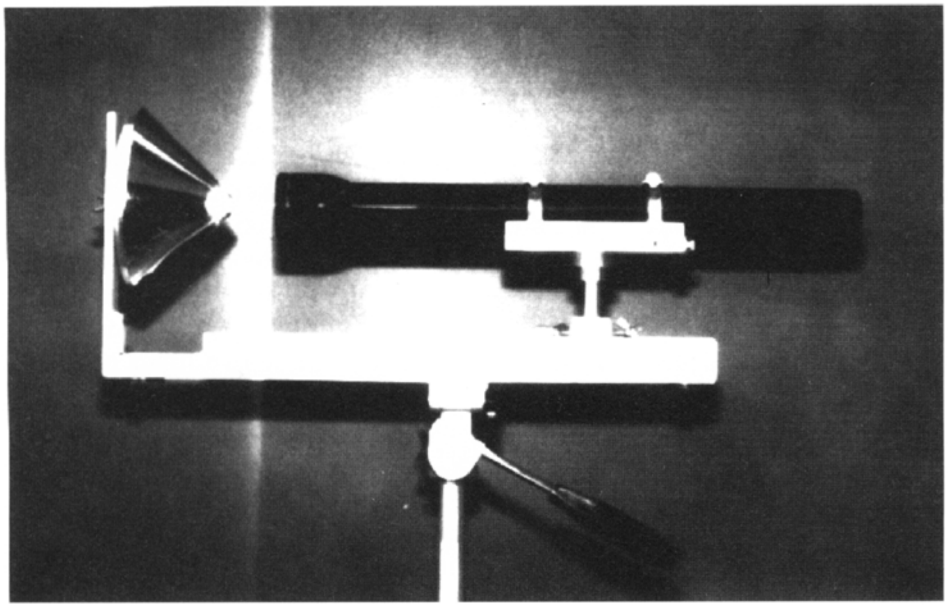

Fig. 3. Light projection apparatus, using a focusable flashlight and a cone mirror

Projection instrumentation

The method for projecting a radial sheet of light, developed for the LSM, uses a light source and a mirror to redirect the light radially. Two different light sources are used: focused white light, and coherent (laser) light. Two different types of mirror are used to redirect the light: a static conical mirror and a rotating planar mirror.

The white light source used was a high intensity 32 000 candle power flashlight with a krypton bulb, using a movable parabolic reflector for focusing (Fig. 3). The coherent light source used was a 25 mW red He–Ne laser. In each case, the width of the radial light beam was found to be 10 to 20 mm for small tunnels (4 to 5 m in diameter).

A coherent light source produces a higher proportion of light reflecting off the rock surface. This advantage is largely negated by the fact that monochrome (black and white) film or video pictures tend to be less sensitive to red light than to the other primary colours or white light. The flashlight is far less expensive and is more robust than the laser. It does not need an external power supply and is easier to align with the mirror. The light of a 25 mW laser is potentially dangerous to human eyesight, and requires the use of protective goggles.

The first cone mirror used was a finely machined steel right cone about 100 mm in diameter at the base, with an electroplated chrome finish. A second cone mirror was made about 50 mm in diameter and plated with silver. The silver plating gave higher reflectivity, and the larger size of the first cone was unnecessary, as most of the light was found to reflect off the tip of the cone. The rotating mirror was a small (5 mm diameter) steel cylinder truncated at a 45° angle at one end, covered by a small glass plate, coated with vacuum-condensed aluminum. This mirror rotated at 2000 rev/min, requiring 0.03 s for a complete sweep of the tunnel wall. The cone mirror is less expensive, more robust, and does not need a power source. The rotating mirror had a higher reflectivity (88% as opposed to 80% for the smaller cone mirror). In addition, it was found that when using the laser it was easier to align the rotating mirror. The rotating mirror was found to be too small for the flashlight beam.

The operating combination that was finally decided upon was to use the flashlight with the cone mirror, or the laser with the rotating mirror. Ultimately the flashlight is preferable to the laser because of its flexibility and much lower cost.

In both cases, the light source and reflector were mounted on a rigid aluminum frame which had a scale bar attached. For small and medium sized tunnels a vertical pendulum is mounted on the frame. Two small lights mounted 1 m apart on the pendulum define both the scale and the vertical (Fig. 4). For larger tunnels, a 2 or 3 m horizontal bar can be used, provided it is positioned with a spirit level. One of these two lights or a third small light can be used for positional reference.

Imaging equipment

Images can be acquired with standard still photography or with video cameras. In either case the captured image must be digitized in preparation for image processing and analysis.

Still photography requires either highly sensitive film and/or long exposures. To reduce the time needed for photographic processing and printing, Polaroid cameras can be used. With these, the photographic processing takes place automatically, and is complete about 1 min after the picture is taken. For the work described here, both 35 mm cameras and a larger format camera with a Polaroid back were used. Both slide and negative (colour, and black and white) film were used at various times. Film sensitivities ranged between 100 and 3000 ASA.

The use of video cameras requires both a high resolution format for image acquisition and storage, and sensitivity to low light conditions. For much of the work described here, a commercially available camcorder using S-VHS video tape and format was used (an example of the results of using this equipment is shown in Fig. 4). The maximum sensitivity of this camera was 1 lux. Experiments are currently being conducted with a monochrome camera with maximum sensitivity of 0.07 lux. Special cameras are available with sensitivities of 0.001 lux, but with lower resolution.

The advantage of the still photography is its greater sensitivity to low light conditions, and potentially higher spatial resolutions. The disadvantages include higher unit costs, a longer processing time if applicable, and the sheer bulk of the number of photographs generated.

Equipment positioning

The light-projection apparatus is situated at the given chainage along the tunnel. In theory, it can be positioned anywhere with respect to the perimeter of the tunnel; deviation from the centre of the tunnel does not introduce distortion into the analysis.

However, a precise reference point must be included in the photographed image. This is accomplished by using a positional reference lamp mounted on the projection apparatus, situated at a known point with respect to the theoretical tunnel profile. The reference lamp can be positioned by theodolite surveying, by measuring from existing survey points on

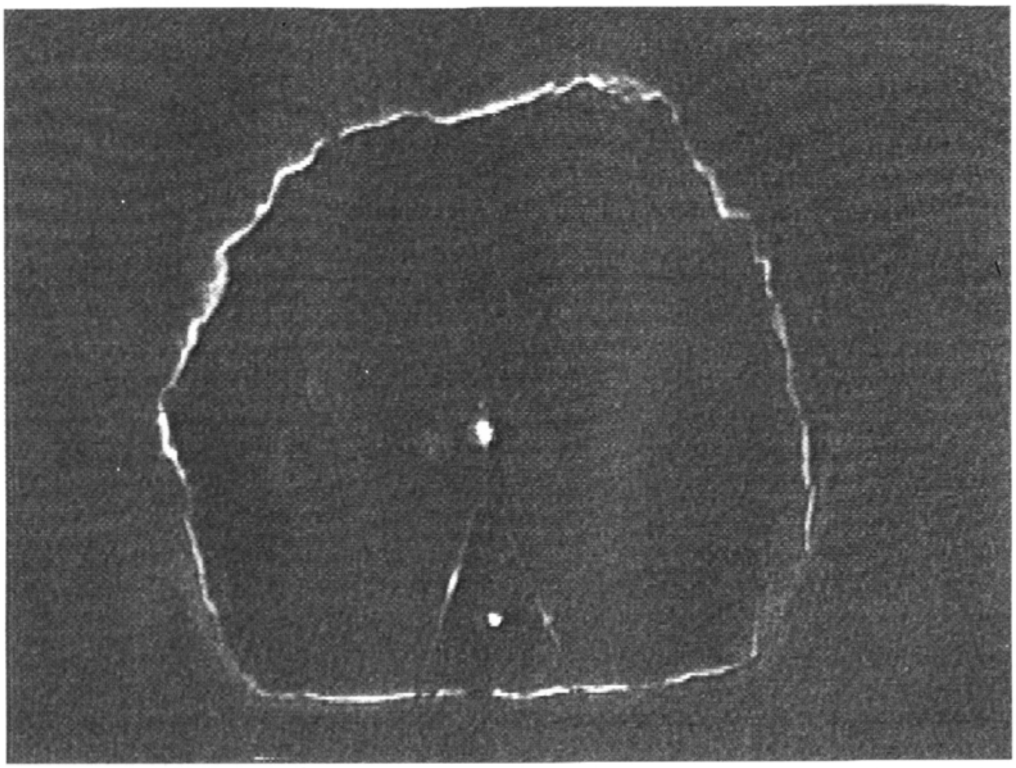

Fig. 4. Digitized greytone image of a profile taken by video camcorder. The central point of light is the control point, and the lower point is exactly 1 m from the control point, along a free-swinging pendulum

the tunnel wall, or by alignment with a small surveying laser. Even though the projection apparatus need not be centred in the tunnel, the analysis becomes simpler if it is. In large tunnels, where it would be difficult to get the equipment high enough, it can at least be positioned horizontally in the centre of the tunnel.

The photographic or video camera needs to be positioned some distance from the projection apparatus along the tunnel axis, and theoretically in the centre of the tunnel. The distance between the camera and projection apparatus depends on conflicting criteria. Assuming that the camera has a telescoping (zoom) lens, which allows the profile to fill the entire image regardless of the distance to the projection apparatus, the following criteria apply: moving the camera away from the projection apparatus (and zooming in at the same time) reduces photographic radial distortion, but moving the camera towards the projection apparatus (and zooming out) reduces the proportion of the tunnel profile that may be obscured by overhanging rock ledges. The selection of the ideal distance depends on the individual circumstances. The camera should be positioned in the centre of the tunnel, if possible. If not, the camera may be placed in the horizontal centre of the tunnel, making the following correction for the vertical deviation:

$$1/\cos\left[\tan^{-1}\frac{h}{d}\right]$$

where h is the vertical distance from the position of the camera to the centre of the tunnel, and d is the horizontal distance between the camera and the projection apparatus.

Image digitization

The captured image, whether on video tape or photographic prints or slides, needs to be digitized to be processed and analysed by computer. A typical low-cost digitizer (frame grabber), can take a standard analogue video signal (RS 170, NTSC) and discretize it into 245 760 picture elements or pixels (480 lines by 512 or 640 samples per line), with a brightness resolution of 256 grey levels. The resulting image is known as a greytone image (Fig. 4). Higher resolution digitization can be done using more expensive digital cameras or scanners.

Image enhancement

The image-enhancement procedure is one which seeks to change the raw greytone image (Fig. 4) into a binary image representing the tunnel profile. The following are the processing steps:

(1) The scale of the image is defined by matching the length of the (pendulum) scale bar in the image to its actual length;

(2) The image is rotated into the vertical position by using the pendulum to define the vertical direction. Careful positioning of the camera at the time of image acquisition can make this step unnecessary;

(3) A low pass filter is applied to the image. This blurring is designed to remove as much as possible of the high-frequency noise, while retaining as much as possible of the useful information in the image;

(4) If necessary, additional noise is manually edited from the image. This could include extraneous light sources or unwanted reflectors present in the image. This step can be avoided by turning off all extraneous light sources at the time of image acquisition, and proper exposure control;

(5) The rather fuzzy tunnel profile is sharpened by a thresholding procedure, in which all pixels above a threshold value are set to white, and all pixels below this value set to black, thus creating a binary image;

(6) The tunnel profile is thinned to a unique line of unit thickness by a skeletonization algorithm, a multiple-erosion procedure which retains the topological integrity of the profile, at a thickness of exactly one pixel;

(7) Several automatic, semi-automatic, or manual procedures may be used to reconstruct small sections of the tunnel profile, which are missing at this stage, either because of inadequate lighting or reflectance, or because of overhanging rock ledges.

After these steps, the image is fully enhanced, and available for analysis.

Image analysis

The image-analysis procedure is one which compares the theoretical tunnel profile with the measured one, using the principle of Venn diagrams. First, the theoretical tunnel profile (A, B, and C lines) are superimposed on the actual tunnel profile. On the actual tunnel profile (Fig. 5a): excavated zone is X, *in-situ* rock is R. On the theoretical tunnel

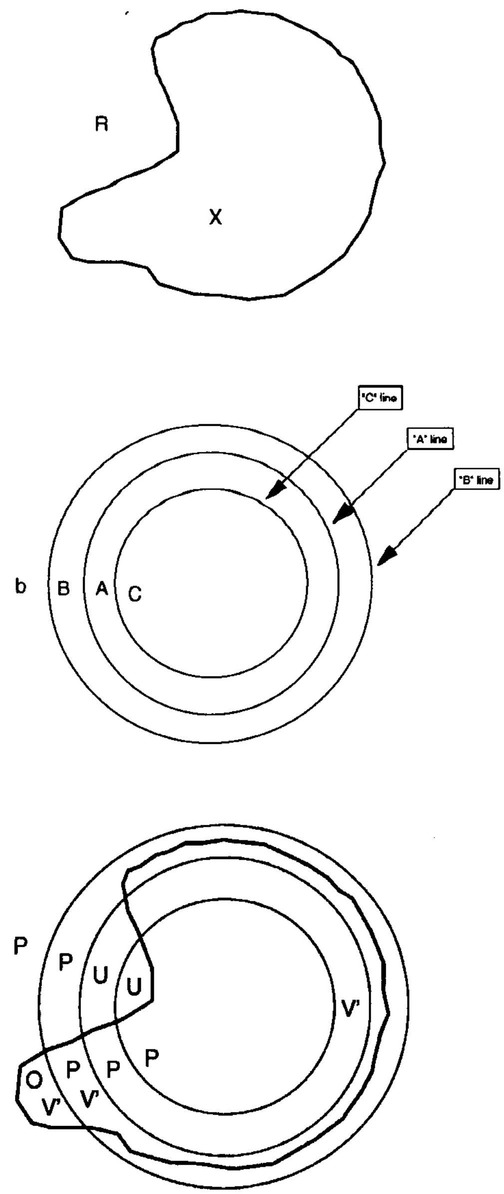

Fig. 5. (a) Idealized excavated tunnel profile (with overbreak and underbreak), (X = *excavated part*, R = *in-situ* rock). (b) Theoretical tunnel profile limits (b, B, A, C represent the various zones divided by the design lines). (c) Superimposition of excavation and design lines (O = overbreak, U = underbreak, P = properly excavated/non-excavated rock, V′ is the concrete zone)

profile (Fig. 5b): inside the concrete (C) line is *C*, inside the maximum excavation (A) line but outside the C line is *A*, inside the excavation payment (B) line, but outside the A line is *B*, outside of the B line is *b*.

Superimposing the two images at proper scale, rotation, and position (Fig. 5c), we find the following relationships, where $\cap$ is the intersection operator:

$$\text{Overbreak } O = X \cap b$$
$$\text{Underbreak } U = R \cap A + R \cap C$$

$$\text{Proper excavation } P = R \cap b + R \cap B + X \cap B + X \cap A + X \cap C$$

$$\text{Volume concrete } V' = X \cap b + X \cap B + X \cap A$$

This last relationship holds true only if no underbreak is present. If it is, the actual concrete volume (V) will be the designated volume (V') plus the underbreak volume (U), plus the further volume of rock excavated past the A line when the underbreak is removed (V_e):

$$V = V' + U + V_e$$

or

$$V = (X \cap b) + (X \cap B) + (X \cap A) + (R \cap A) + (R \cap C) + V_e$$

V_e cannot be predicted, so to measure concrete volumes accurately the entire analysis needs to be redone after the underbreak has been removed.

This analysis is presented both in statistical form, and graphical form (Fig. 6). The analysis furthermore displays the underbreak and overbreak components in terms of directional rosettes (Fig. 7).

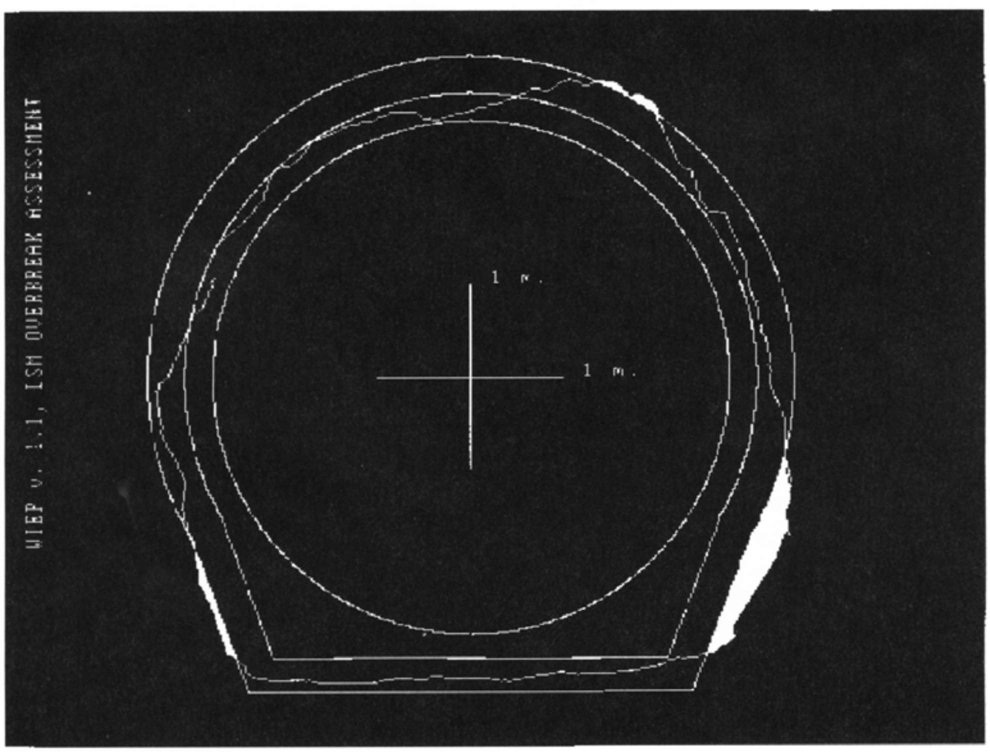

Fig. 6. Graphical result of analysis, showing tunnel design lines superimposed over the actual tunnel profile. Overbreak is shown in light grey, and underbreak in dark grey

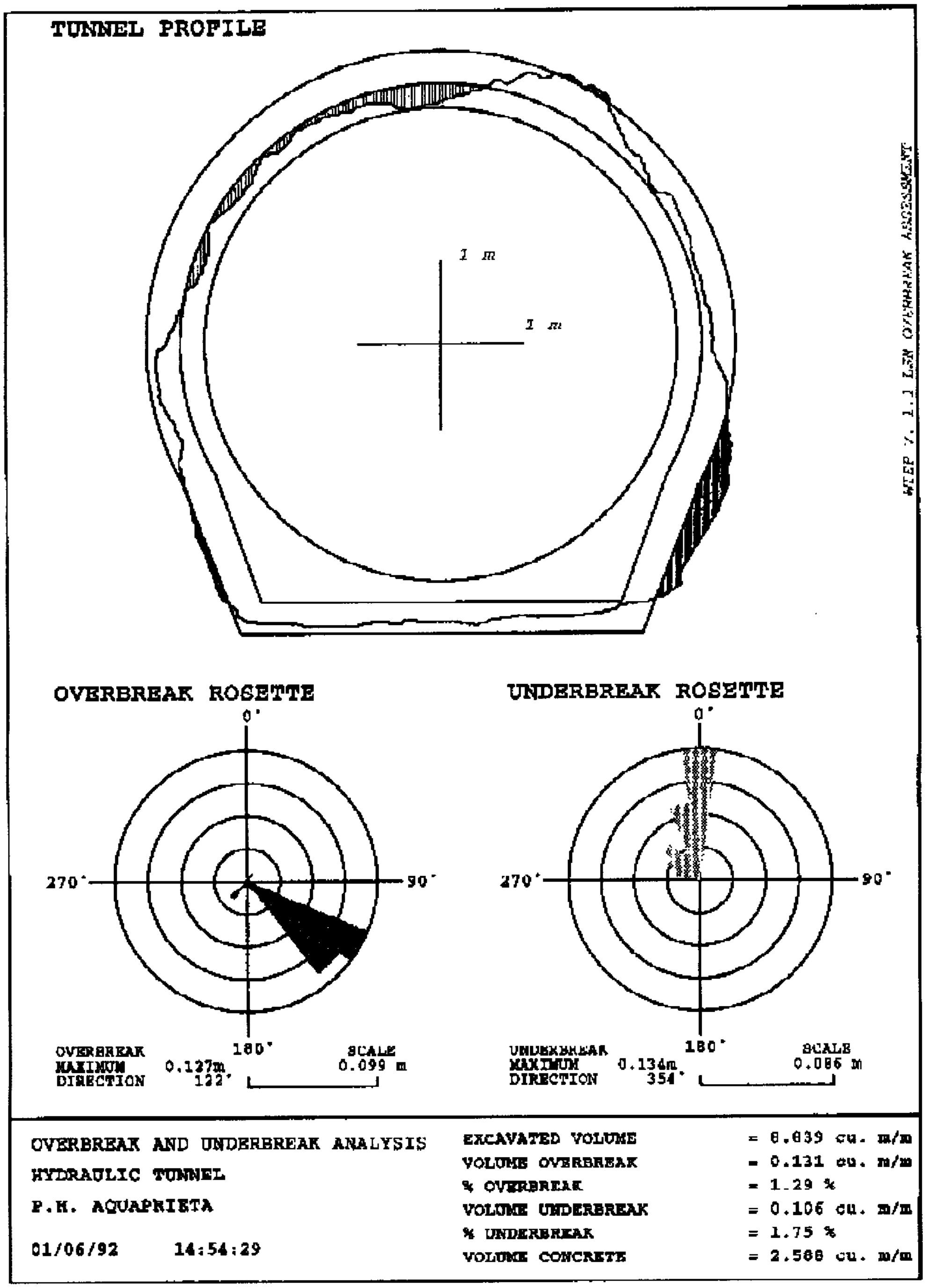

Fig. 7. Graphical and numerical results of analysis, including overbreak and underbreak directional rosettes

Application and evaluation of the method

Preliminary evaluation

The method was first tried out in a relatively smooth-walled brick-lined pedestrian underpass, of 3.7 m by 2.9 m, in Cambridge, Ontario, Canada. In this experiment the cross-sectional area of the tunnel was carefully measured by tape, and then using the digital LSM method. Differences between the manual and digital measurement were found to be about 1%.

Manual comparison: Ansil Mine

A field trial was conducted at the Ansil Mine, Quebec, Canada, where a drift in andesite with an average diameter of 4.6 m was evaluated. The profile of the drift was manually measured at 16 points, and the cross-sectional area calculated by graphical measurements. When compared to the LSM method which samples the profile at about 1500 points, the difference in the measurements was 3%. Because of the greater sampling rate (about 3 times faster), the LSM is considered the more reliable.

Manual comparison: Trigomil Irrigation Tunnel

Further trials of the LSM were conducted in a 3.5 m tunnel at the site of the SARH (Secretary of Agriculture and Hydraulic Resources) Trigomil Hydraulic Project, 150 km SW of Guadalajara, where the conduction tunnel was constructed by the Federal Commission of Electricity (CFE) of Mexico, excavated by drilling and blasting (Ibarra, 1990).

In this experiment 22 cross-sections were profiled using the LSM, and compared with profiles obtained manually by the Surveying Department of CFE using a theodolite. The overbreak and underbreak calculations of the two methods resulted in differences of between 4% and 6%. The light sectioning method reproduced the shape of the tunnel continuously, whereas the manual method used an average of 22 points (interpolations about 500 mm apart) around the perimeter of the tunnel.

Low reflectivity: Aguaprieta Hydroelectric Tunnel

Further field trials were conducted in the 6.5 m conduction tunnel in basaltic rock at the CFE Aguaprieta Hydroelectric Project, on the outskirts of Guadalajara, Mexico. The objective was to determine the lighting and photography requirements in larger diameter tunnels with low rock-reflectance factors.

Using a flashlight, cone mirror, and a 1 lux video camcorder, images were taken in which only 70% of the profile length was visible, primarily because of the low reflectivity. Using a 25 mW He–Ne laser and a higher reflectance mirror, images obtained showed more than 92% of the profile length. Not all missing portions of the profile are as a result of poor lighting; some may be the result of overhanging rock ledges.

Large tunnels: Aguamilpa'Diversion Tunnel

More trials were conducted on the diversion tunnel for the Aquamilpa Hydroelectric Project located about 275 km NW of Guadalajara, Mexico. Here tunnel diameters of up to 22 m were found. Despite a relatively high reflectivity, the large dimensions led to a high degree of missing segments in the profile.

Using the laser and higher reflectance rotating mirror increased the amount of light projected onto the tunnel wall. However, it was necessary to use a Polaroid camera with time-lapse exposure to get the best possible profile.

Conclusion

The light sectioning method uses a radial sheet of light to measure a tunnel profile. An image of the final tunnel profile is acquired and digitised. This profile is superimposed over the design profile in order to identify and quantify zones of overbreak and underbreak.

The LSM for tunnel profiling has been found to be inexpensive, reliable, and simple to implement. Using automatic image processing, accurate results are available quickly with graphic clarity.

Comparisons with manual profiling have revealed the method to be as accurate or better in small tunnels, and considerably easier in larger tunnels. The equipment is considerably less expensive than laser surveying instruments.

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