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Report to ITA Working Group on Maintenance and Repair of Underground Structures:

State-of-the-art of Non-destructive Testing Methods for Determining the State of a Tunnel Lining

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Abstract—*This report describes various methods of non-destructive testing for tunnel linings, based on information presented to and contributed by members of the ITA Working Group on Maintenance and Repair of Tunnels. The report defines the requirements for non-destructive testing methods, and briefly describes and compares various methods, including mechanical oscillation techniques, radiation techniques, electric and electronic techniques, and optical techniques. Georadar, thermography and multispectral analysis, as applied for high-speed investigation work, are considered in detail. The authors discuss results of tests performed by the German research organisation STUVA, relating to rapid inspection of tunnel linings. The report includes descriptions of the types of investigations carried out in eight countries.*

Résumé—*Cet article décrit diverses méthodes d'essais non destructifs pour les revêtements de tunnels, basées sur des informations fournies et discutées par les membres du groupe de travail de l'AITES "Maintenance et réparation des tunnels." Le rapport définit les spécifications relatives aux méthodes d'essais non destructifs, et décrit brièvement, en les comparant, diverses méthodes incluant, les techniques basées sur les oscillations mécaniques, les radiations, ainsi que les méthodes électriques, électroniques et optiques. Les analyses par géoradar, thermographie et multispectrales, appliquées pour les travaux de reconnaissances rapides, sont examinées dans le détail. Les auteurs discutent des résultats d'essais réalisés par la STUVA, organisme de recherche allemand, portant sur l'inspection rapide des revêtements des tunnels. La rapport comporte des descriptions des types d'investigations conduites dans huit pays.*

1. Introduction

In 1991, the International Tunnelling Association's Working Group on Maintenance and Repair of Underground Structures began a study of available techniques for non-destructive examination of tunnel linings; and, especially, of ways of looking into and through the lining into the surrounding ground.

The Group was fortunate that the German research institute STUVA (Research Association for Underground Transportation Facilities) was at the same time carrying out basic research into this topic. The Vice-Animateur of the ITA Working Group, Dr.-Ing. Alfred Haack, who is also the director of STUVA, shared the results of this work with the Group. A report by STUVA dealing with non-destructive testing was presented to the Working Group at its 1992 meeting.

This report summarises the STUVA report and also incorporates comments and suggestions submitted by members of the ITA Working Group. In particular, Section 5 compares the types of testing of tunnels that is currently performed in various ITA countries, based on contributions of the Working Group members and other ITA representatives.

The research carried out by STUVA related to rapid inspection of tunnel linings: for example, using equipment mounted on vehicles moving at speeds of several kilometres per hour. The testing that was carried out, which is described in Section 6 of this report, was related to that work and to the discovery of defects in tunnels lined with *in-situ* concrete.

This report should be considered an interim document, as it does not fully explore the full range of possibilities for non-destructive inspection of linings. These techniques constitute a developing topic, and one that will occupy the Group again in a future study. Suggestions for research that remains to be done in the field are given in the closing section.

2. Requirements for Non-destructive Testing Methods

The aim of non-destructive testing methods is to obtain complete, reliable and reproducible data on the state of the entire tunnel shell. These methods may be applied:

- In approving new tunnel structures;
- For long-term monitoring of existing tunnels; and
- For examining the outcome of rehabilitation measures in tunnels.

The prerequisite for successfully applying non-destructive testing methods in tunnels is that the methods must fulfill certain requirements dictated by the special conditions prevailing in traffic tunnels. To fulfill these requirements, equipment manufacturers will need to adapt existing testing methods which, so far, have largely been used in other fields, to the specific conditions found in tunnels; and de-

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velop new testing methods especially for such applications.

In addition, the requirements catalogued below are intended to provide a means of evaluating the suitability of existing non-destructive testing methods for application in tunnels, so that conventional tunnel inspection procedures can be improved or replaced with better ones.

2.1 General Requirements

Specific constructional characteristics of tunnels make the application of non-destructive testing methods more difficult in some cases, as, for example:

- When the tunnel lining is accessible only from one side.
- For some wall and roof linings (tiles, coatings as well as metal linings).
- When some tunnel installations, such as lighting, ventilation plants, and contact lines, are present.
- When steel reinforcement in concrete has been used.

Despite the complications these conditions present, a non-destructive testing method should be capable of providing a description of the state of the entire tunnel lining, without the removal of the tunnel installations, if possible.

The following general requirements apply to non-destructive testing methods designed to trace damage from moisture or cavities:

1. With the aid of non-destructive testing methods, it should be possible to trace and identify defects in the entire tunnel shell (e.g., leaks, cracks, corrosion, cavities).

2. The control units must be capable of tracing defects from the inside of the tunnel only.

3. It must be possible to use non-destructive testing methods successfully in tunnels having different types of linings, such as tunnel shells made of natural stone, concrete or cast iron.

4. The results of non-destructive testing methods should never be influenced or falsified by installations in traffic tunnels (such as lighting or ventilating systems) or by the overhead contact line. Furthermore, the testing methods themselves must not interfere with the operation of tunnel installations or the safety of the control systems.

5. The control units must be resistant to vibrations.

6. The testing methods must operate properly in the climatic conditions encountered in the tunnel. In this regard, air temperatures varying from approx. 0°C to 25°C, relative humidities between 40% and 90%, and air speeds of up to approximately 2.5 m/s have to be taken into consideration.

7. The control units used for examining the tunnel must be provided, to the extent necessary, with a back-up power source that is independent of the main supply.

8. As far as possible, the test results should be available immediately after the investigation in the tunnel itself, in order to facilitate a direct analysis of potential defects. Furthermore, a visual presentation or a digital recording of the test results should be available for documentation purposes.

9. The control units must not constitute a source of danger for tunnel users or for the operators.

2.2 Requirements of Non-destructive Testing Methods for Rapid Preliminary Investigations

Non-destructive testing methods for rapid preliminary investigations are intended to provide an initial survey on the state of the tunnel. They must fulfill the following requirements:

10. An attempt must be made to examine the entire tunnel shell thoroughly using the non-destructive testing methods.

11. The examination of lengthy sections of tunnel must be carried out as quickly as possible, e.g., during short breaks in operation. To accomplish this objective, the travelling speed of an inspection car carrying one or more test control units should be at least 5 km/h.

12. The accumulated data must be stored for subsequent evaluation purposes. It must be possible to adjust the storage capacity of the recording units to given requirements, such as frequency of measuring points and length of the tunnel.

13. Defective zones must be established as accurately as possible. The results should be reproducible in order to obtain valid statements within the framework of long-term monitoring.

2.3 Requirements of Non-destructive Testing Methods for Detailed Investigation

After defective zones have been localized with the help of rapid but thorough preliminary investigations (see Section 2.2), detailed investigations are needed in order to obtain more precise information on the extent of the damage. The following requirements pertain to testing methods for detailed investigations:

14. The testing methods should be essentially non-destructive in order to ensure, for example, that the tightness of the joints and sealing systems is not affected. Consequently, material samples should be taken only in exceptional circumstances.

15. It should be possible to carry out the examination at any point of the tunnel shell, as well as in an overhead or an inclined position.

16. The control unit should not weigh more than 10 kg, so that it can be carried and utilized by one person over a long period of time.

3. Techniques Examined

3.1 General

Techniques that require access to both sides of the structure, or which use equipment appropriate only to the laboratory, were not included in this study. The techniques considered are briefly described below. Table 1 summarises the scope of advantages and disadvantages associated with the techniques discussed below, and conclusions regarding their applicability for both rapid and detailed investigation of tunnel linings.

3.2 Techniques for Measuring Tunnel Distortion

By measuring the internal profile of the tunnel at known points, at regular intervals of time, and with sufficient accuracy, deformation of the lining can be observed and monitored. The technique is well-known and several methods, including laser profilometer and stereoscopic photography, have been developed.

3.3 Mechanical Oscillation Techniques

These techniques include:

- Structural dynamic methods (direct vibration).
- Seismic reflection and refraction.
- Microseismics and sonic emission analysis.
- Ultrasonics—reflection and indirect surface transmission.

All of these techniques involve measuring the response of the structure to an artificially induced vibration. The response pattern of a "sound" structure is established by reference to known details of the lining and observation of proven good sections of the tunnel. Defects will cause the response pattern to vary. These techniques are well known in the engineering industry generally.

3.4 Radiation Techniques

These techniques, which include gamma ray backscatter and neutron backscatter, measure the effect of the target mass on a beam of sub-atomic particles. They are used especially in road construction, to determine the density and moisture content of road base and slab materials.

Table 1. Advantages and disadvantages of various techniques for non-destructive investigation of tunnels.

Techniques		Mainly Applied for:	Value for Tunnel Application	Problems With:	Advantages
Mechanical Oscillation Techniques	Structural dynamic methods (direct vibration)	Bridges; aboveground buildings	Very low	Uneven wall thickness; rock in-homogeneity; varying ground water level	None
	Seismic reflection	Geological investigations; determination of layer thickness	Low	Accuracy; speed	Only connected with very large cavities behind the tunnel lining
	Microseismics and sonic emission analysis	Coal mines; laboratory tests	Very low	Reproducibility; accuracy	Investigation of structure-borne noise
	Ultrasonics—reflection and indirect surface transmission	Steel construction; mechanical engineering; pipelines; tanks	Very low	Coupling to test ground, concrete inhomogeneity; speed of diffusion by aggregates; accuracy	None
Radiation Techniques	Gamma ray backscatter	Road construction, earth construction; investigation of moisture content and density	Very low	Speed; penetration depth	None
	Neutron backscatter		Low	Speed, penetration, depth	Indication of moisture content point-by-point
Electric and Electronic Techniques	Eddy current methods	Electricity conducting metals; crack detecting for pipelines, indication of reinforcement	Low	Speed, non-conducting materials; penetration depth.	Indication of reinforcement
	Georadar	Ground investigation of bridges and tunnels	High	Evaluation; reflection by metallic cladding; speed	Good penetration depth
	Electrical potential methods	Detection of corrosion of reinforcement	Low	Speed; penetration depth	Detection of corrosion
Optical Techniques	Infrared thermography combined with visual determination	Check of thermal insulation; tunnels	Very high	Certain tunnel climates; evaluation; heat release of installations	Detection of cavities and moist patches, cracks, etc.; high speed
	Multispectral analysis	Monuments, buildings, tunnels	High	Speed; vibration; demand of powerful lighting; evaluation; penetration depth	Detection of small and dry cracks

Table 2. Dielectric constant and diffusion speed of electromagnetic waves in various materials (Boscomer Services S.A. 1989; van Egmond 1987; Gesellschaft für Geophysikalische Untersuchungen 1988; Pezzati et al. 1985).

Material	Relative Dielectric Constant	Diffusion Speed (m/s), approx.	Conductivity (mS)
Air	1	$3 \cdot 10^8$	0
Water (pure)	81	$3,3 \cdot 10^7$	0,1 - 0,3
Salt water	81	$3,3 \cdot 10^7$	400
Ice	4	$1,5 \cdot 10^8$	0,1 - 0,3
Concrete (dry)	6	$1,2 \cdot 10^8$	1
Concrete (moist)	12	$0,86 \cdot 10^8$	5
Granite (dry)	5	$1,3 \cdot 10^8$	< 0,001
Granite (moist)	7	$1,1 \cdot 10^8$	1
Limestone (dry)	7	$1,1 \cdot 10^8$	< 0,001
Limestone (moist)	8	$1,06 \cdot 10^8$	25
Sandstone (moist)	6	$1,2 \cdot 10^8$	40
Basalt (moist)	8	$1,06 \cdot 10^8$	10
Concrete, sandy (dry)	4	$1,5 \cdot 10^8$	0,1
Concrete, sandy (saturated)	30	$5,5 \cdot 10^7$	7
Clay (saturated)	10	$0,95 \cdot 10^8$	30
Metals	1	$3 \cdot 10^8$	$> 10^8$

3.5 Electric and Electronic Techniques

These techniques, which include eddy current methods. georadar and electrical potential methods, are widely used in the construction industry. Eddy currents are used to detect the presence of reinforcement. Georadar is used to detect anomalies in the structure or ground mass. Measurement of electrical potentials between reinforcement bars will indicate corrosive activity that may be taking place.

3.6 Optical Techniques

Optical techniques include infrared thermography and multispectral analysis. Both methods involve photographing the surface of the lining, using film and filters that are sensitive to the visible light spectrum or to infrared wavelengths, respectively. Anomalies in the surface of or within the lining cause changes in the photograph pattern, thereby revealing surface defects that are not visible to the eye.

3.7 Discussion

Table 1 summarises the scope advantages and disadvantages of the techniques mentioned above and conclusions about their applicability for both rapid and detailed investigation of tunnel linings.

4. Methods Suitable for High-speed Investigation Work

Of the methods mentioned in Section 3 that at least partly fulfill the requirements discussed in Section 2, three seem to be suitable for rapid preliminary examinations: georadar, thermography and multispectral analysis. In this section, these methods are examined in more detail.

4.1 Georadar

In principle, the georadar method is similar to the seismic reflection method (see Section 3.3): the difference is that georadar operates with electromagnetic waves rather than with sound waves. The main frequencies of the antenna are located between 80 and 1,000 MHz. The diffusion of the electromagnetic waves is primarily influenced by two physical properties of the material: conductivity and dielectricity.

Conductivity—the ability of a material to conduct electricity—has a major influence on the amplitude attenuation of the waves in the material. Dielectric properties govern the diffusion speed of electromagnetic waves in a material. The conductivity and the dielectric constants for various materials are given in Table 2.

As the radar waves pass through a structure, the intensity of the continuous waves is constantly weakened. This occurs, first, due to reflection against good electric conductors and against discontinuity points of the dielectric; and, second, through amplitude attenuation resulting from conductivity (heat losses). In the latter process, the frequency of the waves has a major influence on the attenuation. Reflection, conductivity and frequency are thus the major factors governing the penetration depth of the waves into the structure. An increase in the frequency or the conductivity decreases the penetration depth (Pollmeier 1972; Peter and Ulriksen 1982).

The lateral resolution (i.e., the smallest lateral gap at which two objects can still be perceived) amounts, on average, to half of the wave length (Kirsch and Reinhold 1986):

$$\frac{\lambda}{2} = \frac{c}{2\sqrt{\varepsilon_R}\, f}$$

λ = wave length.
ε_R = dielectricity constant.
f = main frequency of the radar wave.
c = speed of light.

Thus, the lateral resolution amounts to approx. 7 cm in the event of a unit with a 900-MHz antenna in dry concrete ($\varepsilon_R = 6$). Given favourable conditions, the value is far below this; however, in unfavourable conditions, the practical resolution is considerably poorer.

As the frequency increases, the resolution improves accordingly, as shown by the above equation. However, it must be taken into consideration that at the same time, the penetration depth is reduced.

The exact location of a reflector (defect) can be determined from the measured transit time of the signal and the diffusion speed in the material, as

$$s = 0.5\, V_M \cdot t$$

where

s = depth (m)
V_M = diffusion speed (m/s)
t = time (s)

The factor 0.5 takes into account double signal transit time for the path from the tunnel shell surface to the reflector and back again. If the diffusion speeds are known, the depth of boundary layers against which reflections take place can be determined from the transit times. In favourable conditions, boundary layers that are only 1 cm apart can be recognized.

The diffusion speed of V_M depends on the dielectric constant of the material and may be expressed approximately by (Boscomer Services S.A. 1989):

$$V_M = \frac{c}{\sqrt{\varepsilon_R}}$$

where

V_M = diffusion speed
c = speed of light in vacuum = $3 \cdot 10^8$ m/s
ε_R = relative dielectricity constant of the material.

Table 2 provides examples of the dielectric constants and diffusion speeds of radar waves in various materials.

The ability to identify an object depends on the intensity of the reflected waves, which, in turn, depends (among other things) on the reflection coefficients (amplitude ratio of the reflected wave to the incidental wave). The higher the reflection coefficient, the greater the intensity of the reflected wave—and, as a consequence, the contrast—when the radar investigation is presented.

At boundary layers between two media with different dielectric constants (Table 2), the reflection coefficient works out at (Pezzati et al. 1985; Girot and Godard 1987/88).

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$$

with R = reflection coefficient
$\varepsilon_1, \varepsilon_2$ = dielectricity constants of the two media.

The formula shows that the reflection coefficient increases with the increasing difference between the two dielectricity constants.

Reflections against boundary layers between a non-conductive and a conductive material can occur. For example, radar waves are partially reflected by moist patches, where the water possesses relatively good conductive capacity, thanks to the presence of minerals; they are completely reflected against metals, which are extremely good conductors.

Apart from the reflection coefficient, the extent, location, and the surface roughness of the object (defect) also influence the intensity of the reflected wave-and, thus, its identification.

The antenna of the georadar unit has a reflection angle of approximately 60°, so that defects are recognized before the antenna is located directly above them. As the antenna is guided above the surface of the structure, towards a defect, the signal's transit times become shorter and shorter, until the antenna is located directly above the fault (see Fig. 1). When the antenna subsequently is guided away from the fault, the transit times increase again. As a result, a typical hyperbolic transit time curve is obtained when a defect is present.

Registration of the signals that are received usually is carried out by means of a graphic plotter. In this case, every signal for which the amplitude exceeds a certain threshold value is reproduced on paper in black ink, according to the transit time (penetration depth), as shown in Figure 2. The results obtained can also be stored on a magnetic tape or an EDP system for further evaluation.

One study in Germany used georadar and infrared thermography (see Section 4.2) for a comparative investigation of the lining of a tunnel (Jenni 1988). Defects were registered by both methods only in exceptional cases, and neither of the two methods was capable of detecting all of the irregularities. Furthermore, not all of the disturbances indicated were actually damage-related; and, in some cases, they could not be clearly identified through follow-up examinations using other methods. As a consequence, a number of questions regarding the application of georadar in tunnels, have yet to be clarified. For example:

1. How closely must the line profiles be drawn in order to produce a comprehensive examination?

2. How does the resolution depend on the depth?

3. Does a combination of a number of antennas with various frequencies (e.g., 500-MHz and 900-MHz antennas) present a considerable advantage?

4. How is the detection of a defect affected by its form and its location? For example, can a circular-shaped cavity be detected as well as a cube-shaped one? Or, does the signal change if an edge of the cube is facing the antenna instead of a side area of the cube?

5. Is it possible to differentiate between cavities and moist patches on the basis of the given signal form?

6. How strongly is detecting of damage influenced by a reinforcement located close to the surface? How is an obstruction affected by the mesh of the reinforcement?

7. Can a more deeply located (30 to 40 cm) corroded reinforcement be detected by georadar?

4.2 Infrared Thermography

Infrared thermography (see Section 3.6) makes use of thermal radiation, which is radiated by every surface. Thermal radiation, also known as infrared radiation, borders on the spectral range of light visible to humans. The infrared wave length range is located between about 0.75 mm and 800 mm.

For technical infrared recordings, the middle infrared ranges (from about 2 to 6 mm or 8 to14 mm) are usually used (Boscomer Services S.A. 1989; Kippel 1987; Spacetec Datengewinnungs GmbH 1988; Virdis and Frank 1983; Nägele 1988).

Infrared registration techniques yield a visual presentation of the temperature distribution on a surface. The temperature distribution on the surface represents the thermal flow through this surface. A thermographic shot displays the thermal radiation of the surface of the given body by photographic means. The thermal performance depends on the temperature on the surface of the body.

On the other hand, the temperature on the surface of the body is governed

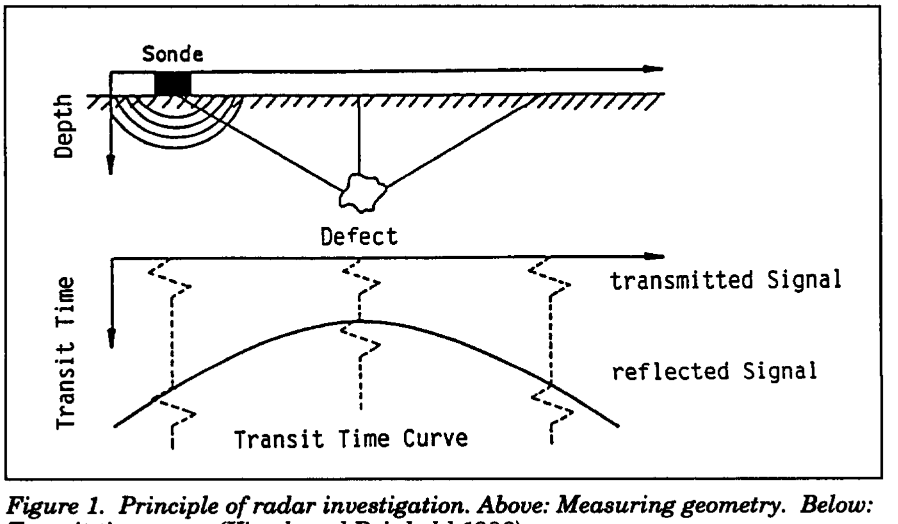


Figure 1. Principle of radar investigation. Above: Measuring geometry. Below: Transit time curve (Kirsch and Reinhold 1986).

by the thermal flow and the related thermal conductivity through the structural part.

The thermal conductivity of the tunnel lining is influenced by defects such as cavities and moist patches, as well as by the materials used for the tunnel wall (Jenni 1988; Brasser and Kull 1988; Köppel 1987; Boscomer Services S.A. 1989; Florin & Scherler AG; Spacetec Datengewinnung GmbH 1988).

A thermal flow can be created through a current of gaseous material (e.g., air) or a liquid material (e.g., water). Points affected by such thermal flows are generally characterised by a pronounced increase or decrease in temperature, in comparison with their surroundings (Jenni 1988; Spacetec Datengewinnungs GmbH 1988). In this way, possible damage in the tunnel lining can be determined through the use of infrared thermography. With the aid of thermography, differences in temperature from 0.1°C and upwards can be detected.

In order to interpret the thermographic photo, it is very useful to have an evaluation model in the form of a computer programme that simulates the thermal current of the tunnel shell, taking into account the known factors (e.g., temperature gradient, material and layering of the lining). In some cases, special follow-up examinations will be required.

The prerequisites for conducting thermographic investigations in tunnels are:

• A stationary thermal flow through the tunnel wall.

This flow depends on an almost constant difference in temperature between the rock and the air in the interior of the tunnel over a certain period of time. A difference in temperature normally occurs following a change in the climate. This difference in temperature should be at least 4°C (or 2°C, in the case of new scanners with a temperature resolution of 0.1°C), since, otherwise, the application of infrared thermography cannot supply reliable results. Consequently, the temperature gradient of the rock via the tunnel wall to the air must be observed over a lengthy period before investigations are carried out (Rücker 1987; Spacetec Datengewinnungs GmbH 1988; Amberg 1987).

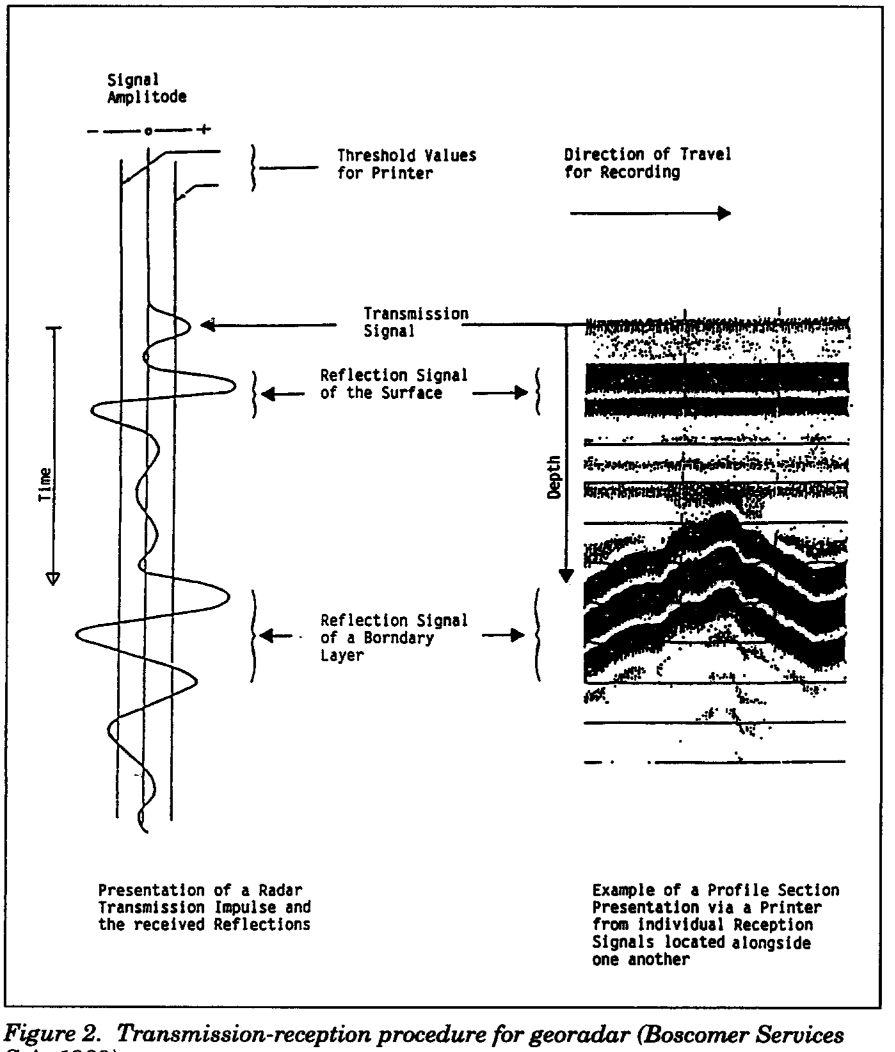


Figure 2. Transmission-reception procedure for georadar (Boscomer Services S.A. 1989).

• Direct, unhampered visual contact with the tunnel shell.

Installations, wall coverings or coatings do not permit thermal radiation to penetrate and, as a result of their insulating effect, change the temperature level and the thermal flow in the tunnel shell. Their presence prevents proper application of infrared registration techniques on the sector where they are located. On the other hand, smaller installations (e.g., contact lines, signs), result in local disturbances that affect the evaluation results only to a minor extent and which therefore can be tolerated.

In tunnels, infrared photographic surveying is carried out by means of a scanner that is installed on a moving vehicle (e.g., a railway wagon). The scanner is an optic-electronic measuring device that rotates around its own axis (see Fig. 3). The scanner basically surveys the entire tunnel lining over its full area, so that the intensity of the thermal radiation of every element of surface amounting to 15 cm in size is registered and stored digitally (Rücker 1987; Jenni 1988; Boscomer Services S.A. 1989; Spacetec Daten-gewinnung GmbH 1988).

The scanner must be set up in front of the measuring car, since the waste heat (thermal radiation, cooling air) affects the thermal radiation pattern of the tunnel shell surface and prevents proper evaluation. For this reason, this method cannot be applied when traffic is moving through the tunnel.

In addition to registering the temperature, a visual picture of the tunnel shell can be recorded by the scanner at the same time, depending on the type of unit used.

Currently, a resolution of up to approximately 1 cm² is arrived at for both the infrared and visual components (Boscomer Services S.A. 1989; Spacetec Datengewinnung GmbH 1988; Amberg 1987). If the entire tunnel vault can be covered by means of a single shot, thanks to favourable positioning of the scanner, then average registration speeds of approx. 4 km/h are possible. However, if the scanner's camera angle is restricted, additional survey runs will be necessary.

The film strips shot by the scanner can either be reproduced on-site by a printer, or stored on a magnetic tape and processed after the survey by means of a computer. Distortions in the photo taken—resulting, for example, from irregular travelling speeds, changes in the cross-section, divergent scanner positions in the tunnel cross-section, uneven tracks, or bankings—can subsequently be compensated for during evaluation. Fixed points in the tunnel (e.g., level marks, reference plates) whose position is known have to be used in order to obtain a true-to-scale rectified presentation.

In evaluating and interpreting the data through computer programmes, the thermographic and visual pictures are assessed individually and also compared with one another. The result is a synthetic picture of the tunnel shell, in various shades of grey or in the form of a false-colour presentation, in which the inhomogeneities of the tunnel shell (e.g., faults) can be distinguished through different colouring.

In tunnels that have been investigated using infrared thermography, moist patches in the tunnel shell (see Fig. 4), as well as water seepage behind the tunnel shell, have mainly been identified. In model tests in an experimental tunnel, artificially created cavities and zones with poor bonding between the tunnel shell and the rock were also identified (Amberg 1987).

According to theoretical calculations, the detection limit for spherical or cylindrical inclusions roughly amounts to a depth-radius ratio of 3:1 (Oelsner 1979). During the inspection of a tunnel (Jenni 1988) by means of georadar (Section 4.1) and infrared thermography, there remained some uncertainties and even contradictions in the data supplied by the two methods with regard to the detection of defects. In this case, a suitable evaluation model for the further processing of the picture material was able to provide better data.

So far, it has not been possible to detect other defects (e.g., corrosion, dry cracks, etc.) properly. To do so will require development of additional investigatory methods.

The following questions remain to be clarified with regard to applying thermography in tunnels:

1. How good is the resolution of the thermographic method in detecting cavities and concealed moist patches? Theoretical calculations indicate that spherical and cylindrical cavities can be detected down to a depth equalling three times their radius (Oelsner 1979). It remains to be seen whether these results also can be confirmed experimentally on concrete walls.

2. Is the detection of faults influenced by a wall covering or a coated tunnel shell? This question is raised because in many metro stations and road tunnels, the tunnel shell is lined with glazed tiles or provided with an epoxy resin coating.

4.3 Multispectral Analysis

In the case of multispectral analysis, photos of the surface of an object are taken in similar fashion to colour photography (see Section 3.6). The main difference between multispectral analysis and colour photography is that when a shot is taken using the former method, the entire light spectrum is not registered all at once; instead, small spectral areas are filtered out. Normally, six special filters are used for this purpose. Each filter possesses a transmission range of 40 to 100 nm, and altogether the filters cover practically the entire spectral range of 400 to 900 nm. At least one shot of the same section of a structure is taken per filter. In this way, the information content of the light spectrum remitted by the surface is divided up and recorded.

In this connection, it is advantageous that surface areas, which display a change in colour that is barely perceptible to the human eye, are particularly strongly emphasized in one of the six shots. The prerequisite for achieving this is that the photo must record the particular spectral range in which the change in colour is so pronounced.

A multispectral projector is used to evaluate the shots. To do so, the black-and-white photos taken in the tunnel are provided with a colour backdrop so that the fine shades of grey become visible to the human eye. In addition, pictures that have been taken of the same section of the structure with different filters can be superimposed in the multispectral projector in order to make the fine spectral differences visible. In this way, contrasts can be enhanced or reduced. Multispectral analysis can be used in this way to highlight fine cracks as bright lines against a dark background.

In tunnels, the multispectral analysis method has been used experimentally to detect cracks. Thanks to the high resolution possible with this method, cracks as thin as 0.5 mm could be identified. Furthermore, increased deposits of carbonate, as well as moist patches, were detected on surface areas. However, targeted follow-up investigations (e.g., material samples) are required in order to arrive at the definite correspondence of such defects with the colours of the multispectral pictures.

During an investigation in a Stuttgart (Germany) S-Bahn (urban railway) tunnel, an approx. 8-m tunnel section could be photographed from one location. The cross-section had to be divided into four sectors. In this way, each shot could cover some 50 m^2 of tunnel surface. Each section of the structure was photographed using three different special filters. Lighting was provided with a lamp that had a power consumption of about 2 kW. It took roughly three hours to cover the 25-m-long tunnel section (Iseco 1988).

During another investigation in the Dietershan Tunnel (near Fulda, Germany), two cameras were mounted on a tool wagon and lamps that used a total power output of approx. 5 kW. The cameras were fitted with an extreme wide-angle lens, so that it was possible to photograph a tunnel section

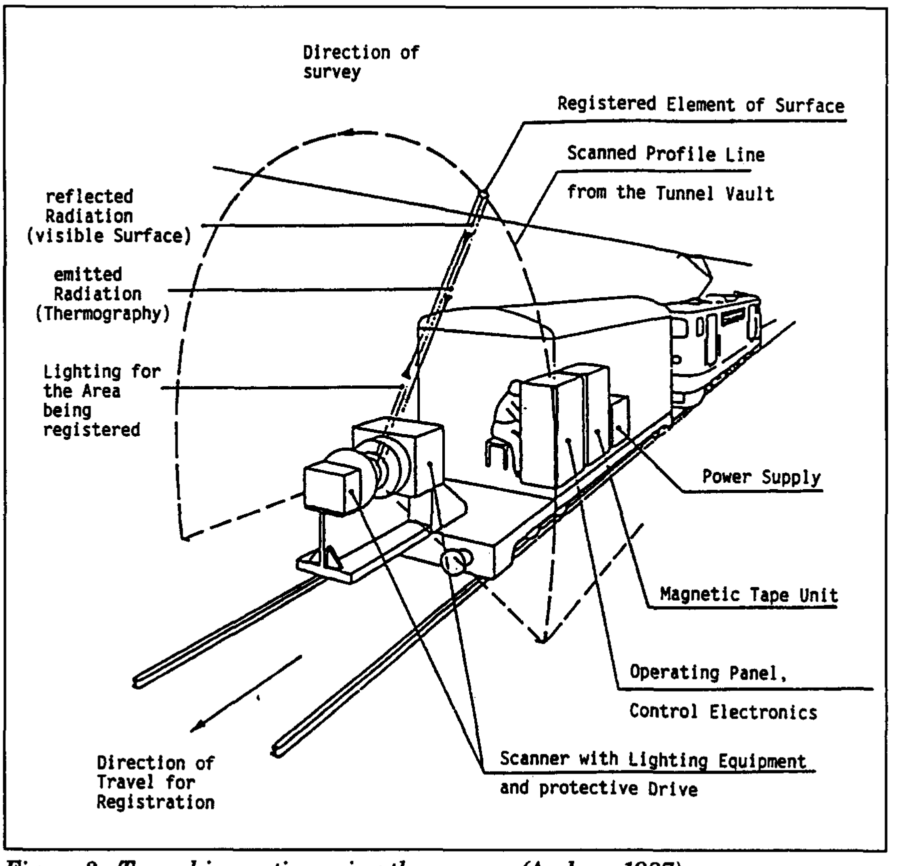


Figure 3. Tunnel inspection using the scanner (Amberg 1987).

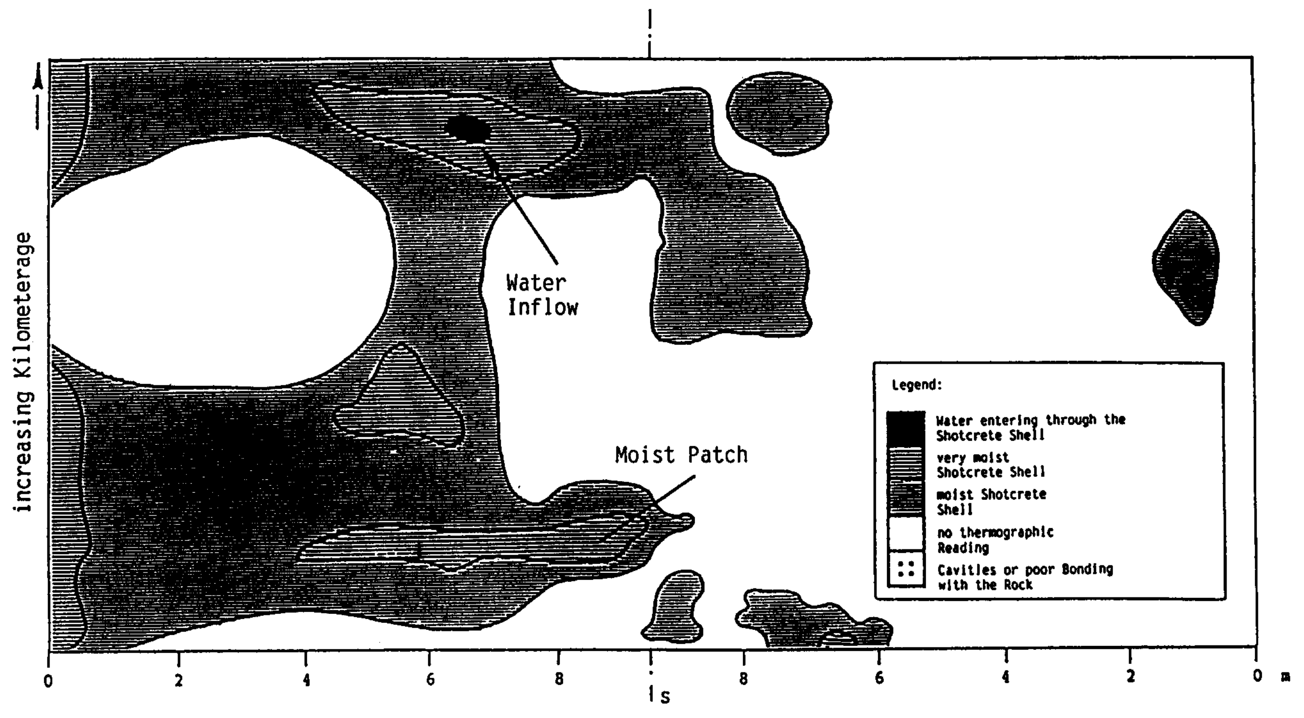


Figure 4. Example of a thermography investigation result for a tunnel section (Spacetec Datengewinnungs GmbH 1988).

of 14 m with two shots. The investigation verified that a registration speed of about 0.5 km/h is feasible with this set-up—a speed that is still too slow for fast preliminary examinations.

The following points have yet to be clarified with respect to applying multispectral analysis in tunnels:

1. How good is the resolution? Can dry cracks as small as 0.3 mm still be identified, given the usual distance for photographing in tunnels (approx. 10 m)?
2. Which spectral ranges are required or are adequate for tunnel investigations?
3. Which lamps or films are most suitable for tunnel investigations?

5. Types of Testing in Various Countries

5.1 Czech Republic and Slovakia (formerly Czechoslovakia)

The frequency and nature of investigations carried out in Czechoslovakian tunnels differ from investigations of similar tunnels in other countries. The typical inspection procedures for tunnels in the Czech Republic and Slovakia are described below.

a) *Subway Tunnels*

Frequency of inspections: weekly, monthly, or yearly.

Inspection methods: measurement and checking of tunnel lining. All defects that are found are entered into the tunnel book. Special non-destructive methods are not applied.

b) *Railway Tunnels*

Frequency of inspections: monthly and yearly inspections; one main inspection every five years.

Inspection methods: the same as for subway tunnels (see above).

c) *Road Tunnels*

Inspections are similar to those for bridges, i.e., twice a year with additional special inspections as needed. Current inspections are carried out by the owner (Local Highway Administration). Checks are carried out on the state of the lining, groundwater seepage, visible cracks, temperature measurements, etc. In Prague, control inspections are carried out by the owner once a year, and main inspections once every four years. The technical installations of road tunnels in Prague are checked according to the operating regulations for concrete tunnels.

d) *Hydroelectric Power Station "Lipno I"*

Inspections of the entire construction are carried out once a year. Additional detailed inspections of pressure shafts and the waste tunnel are undertaken once every five years after the water is discharged. In the cavern, the drainage system is cleaned once every five years. In addition, regular inspections are carried out by geologists.

5.2 France

In France, practical experience with non-destructive testing methods was initiated in the mid-1980s, especially with respect to the investigation of road tunnels. Details of experience with three such methods are given below.

a) Georadar

Georadar tests were performed by the research organisation CETu (Centre d'Etudes des Tunnels) in the Epine Motorway Tunnel, along the Motorway A43 east of Lyon, in 1987. The task was to investigate the voids behind a recently formed concrete shell. The geology of this 3,100-m-long tunnel consists mainly of limestone and marls.

During the two-day investigation, the following antennas were used:

- 500 MHz, with a maximum investigation depth of 7 m; and
- 900 MHz, with a maximum investigation depth of 1 m.

Two profiles at each section were investigated. The GSSI radar system was supplied and operated by Messrs. Geomega. The output was recorded on paper, and the interpretation was made from the paper records. Some investigative boring was carried out in order to correlate the results.

The surrounding ground at the eastern end of the tunnel consists of marls. Almost no reflections were observed in this medium, despite the presence of decompression phenomena identified in the construction documents.

The presence of voids was detected by the radar unit, thus facilitating preparation of a contract for remedial grouting. The main voids that were found and filled during the grouting contract were not, however, detected by the radar, because they were located behind steel profiles, which acted as radar reflectors.

It was also apparent from this investigation that, because the investigative width of the radar beam is limited, the distance between the profiles should be planned carefully in order to avoid omitting any desired information.

The general costs of the investigation were about 60,000FF for every 1,000 m tested.

The following basic issues were not answered satisfactorily by these tests:

1. Because the revolution of the antennas is not symmetrical, the impact of their orientation with respect to the investigation axis remains unknown.

2. The lateral resolution appeared to be half the wavelength of the source, although this needs further study. The variation of resolution with depth also requires investigation.

3. A variation in the reflection angle resulted in an echo on several recording meters. Interpreting these images was very difficult.

4. The existence of water in the medium investigated resulted in a weakened wave (function of the dielectric constant), which reduced the georadar investigation depth. It is not only interesting, but also necessary, to understand how the use of radar may be affected by the degree of moisture of the investigated medium.

Cariou's report (1989) deals with research performed within an LPC/SNCF/RATP joint programme to develop a synthetic impulsion radar method. The article proposed analysis criteria for the georadar performances. [This work, performed in cooperation with Société du Radant (military radar), was halted when this firm was purchased by Thomson-CSF and the engineer in charge of the study gave up the project.]

The synthetic impulsion radar antenna emits a wave whose frequency varies slightly. This arrangement is different from "conventional" radar, which uses mono-frequency antennas with restrictions peculiar to each antenna type. In contrast, for each frequency emitted by the antenna of the synthetic impulsion radar, the reflected wave is analyzed for its amplitude and phase, thus allowing the characteristics of the material to be determined within a wide frequency range.

b) Ultrasonic Methods

CETu recently gained experience in ultrasonic testing methods through the investigation of unlined wall parts in the Epine motorway tunnel. The so-called "dynamic investigation unit" generates a mechanical wave and measures its propagation speed in the wall. The wave is generated and received by two piezoelectric caps, which transform an electric voltage into mechanical impulses, and vice-versa. Both transducers were set up on the same surface.

Knowing the distance between the transducers and the time required for transmission of the signal, the velocity of the wave can be calculated.

In the Epine motorway test, the following values were applied:

- Frequency of the wave carrier: 50 KHz
- Pulse train frequency: 6 Hz
- Measurement range (dynamic): 0-980 μs

The longitudinal and transverse wave velocities are a function of the dynamic elasticity modulus of the tested medium.

If the wall is weathered or scaled, or is located in a section where the wall lining is homogeneous, the transmission velocities are representative of the degree of decompression of the wall lining. The tested depth can be varied by varying the spacing of the electrodes.

In summary, ultrasonic methods of testing have the following advantages:

- The equipment used is generally inexpensive and does not require a specialized staff to operate it.
- The equipment is easy and quick to use (30 seconds per test).

However, there are also some inconveniences associated with ultrasonic methods, e.g.:

- The need for repeated point-by-point tests; and
- Mechanical borings may be required for calibration.

c) Infrared Thermography – Scanner

Testing has been done by the Laboratoire National d'Essais in cooperation with the Swiss firm Eurosat on the trafficked sections of the Fourvière and Croix-Rousse Tunnels in Lyon. The testing series used a scanner set up at the front of the measuring car, which travelled at around 2 km per hour.

In the Fourvière Tunnel, the information provided concerned only the structure of the ceiling plate. The tunnel has a plastic sheet insulation, and is therefore almost permanently dry. The steel plates of the sidewall lining act as a screen.

In the Croix-Rousse Tunnel, the water inflows on the sidewalls could be investigated precisely. However, it should be noted that this method did not detect any of the seven ventilation shafts in the tunnel, which lie above the ceiling plate.

This infrared thermography technique seems valuable for rapidly establishing the basis for the visual inspection documents, as well as for obtaining a quick report on the water inflows in tunnels with watertightness problems. For identifying deep structure anomalies, however, this method seems a less obvious choice.

5.3 Germany

Federal German Railways (DB) tunnels are inspected by experts at three-year intervals in accordance with DS 803, "Regulations for Monitoring and Testing Bridges and Tunnels" [Martinek 1986; Martinek 1987; DS 853, 1990]. For this purpose, the DB uses a mobile tunnel inspection car with working platforms. From these platforms, the internal areas of the tunnel vault can be examined visually for any damage or defects, such as cracks, moisture, changes in colour, and chipping. Additionally, random tests are carried out with a hammer to determine cavities. The standard clearance can be tested using a fold-up measuring frame.

The average travelling speed of the car—usually about 1 to 3 km/h—depends mainly on the number and nature of the cracks determined. A crew of up to 10 persons, including the driver, is required for inspection purposes. Faults and damages discovered are entered by hand onto diagnosis sheets. A report on the state of the tunnel is subsequently compiled from these sheets, and helps in making decisions on any possible repair measures that may be required.

If necessary, a mobile tunnel-surveying car from the DB is used to take deformation measurements on the tunnel walls. Modern electronic surveying units (e.g., electronic laser tachometer units), with an accuracy of down to a few centimetres, permit any required cross-sectional forms to be registered. However, it is not possible to obtain data on the development of damage in or behind the tunnel linings unless it has already caused considerable deformations in the tunnel shell.

Tunnel inspections of road and rail commuter transport tunnels are carried out in accordance with the guidelines laid down in RABT (1985) and BOStrab (1987). Generally, such inspections are undertaken annually, either by foot or using existing maintenance vehicles equipped with platforms. The surface of the tunnel lining is visually scrutinised. A crew of two to three persons can inspect tunnel sections of up to approximately 1,000 m per day. However,in some cases the examination of the supporting tunnel shell is difficult.

In road tunnels in particular, additional wall linings are very frequently installed, making access to the original supporting tunnel shell difficult or even impossible. In such cases, the wall lining has to be removed in order for an appraisal of the tunnel shell to be carried out. This involves considerable costs.

Any zones suspected of being defective are registered in record sheets and

Table 3. Frequency and methods of tunnel inspection in Japan.

Type of Tunnel	Frequency and Methods of Inspection: Frequency	Methods
a) Metro Tunnels	Tokyo Metropolitan Subway 1) Inspection for uneven settlement (once within every two years) 2) Inspection for phenomena other than uneven settlement (once within a year) Teito Rapid Transit Authority 1) once in every two years	1) Visual Inspection 2) Crack Measurement 3) Measurement of the deformation in linings 4) Investigation of lining thickness and surrounding ground (Non-destructive inspection, boring survey) 5) Lining material test 6) Measurement of deformation of surrounding ground 7) Investigation on water leakage 8) Investigation to examine lining reinforcement methods
b) Railway Tunnels	1) Routine inspection: Inspection to investigate any deformation or its aggravation, changes in circumstances, and to check any existing or potential sources of problems - Periodic inspections (once within every two years) - Irregular inspections (as the occasion demands) 2) Detailed inspection: Highly precise inspections to assess causes of deformation and the extent of damage and to determine methods and timings for suitable measures to be taken (as the occasion demands) 3) Environmental survey: Survey to investigate the effects of environmental changes in the surrounding areas on the railway tracks, using aerial photographs (as the occasion demands)	
c) Road Tunnels	Ministry of Construction: Usually once or twice a year Japan Highway Public Corporation 1) Routine inspection: Visual inspection principally from a car (daily expect holidays) 2) Periodic inspection: Close inspection periodically conducted on foot (once a year) - Periodic inspection A: Inspection to ascertain the general state of structures in the whole maintenance area - Periodic inspection B: Inspection to ascertain in detail the state of each structure 3) Unscheduled inspection: Inspection conducted as necessary, to complement routine and periodic inspections (as the occasion demands) Tokyo Expressway Puplic Corporation 1) Simple inspection: Visual inspection on patrol car (once a day) 2) Periodic inspection: Visual inspection on foot (once a year)	
d) Other Underground Structures	Tokyo Metropolitan Sewerage Network - No inspection conducted (due to constant water flow prohibiting entry) Electric Utility 1) General inspection: Inspection to ensure maintenance of functions, to prevent accidents, and to ascertain existence of defects and progress in deformation - Tunnels requiring special attention (once a year) - Other Tunnels (once in two years) 2) Special inspection: Inspection of tunnels requiring special attention, so as to investigate causes of defects and to select a preventive method (as the occasion damands) 3) Measurement and study: Measurement and study to ensure perfect operation and obtain design data for future requirements (as the occasion demands) Nippon Telegraph and Telephone Corporation 1) Crack and leakage inspections: (routine inspections performed on patrol, periodic inspection every six months) 2) Close examination for deterioration of concrete: (as the occasion demands) 3) Close examination for deformation and subsidence: (as the occasion demands)	

Table 4. Frequency and methods of tunnel inspection in Norway.

Type of Tunnel	Frequency and Method of Inspection
A Metro Tunnels, Oslo Sporveier	Visual control every week. Closer investigations if it seems necessary.
B Railway Tunnels, Norges Statsbaner (NSB)	Continuous control in connection with rail inspection. Any fallen stone calls for a closer inspection. Any section or zone that represents a potential danger is controlled once a year. All tunnels are systematically controlled every fifth year.
C Road Tunnels	There are hardly any regulations pertaining to the frequency of inspection. The frequency seems to be based on the experience of the local road authorities that are responsible for the various tunnels. However, shotcrete is checked through core drilling every fifth year, particularly in difficult sections and sections where salt water leakage has occurred.
D Other Underground Structures	There are hardly any regulations.

examined in follow-up inspections. For this purpose, conventional measures—tapping to trace cavities, testing the concrete with the Schmidt hammer, endoscopy in boreholes, taking core samples, and laboratory examinations (e.g., compressive strength, E-modulus, depth of carbonatisation, etc.)—are used (Martinek 1987, Jolissaint 1984).

In the case of both standard and main inspections, according to DIN 1076 (Ingenieurbauwerke im Zuge von Straβen und Wegen 1983; Knabenschuh 1983), in addition to the testing methods mentioned above, surveying work and measurement of the movements of joints and cracks are carried out at intervals of approximately three to six years (maximum 10 years, in accordance with BOStrab [1987]). All observations made during the inspections are registered in the tunnel books and serve as the basis for planning rehabilitation measures. However, it usually is not possible to obtain data on the state of the interior or the outer side of the tunnel shell.

5.4 Hungary

Subway tunnels are inspected every night during non-operational hours and at spots where detailed checking is essential. A general and detailed investigation of the quality of prefabricated relinings was completed in 1994, and a similar examination of cast-iron lining is taking place. This examination includes corrosion control-by both electric and standard methods-using an ultrasonic device. It will be followed up by checking of steel sheet seals. No detailed regulations for checking subway tunnels currently exist.

Hungarian State Railways regulations on the frequency of inspections state that tunnels should be inspected every two years, and that the clearance should be controlled at the same time. The track is inspected more frequently, and the person in charge is required to report any irregularities concerning the tunnel.

5.5 India

The following information on inspections of subway tunnels was obtained from India:

Station structures are inspected once a month by inspectors and once every three months by assistant engineers. Running tunnels are inspected once every three months by inspectors. Special attention is given to tunnel walls, tunnel roofing, drainage, leakage, etc.

5.6 Japan

Table 3 is a survey of the inspection methods applied in Japan and the intervals at which such inspections are carried out.

It is evident from the data provided that non-destructive testing methods have been applied in only a few cases to date.

5.7 Norway

Table 4 gives an overview of tunnel inspections in Norway. So far, non-destructive testing methods have not been used in monitoring Norwegian tunnels.

5.8 People's Republic of China

In Shanghai, metro tunnels are inspected two or three times per year. Inspection is mainly carried out with the naked eye and by plotting a graph indicating the presence of seepage water.

6. STUVA Testing on Experimental Panels

6.1 Test Panels and Methods Used

In order to be able to calibrate the non-destructive testing methods, to determine their limits of application, and to become familiar with their way of indicating faults as an important basis for any evaluation and interpretation, a set of four different test panels was designed in January 1991.

Each of the four test panels cast was 2,200 mm square and 480 mm thick. [Those who may be involved in the development and use of such inspection techniques are informed that the STUVA test panels are still available for use by arrangement with the Director of STUVA, Dr. Alfred Haack.] The panels were arranged in pairs, as shown in Figure 5. The water between the panels could be heated.

The panels contained a variety of defects, as shown in Figures 6 to 9. Parts of the panel exterior surface were covered with tiles or with an epoxy resin coating, simulating decorative finishes applied to many tunnels. The reinforcing rods in Panel 3 were inserted in plastic sleeves so that varying reinforcement spacing and unrein-forced structures could be simulated.

Tests were carried out using georadar, thermography and multispectral analysis. The work was performed by STUVA and the following German companies:

- Projektgemeinschaft Ingenieurbüro EDR GmbH, Munich;
- Boscomer Services S.A., Switzerland (Georadar);
- Gesellschaft für Geophysikalische Untersuchungen (GGU), Karlsruhe (Georadar);
- Deutsche Montan Technologie (DMT), Essen (Thermography);
- Spacetec Datengewinnung GmbH, Freiburg (Thermography);
- ITC Industrie Technologie AG, Cologne (Multispectral Analysis).

6.2 Thermography Tests

Laboratory tests showed that it was possible to locate various defects in the test panels using thermographic methods of investigation. For example, Figure 10 shows a thermographic shot of wall element No. 4, in which large defects of approximately 25 cm x 25 cm x 25 cm were installed (see Fig. 9). The concealed moist patches 4/2 and 4/4 were registered on the surface, thanks to their better thermal conductivity as compared to concrete, as a local increase in temperature.

On the other hand, Cavity 4/1 caused a localized minimum surface temperature because of its poorer thermal conductivity. Similarly, the latent heat present in the case of moisture on the surface (in Fault 4/3) caused a pronounced temperature minimum value.

The tests showed that the defects, which had an area parallel to the concrete surface greater than their corresponding depth (concrete covering) could be identified. Further-more, it was possible to detect poor bonding between a tiled lining and the mortar subsurface. However, dry cracks were not made visible through thermography.

The prior conditions for the successful application of thermography include a temperature gradient through the tunnel shell of at least 2°C/m. Continuous temperature measurements should be carried out at certain points of the tunnel shell to be investigated, in order to determine a favourable point in time for the thermographic investigation. If the tunnel shell has a metal covering, then the infrared rays from the shell will be shielded and it will no longer be possible to detect defects.

6.3 Georadar Tests

Laboratory tests confirmed that georadar is suitable for tunnel investigations. By means of georadar, nearly all of the defects in the experimental walls could be detected. Even a small cavity (with a volume of approx. 1 dm^3) at a depth of roughly 30 cm could be identified with this method. Dry cracks were among the defects that could not be identified because the resolution of the radar waves was not sufficient for this purpose. Furthermore, faults beneath the tile covering were not detected. The wire mesh (5 cm x 5 cm mesh), which provides better support for the mortar beneath the tiles, almost completely shielded the radar waves. The same applies to tunnel shell linings made of metal. Therefore, it is not advisable to apply georadar in such cases.

The detection of defects, particularly small ones, is made more difficult through reinforcing steel in concrete (gap of approx. 15 cm between rods). In such a case, it is advisable to use antennas for shorter waves (900 MHz and 1,000 MHz) because the shorter the wave length, the less the radar waves are shielded by reinforcing steel mats.

The penetration depth also must be considered when choosing the proper antenna. The depth is greater in the case of the 500-MHz antenna than in the case of the 900-MHz antenna. The radar method operates line by line. Laboratory tests showed that a distance of roughly 20 cm from the profile is necessary in order to obtain a comprehensive examination with 500-MHz and 900-MHz antennas.

Figure 11 shows an example of the result of this kind of comprehensive examination on the experimental wall. In order to create this picture, the data for the individual radar photos for each profile were compiled to form a time slice, with the help of a computer. In the process, the anomalies of the experimental wall were reproduced from the transit time range of the radar signal between 3.7 and 4.8 nsec. This corresponds to a depth of roughly 9 cm to 16 cm for the concrete of the experimental wall. However, the moist patch 4/4 in Figure 6 was located at a depth of 18 cm and therefore could not be reproduced in this picture.

The time slice clearly shows the individual reinforcing rods, which were located in a dry environment in the upper part of wall element No. 3 during the test in question. However, the reinforcing rods in a wet environment (i.e., the lower half of the wall) could no longer be detected individually. In order to identify as many faults as possible, a number of time slices for various time ranges (depth sections) should be produced if necessary. The time required for a comprehensive examination is relatively long, because many profiles have to be photographed. Consequently, a number of antennas should be employed simultaneously for tunnel shots, in order to speed up the process.

6.4 Multispectral Analysis Tests

Laboratory tests showed that with the aid of multispectral analysis, cracks as small as 0.3 mm could be detected on the concrete surface. Moist patches on the concrete surface also could be well identified (see Fig. 12).

The surveying speed for documenting the damage sustained by tunnel

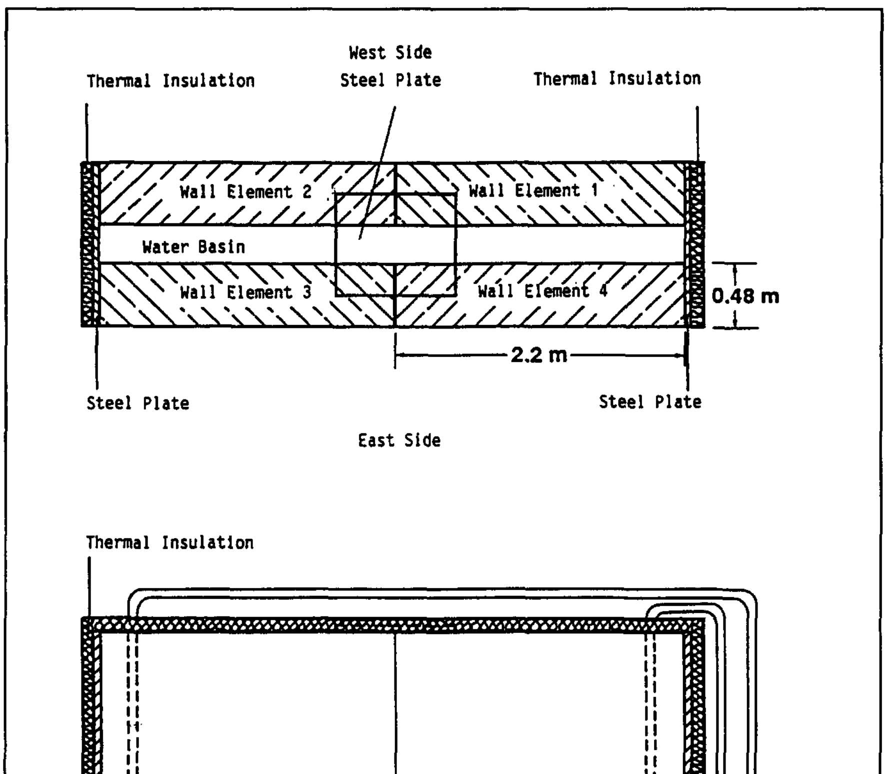
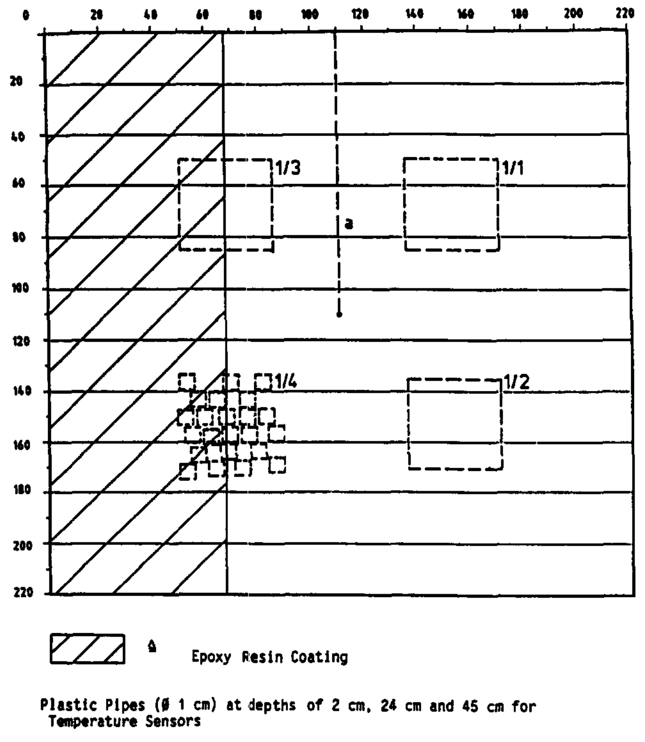
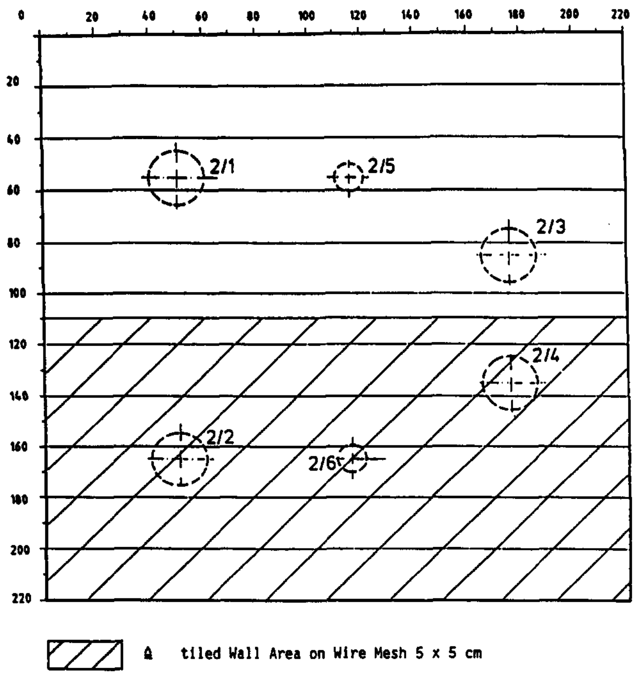


Figure 5. Arrangement of the wall elements with thermal insulation and filter circulation plant with heat exchanger.



Faults		Dimensions (cm)	Concrete Cover (cm)	Remarks
No.	Type			
1/1	Cavity	35 x 35 x 3	40	
1/2	Cavity	35 x 35 x 3	5	
1/3	Cavity	35 x 35 x 3	20	
1/4	Cavities	6 x 6 x 6	5–37	Gap 6–10 cm One side parallel to wall surface

Figure 6. Wall element Number 1.



Faults		Sphere Ø (cm)	Concrete Cover (cm)
No.	Type		
2/1, 2/2	Cavities	20	25
2/3, 2/4	Cavities	20	5
2/5, 2/6	Cavities	10	33

Figure 7. Wall element Number 2.

linings-equal to two shots per object setting-currently is only 0.5 km/h.

The tests on the experimental wall clearly revealed that the number of shots can be reduced through the use of colour film and the corresponding increase in surveying speed.

6.5 Conclusions

The results of the testing are summarized in Table 5. It can be seen that each of the three techniques is useful for rapid examination of tunnel linings. Suggested improvements and modifications for the equipment and procedures are discussed below.

Depending on which type of damage is displayed in the tunnel shell, one of these three methods for nondestructive investigation of tunnel linings can be chosen. For example, multispectral analysis is recommended if cracks are mainly to be detected. Because the three methods discussed above complement one another in tracing defects, simultaneous application of all three methods for inspecting tunnels appears advisable under certain circumstances.

6.6 Future Work

6.6.1 Thermography

The data processing for evaluation by thermography should be improved with the aim of better recognition of the detected faults.

In addition, active thermography methods should be tested and further developed. In active thermography, the structure is first exposed to rays, and then the emitted radiation is recorded. In this way, surface structures can be more effectively emphasized so that crack identification becomes possible. Using this method in combination with standard thermography facilitates a more comprehensive analysis of the damage. To date, very little experience has been gained in the field of active thermography.

When investigating large tunnel lining areas, the time required for evaluation must be shortened considerably, in particular for thermographic photos, for economic reasons. Furthermore, improvements are needed to allow the large quantities of data that are produced to be processed more rapidly.

6.6.2 Georadar

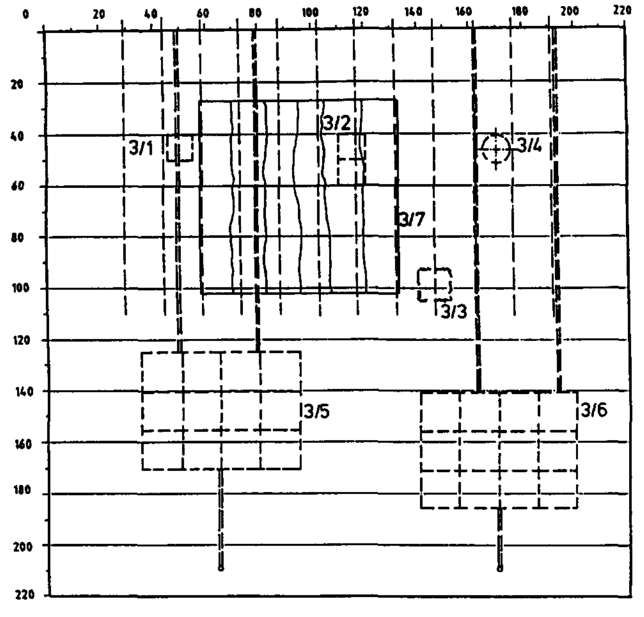
When surveying, a major disadvantage of the georadar method is that the antenna always has to be guided directly along the surface of the object in question. Thus, installations such as contact lines in the tunnel represent a serious hindrance. A possible remedy is to create a special antenna, by means of which the structure can be examined from a greater distance.

In order to be able to increase the surveying speed of georadar during tunnel investigations, the following major aspects should be pursued in research:

- Multi-antenna systems: New measuring systems, in which several antennas can be employed simultaneously, should be developed and tested.
- Increasing the signal impulse rate: Another topic for investigation is whether the signal impulse rate of georadar can be increased. In this regard, the homing potential of the antenna, as well as the measurement evaluation system, should be developed further.
- Efforts should be made to improve the interpretation of the measured values.

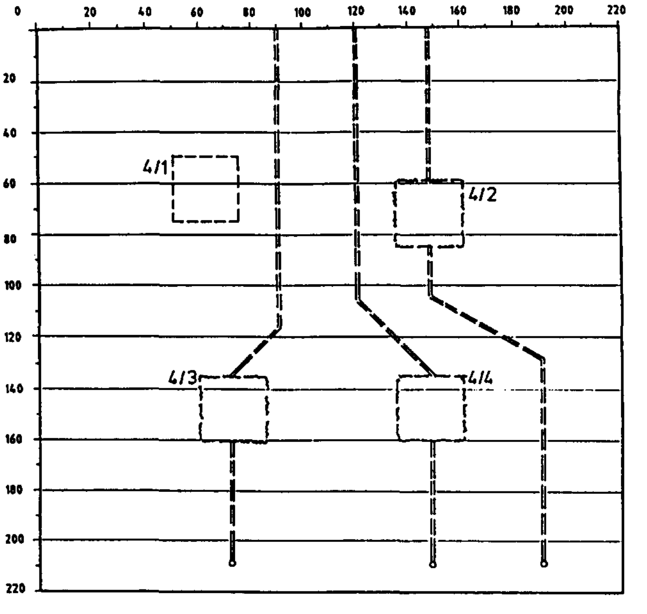
6.6.3 Multispectral Analysis

At present, a considerable disadvantage of multispectral analysis is the still relatively low registration speed when large areas of tunnel lining are involved. Recently, substantial efforts have been undertaken in order to increase the speed. Nonetheless, further research on this topic is imperative.



Faults		Dimensions (cm)	Concrete Covering (cm)	Remarks
No.	Type			
3/1	Cavity	10 x 10 x 10	10	Cube surface parallel to wall surface
3/2	Cavity	10 x 10 x 10	10	Cube tilted
3/3	Cavity	Ø 10	10	Cavity with irregular surface
3/4	Cavity	45 x 60	10	
3/5	Corrosion zone	45 x 60	40	Installed corroded reinforcing mesh 15 cm rod gap, embedded in gravel pocket
3/6	Corrosion zone	45 x 60	5	Installed corroded reinforcing mesh 15 cm rod gap, embedded in gravel pocket
3/7	Crack	75 x 75	0	Zone with surface cracks

Figure 8. Wall element Number 3.



Faults		Dimensions (cm)	Concrete Covering (cm)	Remarks
No.	Type			
4/1	Cavity	25 x 25 x 25	10	
4/2	Moist patch	25 x 25 x 25	10	Gravel pocket with intruding and escaping water
4/3	Moist patch	25 x 25 x 25	2	Gravel pocket with intruding and escaping water
4/4	Moist patch	25 x 25 x 25	18	Gravel pocket with intruding and escaping water

Figure 9. Wall element Number 4.

Table 5. Examples of defects, and whether they can or cannot be identified by various investigation methods.

Type of Defect	Dimension of Defect [cm]	Concrete Cover [cm]	Defect Identified by: Georadar with various antennas	Thermography	Multispectral Analysis
Cavities and moist patches	10	5	yes	yes	no
		10	yes	no	no
		20	yes	no	no
		40	no	no	no
	20	5	yes	yes	no
		10	yes	yes	no
		20	yes	no	no
		40	yes	no	no
	40	5	yes	yes	no
		10	yes	yes	no
		20	yes	yes	no
		40	yes	no	no
Moist patches at surface			yes	yes	yes
Dry cracks with a width of 0.3 to 3 mm			no	no	yes

In addition, only relatively small distances between shots are possible in tunnels; and, consequently, only a relatively small segment of the tunnel is analysed per photo. Approximately 150 shots are required in order to cover 1 km of tunnel shell. As a result, the development of the photos, as well as their evaluation, is extremely time-consuming and costly.

It would be desirable to make use of electronic picture processing for this system. However, the capacity of existing smaller computers is inadequate for processing the major information content of a photograph. The possibilities for processing the pictures using computers must therefore be properly investigated and expanded.

7. Conclusion and Outline for Future Studies

The summary in Section 6 shows the range of applicability of the three techniques that were tested by STUVA as being favoured for rapid inspection of in-situ concrete linings. These techniques also have wider applications, as noted in the preceding discussion. Some of the other techniques mentioned in this report—and discussed more fully in the STUVA report—may be useful for more detailed inspection of particular areas of tunnel, e.g., prior to carrying out remedial work.

Further studies must investigate the application of these techniques for other types of linings, for the contact surface between the lining and the surrounding ground, and for the ground itself.

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