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TITLE:

REHABILITATION OF HIGHWAY TUNNELS – TECHNIQUES AND PROCEDURES

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ABSTRACT: Existing tunnels often exhibit important structural defects in the concrete liner due to ageing, weathering or improper construction techniques. Inspection procedures are described to determine critical points which are then recorded on a GIS-based data storage system (Geographic Information System). Techniques of highway tunnel rehabilitation are presented ranging from light surface repair of inner liner surface to heavy structural repair involving full demolition and reconstruction of tunnel liner. These techniques minimise the duration of tunnel closures, and together with periodic monitoring of safety systems, provide active protection to highway users.

1. INTRODUCTION

Most tunnels in Italy were built during the sixties. Many have been found to have defects of varying seriousness as a result of ageing, freezing-thawing, chloride penetration, carbonation, or faulty construction. Recent legislation and increasing traffic flows make necessary improvements in both quality and safety of the highway network. The investigation of tunnel quality, as part of a regular maintenance schedule, requires an approach aligned with increasing user safety and comfort requirements.

Highway A15 of the Autocamionale della Cisa S.p.A. (Autocisa) in the Apennine region, Italy, has approx. 15 km of double tunnels along its 100 kilometre length. Golder Associates is providing the engineering support for tunnel lining control, monitoring as well as rehabilitation design where necessary.

Tunnels are periodically checked using an approach based on the assessment of structural and geo-related risk. The inspection of many tunnels has revealed common defects not necessarily associated with significant geological causes. Linings often show defects deriving from the quality of materials used or the construction method. This study is therefore mainly addressed to assessing the structural soundness of tunnel liners. In cases where tunnels show significant defects, the surrounding geological conditions are also carefully assessed and investigated.

The present paper presents investigation procedures as well as rehabilitation techniques. A proper investigation allows the detection of major defects that may impact the safety of highway users. Typical defects found in most of the tunnels investigated are:

- Honeycombed concrete or poor concrete quality
- Voids between permanent and temporary steel rib supports
- Exposed rusty re-bar (too close to surface)
- Gaps between successive concrete castings
- Cracks and fissures
- Plugged or damage water drains
- Water leakage from joints or fissures

The following sections present inspection procedures for an immediate assessment or periodical monitoring of tunnel lining status. Defects are recorded on a GIS based system in order to create a geo-referenced database. Rehabilitation design and techniques are then presented to show how solutions are chosen depending on the gravity of each problem. Continuous monitoring of all relevant defects and the establishment of a proactive maintenance schedule are then crucial to ensuring user safety.

Four levels of problem are considered:

- Localised rehabilitation
- General rehabilitation of the lining surface
- Localised rehabilitation of concrete sections
- Extensive tunnel liner reconstruction.

Each level is illustrated in a complete case history of work on an Autocisa tunnel carried out over the past five years.

2. LINING INSPECTION

Lining inspection is carried out in order to collect as much detailed information as possible on tunnel condition. Following tunnel inspections from 1998 to 2000 it became clear that the best approach is to perform a phased investigation as follows:

A) Visual and hammering inspection. A hydraulic platform is used bridging the tunnel width. Two or three technicians on the platform strike the surface with hammers to identify acoustically where concrete is unsound. For example, honeycombed concrete is easily identified by a hollow sound. In such case light demolition is done to evaluate the thickness and extent of the defective area. Operations are directed by an engineer who collects data on a graphic basis and records them together with detailed information on each defect.

The main limitation of this method is its depth range: the liner can be inspected only to a depth of 20-30 cm. To obtain information at greater depth the use of destructive methods may be required.

B) Destructive method. A group of five radial holes is drilled in each section where voids are suspected. This technique allows the determination of lining thickness and the measurement of the void depth between lining and rock. The presence of voids above concrete lining is one of the most often encountered problems: due to imperfect concrete casting or an inefficient pumping system, the crown of the tunnel may be not completely filled and significant void spaces may remain (20-50 cm) between the rock surface and the concrete lining.

Additional holes are drilled for core sampling. The samples are analysed for compression resistance and degree of carbonation. Further checks on the lining are done to evaluate stress conditions where evidence of cracks or strain is found. Additional holes are drilled and a stress-strain assessment is performed by using concrete stress cells and de-compression tests on these holes.

C) Non-destructive method. Ground Penetrating Radar (GPR) is a very useful non-destructive method for the detection of voids above the lining on a continuous basis. However, it cannot be considered exhaustive due to the shielding effects of reinforced concrete. This method provides a powerful tool when supplemented by local inspection: when anomalies are revealed by the radar signal, holes are drilled to verify the actual lining thickness and void depth.

The three-phased investigation procedure described above allows a definitive assessment of superficial lining deterioration, weathering, water inflow and damages due the in situ stress conditions.

3. DATA STORAGE IN G.I.S. FORMAT

Visual inspection results are presented as a graphical field plot of defects. Such information is then entered into an Autocad™ file with GIS[(1)] referencing. Figure 1 shows a sample of the recorded graphical layout where defects are displayed as graphical symbols placed at their exact location along the crown. The symbols are linked to a database with a complete description of the defect. Symbols vary in size from small to large to indicate three levels of gravity of the defect (low, medium, and high, respectively). This system unites the capabilities of the GIS interface with the storage of a quantity of information that could not be handled otherwise. The search for a specific defect type is then possible via queries, and any rehabilitation work is incorporated into a historical record in order to provide a time series as basis for the maintenance schedule of each inspected tunnel.

[(1)] G.I.S. - Geographic Information System. Used here as geographic referencing of the detected defects with related information characterising each point and area inside the tunnel stored in a database.

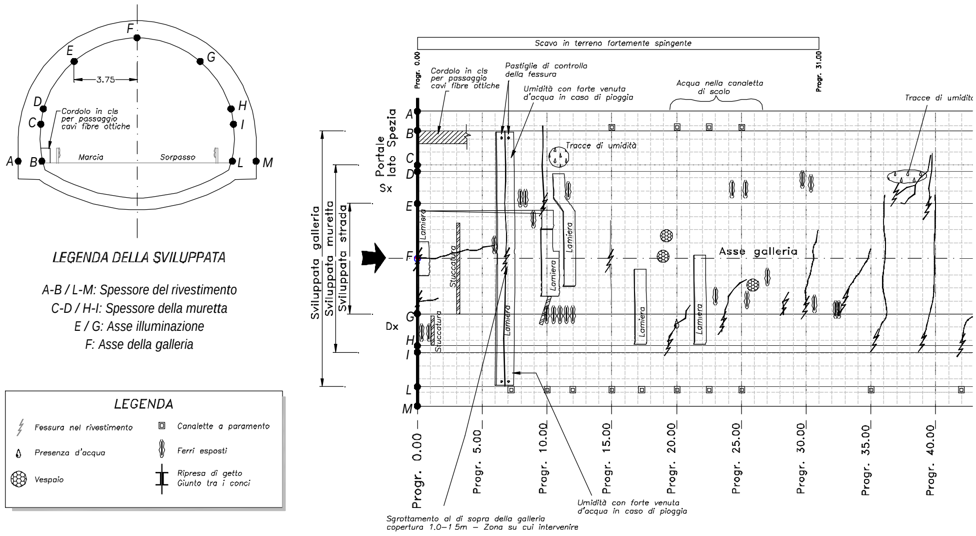

Figure 1 Typical inspection results presentation

This kind of graphical output combined with database accessibility provides a complete tool both for the designer and for the owner for determining the safety and quality status of each tunnel. Such measures allow those responsible to take the right decision on rehabilitation approach, either limited to localised areas or extension to the whole tunnel.

4. LIGHT REHABILITATION

When tunnel defects are localised to limited areas, spot rehabilitation can be carried out to reduce costs and minimise the time that the tunnel will be closed to traffic.
Temporary repair work needs to be both quick and safe. The most frequently used techniques are:

- installation of corrugated steel sheeting fixed by spits or small rock bolts for small damaged areas or minor water infiltration;
- installation of steel sheeting plates fixed by anchors or rock bolts for wider areas with voids or large areas of honeycombed concrete (in case of voids which do not allow the use of anchors, beams can be used to provide support by fixing the end of the beams to stable rock at the sides);
- in cases where unsound rock would require long anchors, the immediate intervention is often the installation of steel ribs inside the lining surface, although this may slightly reduce the tunnel section free space.

Full tunnel surface rehabilitation is indicated when a tunnel has relatively minor surface defects spread out along the entire tunnel length. In such cases restoration of the inner surface of the whole tunnel liner provides complete and definitive rehabilitation.

4.1 Localised Light Rehabilitation

The *case history of the Albiano Tunnel* provides an example of localised light rehabilitation. During the preliminary inspection of the tunnel lining, comprising visual inspection and hammer tests, several instances of superficial lining deterioration, rebar corrosion, faults in the cement, voids and weathering were detected. These damages were due to 30 years of ageing and were amplified by defective construction technique used in the sixties:

a) air pumps, used to pump concrete, caused separation of the gravel from water and cement. For this reason non-homogeneous concrete created zones with honeycombed concrete and other sections where only the superficial layer is well-mixed and compact;
b) plastic drainage channels were covered by cement lacking wire mesh and thus at risk of cracking;
c) time delays between concrete pumping intervals in some sections resulted in separation boundaries (cold joints);
d) only the section nearest the tunnel entrance was made with reinforced concrete.

To gain an understanding of the real conditions of tunnel surface, engineers hydrowashed the entire tunnel length. This procedure uses water at a pressure of 200 bars and a temperature of 85°C.

The degree of lining weathering was evaluated by collecting 10 core samples (ϕ 101 mm).

The zones identified as having defects were demolished by jack hammering. In cases of deeply honeycombed concrete or disconnected concrete sections more than 20 cm thick, two layers of welded wire mesh (ϕ 10 mm, 200 x 200 mm) were placed as shown in Figure 2**,** fastened to the sound concrete with rock bolts perpendicular or parallel to the surface. In cases of shallow honeycombed concrete, a single mesh layer (ϕ 5 mm, 100 x 100 mm) was sufficient to re-establish the original surface.

Once the welded wire mesh was fastened, the area was recovered with dry-mix, rapid-set shotcrete. Shotcrete had aggregates of 0-5 mm, additives to guarantee a good adhesion to the previous concrete surface and high waterproofing characteristics. It also provides good resistance against sulphates, which was also required for the highly aggressive tunnel atmosphere.

Figure 2 - Honeycombed concrete demolished and reconstructed using welded wire mesh and dry-mix shotcrete

Where rebars were exposed, a hydro-scarification process was employed to remove the rust from the bars. An anticorrosive was used to rustproof the bars before applying the wire mesh and shotcrete. Leaking water, from damaged drain pipes or weathered cement, was conveyed to the drainage system, located at the bottom of the tunnel wall, by corrugated steel sheeting.

The project was completed four weeks after the date of initial inspection. Traffic was increasing in this period with peaks on the weekends due to the approaching holidays (Easter) and warm season. Fast temporary rehabilitation minimised tunnel closure while guaranteeing traffic safety. This allowed designers and managers time to decide on and design a comprehensive rehabilitation solution.

4.2 General Light Rehabilitation of Tunnel Lining Surface

Sometime a cost/benefit analysis may determine that the optimum solution to resolving extensive defects to the tunnel lining (honeycombed concrete areas, continuous water leakage from the crown, etc.) is general surface rehabilitation, limited to a thin superficial layer of 3-5 cm along the entire tunnel length. In this case, hydro-demolition is used to remove the damaged parts and to demolish a specified surface thickness where required.

Case History: CASACCA Tunnel

The 350 metre long Casacca twin tunnel was initially investigated in June 1996 and the decision to proceed with definitive rehabilitation was taken in 1999. Tunnel lining thickness and lining stress/strain status were assessed in the initial investigation. It appeared that the stress on the lining was not due to thrust from the surrounding soil. Numerous voids were found above the crown, which was anyway already supported by steel ribs and shotcrete from the original tunnel construction work. A monitoring system (using electronic vibrating wire crackmeters) was installed to verify opening of existing cracks. No relevant movements were recorded over the 3-year monitoring period (1996-1999).

Rehabilitation design focussed on locations where the lining showed insufficient crown thickness or highly stressed, fissured concrete. Before proceeding with hydro-demolition, the existing concrete liner had to be securely bolted (using Feb 44k steel threaded re-bars 4-5 m long) to the surrounding rock mass to guarantee safety and prevent further cracking.

The construction proceeded through the following phases:

Remediation and protection

PHASE 1a Installation of rock bolts in sections of the crown having insufficient concrete thickness and concrete characteristics below acceptable limits.

PHASE 1b Injection of cellular concrete mix through the existing tunnel lining to fill voids and close openings with a lightweight material which establishes solidarity with the surrounding rock while exerting minimal additional loading on the lining.

Hydro-demolition and rehabilitation

PHASE 2a Hydro-demolition of the entire surface to a minimum depth of 3.5 cm. Removal of damaged water drains and demolition of honeycombed concrete areas.

PHASE 2b Capture of water leakage from lining with permanent water drains conveying water from crown down to the side walls and from there to a longitudinal collector drains.

PHASE 2c Smoothing of tunnel walls using dry-mix shotcrete and sealing of water drains.

PHASE 2d Installation of single layer of welded wire mesh over entire tunnel surface and double layer where rock bolts had been installed.

PHASE 2e Final application of rapid-set dry-mix shotcrete over the whole surface.

PHASE 2f Further manual smoothing of sidewalls to height of 4 m using dry-mix shotcrete with higher workability.

Finishing

PHASE 3a Installation of sidewalk and longitudinal water collector along the two sides of the tunnel.

PHASE 3b Spray application of a fibre-reinforced high resistance white cement to create a smooth and brilliant surface.

PHASE 3c Rehabilitation of tunnel entrance portals with high resistance paint coating

The above activities were executed in the year 2000 and the Casacca Southern Tunnel is now fully functional as shown in Figure 3.

The most delicate phase was the hydro-demolition, which requires close control to avoid excessive demolition of concrete liner thickness. The welded wire mesh must be carefully positioned, while the subsequent application of dry-mix shotcrete requires highly specialised skilled labour to provide a homogeneous layer with a smooth surface. The use of white concrete to a height of 4 m on tunnel sides both increases visibility and is easily maintained by washing.

This sort of rehabilitation represents a complete overhaul of the tunnel with structural reinforcement where necessary and an overall enhancement of the tunnel lining appearance. This solution is currently recommended for tunnel lengths up to 500 m. Longer tunnels should be rehabilitated in sections. This way the tunnel can be closed during a low-traffic period, one section can be completed and the tunnel reopened temporarily to accommodate heavy holiday traffic. The subsequent sections can then be completed during the next low-traffic periods.

Figure 3 - Casacca tunnel after lining surface rehabilitation.

5. HEAVY REHABILITATION

Heavy rehabilitation is necessary when the inspection phase detects lining problems that cannot be resolved through light rehabilitation because of their extent or seriousness, or because high geological stress conditions are present. Inspection of certain tunnels has revealed serious defects deriving from construction problems and/or the presence of geological faults. In such cases, the tunnel lining needs to be completely reconstructed, either locally or over extensive portions.

5.1 Localised Heavy Rehabilitation

The rehabilitation of localised areas, where high risk structural conditions are found, necessitates a careful and thorough design phase. Investigations of the surrounding soil or rock are required to evaluate the pressures acting on the tunnel. Monitoring of stress/strain conditions is also required to assess fault zones.

Case History: VALICO *Tunnel*

The 2040 metre long twin tunnel, built in the sixties, is located in the upper elevations (approx. 750 m a.s.l.) of the Autocisa highway and provides a passage from the north-eastern to the south-western Apennine basins.

The entire preliminary inspection (visual inspection with hammer tests) was carried out in one week. The investigation recorded 153 points with superficial lining deterioration and weathering, cracks in the concrete lining, and leaks. In addition, three critical situations were revealed just via visual inspection and hammering: two sections presented voids between the temporary and permanent supports and insufficient thickness of the existing lining; in addition another section had a cavity more than 2 m deep above the lining, linked to a possible fault zone encountered during tunnel construction.

More detailed investigations were needed to better understand the situation in those sections where major damage was recorded. However, because of heavy traffic expected for the upcoming Easter holiday, Autocisa asked for a fast intervention that could guarantee safety while allowing the tunnel to be reopened for the Easter holiday rush.

Temporary repair

After removing the unstable material, each of the 153 defect points was covered with corrugated steel sheeting fixed to the sound concrete by rock bolts. This protected the road from falling material and water leakage.

Tunnel stability was evaluated by consulting past construction information, which confirmed good rock quality. The repair was designed with the following support measures:

1. In the two sections with voids in the crown 2 steel sheets (4 m x 2 m x 3 mm) were installed, each one fixed by 5 dywidag bars (ϕ 25 mm, L = 4 m).
2. In the section with the large void and the risk of large pieces of concrete falling, it was necessary to fasten a steel sheeting plate to the rock by installing 2 steel beams fastened with 4 dywidag bars per beam (ϕ 25 mm, L = 4 m). Another four dywidag bars were installed with 1 metre spacing to anchor the steel plate and the damaged tunnel lining portion. In order to monitor possible stress increases or other hazard situations a load cell was also installed.

These devices allowed the tunnel to be safely reopened for the Easter period. Further investigation and permanent repair design were postponed to a time with lower traffic demand.

Further investigation

In order to investigate the possibility of more extensive support reconstruction in the three critical points where voids behind the supports were discovered, 6 boreholes were drilled ten metres into the crown of the tunnel in each of these sections. Three vertical boreholes were also drilled to verify concrete invert thickness and to assess rock mass conditions.

The analysis of the cores showed that the rock mass comprises thick series of grey, foliated, well-fractured marls with layers of very fractured and schistose grey shale. The cores showed numerous calcareous veins and inclusions and occasional small voids with calcite crystals. During borehole drilling no other voids were found besides those between the concrete lining and the rock surface.

Samples were taken from the cores for uni-axial compression tests and shear tests in order to evaluate the cohesion, the friction angle and the module of elasticity of the highly fractured rock mass. The results of the compression tests on concrete samples generally gave resistance values of 15-20 MPa whereas the rock samples only reached 5-10 MPa.

The investigation was also extended to adjacent zones using GPR (Ground Penetrating Radar). This test provided evidence of anomalies in three other tunnel lining sections. Small diameter drilling tests revealed significant voids over a good portion of the concrete liner that could not be identified from the surface.

Permanent Rehabilitation

After evaluation of the investigation results, the rehabilitation project was designed first to create protection for the workers before demolishing damaged parts of the concrete, and then to re-establish the original (design) thickness of the concrete lining.

The project was executed one year later in a low traffic period as follows:

PHASE 1: Removal of provisional support used for temporary repair. Installation of coupled IPN 180 steel ribs (see Figure 4) and fixing of existing lining with rock bolts.

Figure 4 – Rock bolt installation under protective steel ribs

PHASE 2: Demolition of damaged concrete with protection from rock falling from the crown with dry-mix shotcrete and welded wire mesh.

PHASE 3: Installation of steel reinforcement fastened to sound concrete. Previously installed dywidag bars would have been subsequently embedded in concrete.
PHASE 4: Formworks installation and pouring of concrete grade $R_{ck} \geq 350$ MPa.
PHASE 5: Once concrete was sufficiently hardened, steel ribs were removed and existing rock bolts, plates and nuts were encased in the lining by means of dry-mix shotcrete.

Once all sections of tunnel were structurally completed, holes 65 mm in diameter were drilled into the crown and standpipes were installed for further cellular concrete injection. The voids above the lining were filled with cellular concrete (unit weight approx. 4 kN/m^3) in order to give proper solidarity to the rock and the lining without excessively loading the lining itself. Structural rehabilitation was then completed with surface cleaning, and the highway was safely re-opened.

5.2 Extensive Heavy Rehabilitation

Case History CORCHIA *Tunnel*
The 300 m long Corchia twin tunnel was constructed through a Flysch geological formation during the seventies. During the eighties, transversal and longitudinal cracks developed (up to 50 mm wide) in the concrete lining near the middle of the tunnel. A small stream, Rio Bosco Secco, runs parallel to the tunnel for about 300 m.
The tunnel was closed for inspection and unstable concrete blocks were removed. Steel ribs and plates were then installed to protect vehicular traffic. These temporary measures allow time to set up a proper investigation (which began in 1986) comprising:

- Drilling of boreholes from upper ground level (30 m above tunnel axis) and installation of inclinometers, piezometers and multi-extensometers;
- Drilling of sub-horizontal boreholes from inside the tunnel and installation of drains;
- Drilling radial holes to measure lining thickness and detect any voids;
- Stress detection by installation of concrete load cell on tunnel sidewall;
- Installation of topographic monitoring of surface movement of rock mass;
- Installation of crackmeters for measurement of cracks opening, and convergence meters to monitor sidewall displacement adjacent to the fault zone.

The interpretation of investigation data as well as data collected through further monitoring revealed a slipping surface close to the fault area. Displacement of the rock mass was continuous, with periodical movements associated with water table level variation due to infiltration from the surface water drainage system.
The complete rehabilitation of the tunnel lining was then selected and the design

Figure 5 – Concreting phase

involved creating a stiff reinforced concrete annular segment located crosswise to the fault zone. The adopted design concepts for work in a dangerous area were verified using a finite element method to ensure adequate protection and safety.
The executives phases were as follows
PHASE 1: Cement mix injection on the outer side of the lining to fill voids above the crown.
PHASE 2: Ground treatment of annular soil surrounding the tunnel in a 108 metre stretch centred on the fault zone by installation of radial micropiles (4.5 m length, 1.5 m patch) and controlled injection of cement grout through the micropile sleeves.
PHASE 3 Removal of tempo-rary steel ribs and of loose concrete blocks around main crack. Removal of roadway to expose the concrete invert.
PHASE 4 Demolition of the invert in limited sections (6.5 m long) in order to minimise the effect on the existing lining. Reinforcing bars were then installed and concreting was performed on 3.25 m wide sections linked by re-bars with couplers.
PHASE 5 Demolition and reconstruction of sidewalls and crown. Demolition was performed by means of a head-scraper removing 50 cm thickness from existing damaged lining in 9 m sections. The operation was protected by the previous Phase 2 treatment. Steel reinforcement was installed in 6.5 m sections. Hydraulic operated formwork was installed employing theodolite measurement for correct tunnel alignment. Concreting was performed using R_{ck} 30 MPa grade concrete by means of pumps and vibrators connected directly to the hydraulic formwork.
PHASE 6. Installation of bottom drainage pipes along the full length of the tunnel. The stream drainage canal above the tunnel was also replaced to remove water infiltration allowing the tunnel to be re-opened in complete safety.

Strain gauges and additional convergence meters were installed at all phases of the operation to continuously monitor the work progress. The invert re-construction was the riskiest operation and transducers confirmed the need to use limited section demolition in order to avoid excessive deformation of adjacent sidewalls. The existing slipping surface along the fault was monitored during the work (and continues to be monitored) and an insignificant increase of displacement was recorded.

6. FUTURE DEVELOPMENTS

The rehabilitation techniques considered here provide a complete range of protective measures for each investigated tunnel. Coupled with a continuous, periodical monitoring program of structural soundness and geological context, they provide an effective means of ensuring a high level of tunnel safety.
More comprehensive safety system should be required by law such as efficient lighting systems, fire extinguishers, and fans and blowers ensuring adequate air exchange and evacuation of vehicle exhaust.
For tunnel lengths of greater than 1000 m the requirement for one or more intermediate escape chambers has been proposed. Such spaces must be fire-safe and offer survival possibility to people in the event of accidents inside the tunnels. Water hydrants would be also useful. Regular and continuous maintenance of all such safety systems is essential for minimising risk.
Antennas for cellular phones are already installed and active in all tunnels along the Autocisa to allow patrolling police to be notified of any accidents in real time.

It is recommended that Italian Government together with the European Community should support and sponsor these initiatives in the future years.

7. CONCLUSIONS

Concrete supports of underground constructions require monitoring and maintenance to counteract the effects of concrete ageing, the freeze-thaw cycle, chloride penetration and carbonation, as well as to reveal damage and defects often resulting from the application of inadequate construction techniques.

Visual inspection and hammering technique is suggested as an initial method because it is fast and relatively cheap. However, as the cases studied have illustrated, a certain level of uncertainty still remains after the initial visual inspection. Drilling and core sampling represent further measures for a more detailed and in-depth investigation.

The storage of all information in GIS format creates a complete database for each tunnel which is extremely useful in assessing whether to apply local or extensive rehabilitation.

Once the defects and their level of gravity have been determined, the designer has to take a fast decision in order to minimise the closure of the tunnel to traffic while guaranteeing complete safety. The designer must correctly assess the effective risk and develop the fastest and safest solution, accurately identifying the location and nature of the problem while avoiding causing alarm in the event of limited problems. Good collaboration between highway staff and project designer is crucial to solving problems both in terms of safety and speed while accounting for cost and durability of the solution.

Temporary measures are often required to ensure quick tunnel safety while allowing time for a more permanent solution to be developed. The techniques and procedures illustrated in this paper, intended to ensure safety for one or two years, require that a permanent solution be studied and carried out without delay. The time period may only be extended if a continuous monitoring system is installed and indicates that safety levels are maintained.

The case histories presented here clearly show that many options need to be considered when repairing tunnels with significant structural defects. If damage involves the entire thickness of the concrete lining, new tunnel supports guaranteeing tunnel stability must be installed before demolition can be initiated. The process aims to guarantee safety while optimising tunnel closure time and costs. Continuous regular monitoring is the only way to assess tunnel status through time and determine the schedule of future maintenance operations in order to guarantee enhanced safety conditions for highway users.

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