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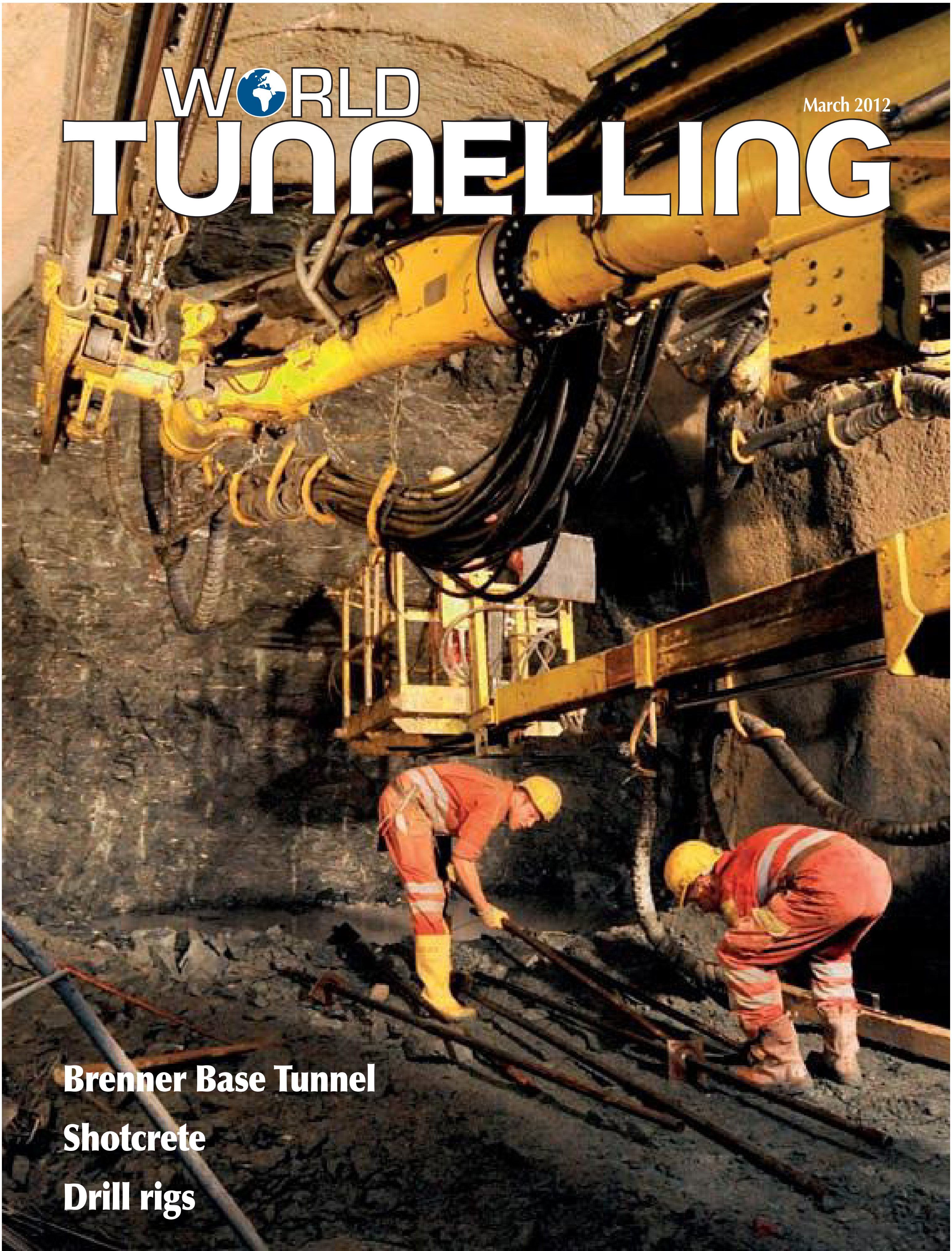

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Potential savings in motion

Urs Müller, Patrick Kuhn & Gabriele Kadner discuss a novel way to boost quality and cost savings, based on kinematic crack detection and profile documentation

IN tunnels, crack detection and documentation of newly built concrete interior vaults and subsequent regular inspections are carried out using traditional standard procedures, such as manual recording from mobile scaffolding.

These methods, which require measurement by hand, only document cracks that have been detected visually during a tunnel inspection. This is also time consuming, requires high personnel effort and is subject to a significant amount of interpretation. A requirement has been identified for complete automated documentation of the overall state of a tunnel.

CUSTOMER REQUIREMENTS

Increasing cost pressures plus the demand for shorter building times, security and quality in tunnel construction have introduced a requirement for novel technical solutions in the field of crack detection and documentation.

The following lists key requirements and customer needs that must be met:

- Time-saving surveying solutions with fast data acquisition and classification;
- Quality assurance through full, high-quality state capture and documentation;
- Absolute positioning;
- Regular repeated measurements;
- Meaningful, high resolution information;
- Detection and documentation of crack widths > 0.3mm;
- Map of cracks with a precision of 0.1mm to predefined classes;
- Simple, automatic data synchronisation (before/after);
- Accurate documentation of structural changes;
- Improved life-cycle management;
- Optimised maintenance after a standard inspection;
- Risk minimisation;
- Reduction and prevention of track closures;
- Extension of tunnel lifetime;
- Combination of crack detection with profile control, and
- Maximum savings potential by optimisation of formwork.

Today, the documentation of all cracks wider than 0.3mm is a standard requirement in tunnel construction. Cracks wider than 1mm, or those with a vertical offset of more than 0.5mm, are documented, classified and must be partially grouted as a minimum action.

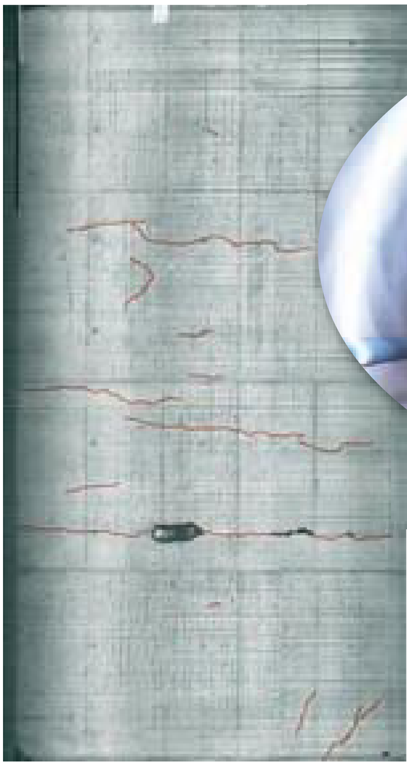

Figure 2: documented block with classified cracks

MARKET ANALYSIS

Modern technology, including high-quality laser scanning, is starting to be adopted for crack detection. With a typical dot matrix of 3mm x 3mm and a measuring point size from 1-2mm, laser scanners can survey a surface precisely and with a high density of geometric measurements. Furthermore, profiles can be derived easily.

A typical laser scanner can capture measured points at 2-3mm spacing. Therefore, laser scanning might not always be a reliable solution if it is necessary to record the shape of cracks at 0.1mm accuracy or better.

CRACK DETECTION & CLASSIFICATION

Modern-day customer requirements, as well as the fact that laser scanning will not always provide the required data accuracy/resolution and quality for crack detection, have motivated terra international (TI) to search for alternative solutions. Traditional photogrammetric recording technology can meet the requirements, but it is no longer economical compared with modern digital image editing.

Figure 1: tunnel locomotive with cameras and lighting

Based on these facts, TI has developed a novel, future-proof system, called t_crack – an economical system that meets all specifications described previously. It is a recording technology that combines high-resolution digital image acquisition with absolute, kinematic positioning technology.

As a subcontractor to Strabag, TI has deployed the t_crack detection system successfully at the Gotthard Base Tunnel project in Amsteg and Erstfeld. In 25km-long tunnels, t_crack has accurately detected, classified and documented cracks within pre-defined tolerances (figure 1).

STRUCTURE, FUNCTION & WORKFLOW

The t_crack system includes ten high-resolution digital cameras, mounted on a site vehicle, which is driven along the centre of the tunnel so that the cameras achieve complete coverage of the internal walls and surfaces. The simultaneous image capture of all ten cameras is controlled by a central computer, mounted on the vehicle. Individual image strips, each covering a tunnel surface area of around 10mm wide, are stored in separate files. The strips are then automatically merged to create continuous, overlapping images.

The speed at which the measuring vehicle can move through the tunnel while capturing images is about 2.5km/h (ie 0.7m/sec of image acquisition can be achieved). Given sufficient preparation, a 10-15km long tunnel can be documented in a single shift.

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CRACK DETECTION

The most important requirement of this measurement procedure is to achieve optimum lighting of the tunnel surfaces. Only a very bright illumination allows sharp image acquisition with short shutter speeds.

Special post-processing procedures align and scale the captured image strips, and rework the images if necessary. Then, the whole image of the tunnel surface is unwrapped into a horizontal plane. A tunnel of 10m diameter would be unwrapped to produce a horizontal plot of around 22m wide and 10m long (typical 'block' joint distance). A consistent scale in the x and y directions enables the image to cover an A4 page, which makes it ideal for printing.

A processed image between two block joints is shown in figure 2. The image shows all the details of the tunnel face and demonstrates that the cracks are easy to identify. In this example, the pixel size is around 0.5mm on the tunnel surface. Using special software to generate a line along the visible cracks, a 0.1mm-wide crack can be recorded and properly classified.

The specification of the inspection is agreed with the client before the start of work and can include a colour key, which defines the classification and corresponding crack length in each image.

Both client and contractor receive a copy of the independently produced inspection report.

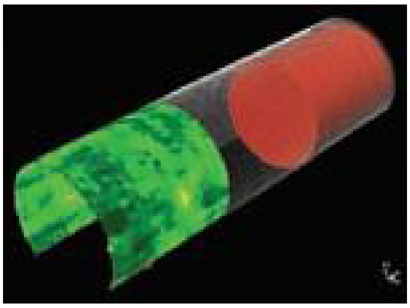

Figure 3: digital formwork fitting

The contractor can use the report to accurately calculate the amount of grouting to be carried out, while the client is kept informed of all work required.

The accuracy of crack identification in the processed images is closely checked on site by the contractor and the site management staff during the grouting process. This is an important phase as the images from the report form the basis for calculating the compensation for this work.

A major advantage of this new crack documentation method is that a very limited amount of preparation work is required by the construction company, but the section of tunnel to be inspected must first be cleared of any obstructions. However, the initial cleaning of the tunnel walls, which is required for manual inspections, can be disregarded.

The t_crack system can be mounted on a variety of vehicles, such as a tunnel locomotive. The use of bulky scaffolding is not required when inspecting tunnels. Closures and restrictions to tunnel access are limited to the one track on which the vehicle is driven. If necessary and if causing an obstruction, the vehicle can be driven temporarily on to a spur track. Using this system requires just two people – a driver and an engineer.

In areas of tunnel without tracks, such as cross-galleries, the same measuring technology can be mounted on to a cart, which is pushed by a driver.

Typically, the recording of cross-galleries should be carried out using a stop-and-go method, where images are recorded every 2m. Processing can be carried out using the same software and workflow as with the fully kinematic solution.

This new method has become the basis for regular site inspections in tunnels because, in addition to being able to supply much more detailed documentation, the overall time spent in the tunnel is reduced significantly. This is particularly beneficial in railway tunnels, where service interruptions can be reduced substantially.

OPTIMISATION OF FORMWORK

Strict requirements regarding minimum formwork thickness and the accuracy of the clearance profile within the tunnel must usually be met before applying concrete to the tunnel surfaces during construction.

The t_crack system can be combined with kinematic laser scanning to provide rapid and accurate positional measurement of tunnel surfaces. When planning and using adjustable formwork, this data can offer very large savings potential, which will become increasingly important in the future.

The kinematic measuring system was originally developed for support at the Gotthard Base Tunnel. It uses several geodetic scanners, with an inertial positioning system mounted on a tunnel locomotive. The absolute referencing of the local coordinate system of the tunnel is made using a total station.

Total stations measure the system's real-time 3D position by following the location of a calibrated prism, mounted on top of the measuring vehicle, and referencing the real-time measured position of the prism into a fixed-point network.

The prism positions are continuously transmitted via radio frequency to the locomotive. The accurate orientation and position of the measuring system is then adjusted in real-time by combining the readings from the initial measurement device. As a result, the scanners can record a high resolution, 3D point cloud of the tunnel surface in the coordinate system of the tunnel.

In order to remove the likelihood of any height measurement errors due to refractions from the prism, multiple total stations must be positioned along the tunnel to allow the prism to be within 150m of a total station at all times. This means that the total stations must not be placed more than 300m apart from each other which, typically, coincides with the distances between cross-galleries.

Total stations are usually positioned in the middle of any sections of tunnel to be measured. The total time required to measure a stretch of 300m is typically one hour, including installation and packing up of equipment. This work can be carried out quickly by two people. The scanning speed depends on the required data density and lies typically between 0.7m/s and 1m/s. At these speeds, the achievable distance between measured profiles is typically 10-20mm.

For control purposes, the point cloud coverage is monitored on site in real time on a display console. Any gaps are closed by an additional surveying pass. The measuring system is often rotated by 180° during a second run to increase reliability, as well as for the more detailed detection of smaller objects.

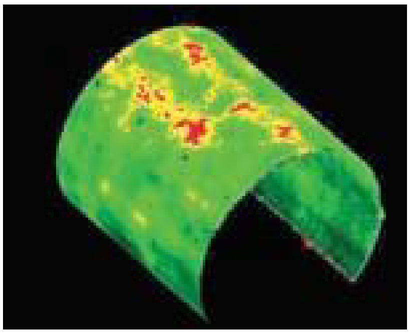

Figure 4: documentation of concrete thickness

DATA PROCESSING FOR FORMWORK

All data from inspection surveys is stored on external hard disks and transferred to an analysis centre. In the first processing step, a plausibility check of all collected data is followed by a thinning out of any scan points to a regular density, using intelligent software algorithms.

This does not simply delete random points – it identifies the most relevant point for the application within a predefined surface area (cell). All other points are deleted. Thus, the amount of data can generally be optimised to less than 10% of the original size without loss of pertinent detail.

The point data is used to form a 3D CAD model of the planned formwork, including all possible adjustment components. The 'digital formwork' is imported into the point cloud data to compare it against the measured tunnel profiles. Analysis ensures all predefined parameters are met and that the calculated volume of required concrete is minimised (figure 3).

Various options for preferred formwork profile solutions are included in the analysis. Where small undulations in the rock face might conflict with an optimum solution, the analysis can suggest a different formwork profile; this might include a need for more concrete, or the system can calculate the amount of rock that would need to be excavated in order to fit the original preferred formwork to the revised tunnel profile.

The most economical solutions, which also profit from minimal required use of concrete, can be derived in this way. Of course, any proposed changes to the tunnel profile must be monitored to ensure there is no impact on the compatibility of a block at its joint with a neighbouring block.

Four reference marks are mounted on the formwork in order to calculate absolute positioning of the required shuttering. The horizontal and vertical offset of the shuttering from the tunnel surface is calculated from these points along the tunnel axis. In preparation for installing the formwork, the engineer can mark additional setting-out points on the tunnel surface in the vicinity of the reference markers.

The formwork reference point values for each block are reported to the foreman as part of the analysis protocol.

Once the defined structure of the formwork is set, the exact volume of required concrete needed to fill the void between the formwork and the measured tunnel surface is calculated. This can be calculated to an accuracy of approximately 0.5m^3 for each block of a tunnel.

In order to document the calculated amount of concrete, the digital surface of the tunnel is unwrapped around the first line of the tunnel and is plotted as a 2D plan of each block. The image is then colour-coded according to the thickness of concrete required. Compliance with the specifications can therefore be documented easily and clearly (figure 4).

COST & POTENTIAL SAVINGS

A cost-benefit analysis can be presented using an example of a tunnel with a 10m-diameter. Unrolling the cross-section from each block provides a surface width of around 22m. This equates to a working area of about 22,000m^2/km, which would need to be optimised. Assuming 20mm of concrete thickness can be saved by adopting the methods above, this would result in a saving of 440m^3/km of concrete. Assuming a standard concrete price of about US$330/m^3, a saving of over US$145,000 can be achieved.

> "This novel process will cost less than one-third of the savings made"

When analysing total cost savings, the end value must be offset by the costs of surveying and data processing. However, compared to traditional measurements and data evaluations, as well as additional costs for adjustable formworks, this novel process will cost less than one-third of the savings made – even for short tunnels.

SUMMARY

Today, with increasing demand for lean design in construction projects, t_crack will meet all requirements and customer needs by increasing the overall quality of construction, reducing costs and minimising waste.

This new technology delivers genuine win-win solutions for all stakeholders. The client receives complete, high-quality documentation of the final structure at cost-effective prices. The site manager receives additional information for improved quality control. And the development of improved project specification, documentation and plans, while minimising construction costs, benefits the contracting company.

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