# Report on the Damaging Effects of Water on Tunnels During Their Working Life

**ITA Working Group on Maintenance and Repair of Underground Structures**

***Abstract***—*This official report of the International Tunnelling Association deals with the adverse effects of water on tunnel structures during their working life (i.e., following completion of construction). The report describes problems and damage caused by water, and discusses various repair methods applicable to different types of building materials and structures. It discusses matters for consideration in designing, construction and operating tunnels, and identifies matters for further consideration. The report includes 48 case histories of tunnels, submitted from 12 countries.*

***Résumé***—*Le rapport officiel de l'Association Internationale des Travaux en Souterrain discute: des différents types de dommage créés par les fuites d'eau; des taux de fuites acceptables; des méthodes de réparation; de l'estimation des frais futurs pour entretenir le traffic existant et les tunnels utilitaires; et de la maintenance des tunnels et des coûts de réparation. Ce rapport inclut aussi 48 cas historiques de tunnels dans 12 pays.*

## 1.0 Introduction

Water is the tunneller's enemy: it causes problems during excavation; it introduces additional expense into the tunnel lining and ground support; it frequently causes ongoing problems during the working life of the tunnel, sometimes affecting not only the tunnel lining but also the structures and fittings within the tunnel.

Not all the defects of water are obvious at the time of tunnel design, as many adverse experiences over the years will confirm. Some problems, indeed, will arise only after the tunnel has been in use for a significant period of time.

In order to improve our knowledge of the way in which water can have an adverse effect on tunnel structures, particularly during their working life, the International Tunnelling Association (ITA) Working Group on Maintenance and Repair of Underground Structures has conducted a study of the damaging effects of water on tunnels during their working life; that is, following the completion of construction.

The Group has sought case histories from around the world concerning problems caused by water originating from the surroundings of the tunnel. When analysed, these case histories:

- Illustrate the problems that are being experienced;
- Provide information concerning the remedial works that have been carried out and their success or otherwise; and
- Provide guidance for tunnel designers concerning means of avoiding similar problems in the future.

By arrangement with the ITA Executive Committee, the Group has had the support of the West German tunnel research organisation, STUVA, during the early stages of this study. STUVA collected and collated the case histories and prepared a report for the Group. This report has been reviewed and further case histories have been added.

The report now includes 48 case histories of damage to tunnels, their surroundings or their contents as a result of the action of water. There must be many more such instances in the world. In many cases, owners are reluctant to publish details of problems; often because of legal implications, sometimes for fear of affecting public confidence in the facility or in its owner. We hope, however, that more case histories can be found so that the future may benefit from the errors and imperceptions of the past. We emphasize that the case histories form the backbone of this report.

In Section 2, the problems revealed by the case histories are analysed and classified. Section 3 sets out the various remedies that have been attempted; and Section 4 gives pointers that may help to avoid at least some of the problems in future tunnel designs. A brief bibliography and an appendix comprising the case histories complete the report.

## 2.0 Description of Problems and Damage Caused

### *2.1 General Introduction*

The damaging effect of water on tunnels during their working life may be classified by:

- A - External effects (on the surroundings of the tunnels, but not affecting the structure).
- B - Structural Effects (affecting the structural adequacy of the tunnel).
- C - Functional Effects (affecting the functional adequacy of the tunnel).

Case histories, mainly relating to B and C, have been collected and are analysed in the following section of this report. As the enquiry to member countries may have been biased towards effects B and C, few case histories for type A effect have been received, although it is known that such effects exist. Supplements to this paper to include more type "A" effects will be a task for future study.

The case histories received have identified many different problems that may be attributed to the effects given above. Table 1 lists the nature of the problems identified, the category of damage and the case histories that apply. (References, e.g., "Case J1", are given in the listing of case histories in Table A1, at the beginning of the Appendix.)

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The features listed in Table 1 are discussed below with respect to the different forms of lining construction.

In addition, it must be noted that frost in conjunction with incoming water can have serious effects on tunnel function, such as:

- Hazards from falling icicles;
- Reduction of section by icicles;
- Reduction or clogging of section of ventilation openings and shafts;
- Icing of the carriageway in road tunnels.

### 2.2 Brickwork Tunnels

Bricks are sensitive to water, even if it is not aggressive, depending upon their firing temperature and chemical nature; and the quality of bricks is not uniform. In the case of freezing or thawing, any damage is usually increased.

Problems with mortar are discussed under "Masonry Tunnels" (Section 2.3, below). In some old tunnels (e.g., case history UK4), workmanship may contribute to problems.

### 2.3 Masonry Tunnels

Effects of water on mortars are well known, especially on mortars made with lime: the mortar loses its strength and becomes brittle. In some cases, chemical reactions from sulphates brought by seeping water result in swelling.

At the time of construction these tunnels are either back-packed with dry stone or ordinary masonry, or the voids are filled and supported by wood. Water aids rotting of timber, leaving voids; and flowing water removes fines in the packing. Voids sometimes result from the shape of the ashlars, as in many cases their outer face is angular and less well shaped than the generally rectangular face on the intrados. Water-filled voids outside the lining lead to instability of the lining.

Ashlars of soft limestone, anhydrite and sandstones can be directly damaged by water.

Freezing and thawing accelerate any damage.

### 2.4 In-situ Concrete Tunnels

These types of tunnels are generally unreinforced. Problems with reinforced linings can include those described under segmental concrete linings in the section below ("Segmental Concrete Tunnels").

The main disorders in reinforced linings are caused either by construction faults—porous concrete, segregation, fractures, cracks due to thermal shrinkage or inadequate joint preparation, loss of cement and water—making concrete more pervious and less strong; or by the chemical

*Table 1. The nature of the problems identified by the case histories (see Appendix A), the category of damage and the case histories that apply. Under "Classification of Damage," B refers to structural damage and C refers to functional damage (see Section 2.1 in the text).*

| Nature of Defect | Classification of Damage | Relevant Case Histories |
|---|---|---|
| Deterioration of mortar internally | B | J1, J2, F1, F5, F6 |
| Corrosion of reinforcement | B | CH1, D1, ET1, EG1, J3, J4, HK1 |
| Degradation/Reduction in strength of concrete | B | CH1, F7, J1, ET1, HK1, UK5 |
| Swelling soil—lifting/ damage to invert | B | CH3, D4, D8, F1, F2, UK2 |
| Erosion of mortar (masonry lining) | B | D2, D3, D4, D5, D6, F1, F2, UK4 |
| Loss of support due to fines transport | B | US1, US2, US3, J4 |
| Dissolution of bitumen external layer by toluol in ground water | B | D10 |
| Rising water table—lack of tightness | B | J4 |
| Chemical action on lining/cast iron | C | UK3, J5, J6 |
| Frost damage and other icing effects | C | A1, A2, A3, CH2, CH3, CH4, D1, D5, D6, D9, N1, F1, F2 |
| Damage to surface finishes | C | A2, C1, F4, UK1, S3 |
| Corrosion of internal fittings | C | A1, A2, C1, CH3, D5, D10, D11, F4, F5, J1, J2, J3, J4, S1, S3 |
| Salt deposits, masonry sealing | C | D11, F3, F6, S1 |
| Clogging drainage due to fines | C | A1, C1, D4, CH3, UK2 |
| Cracks in track/road slab | C | J1, J2, J3, UK2, UK5 |
| Coal tar inflows | C | UK1 |
| Ingress of dissolved gases | C | UK6 |
| No reported damage or effect | - | D7, D8 |

decomposition of aggregates or cements, resulting from an aggressive tunnel environment.

These disorders may occur on the extrados (aggressive water), in the mass (weakening), and/or on the intrados (thawing, erosion by water, etc.). They are made worse by structural deficiencies of the lining (rupture) and inadequate filling (grouting) of external voids.

### *2.5 Segmental Concrete Tunnels*

These tunnels are generally reinforced with steel bars, which are subject to corrosion if adequate concrete cover or positive corrosion protection is not provided. Corrosion may lead to spalling of the concrete and loss of structural capacity.

Lack of watertightness in segmental concrete lined tunnels may occur where inadequate provision is made for sealing the joints between segments or where provisions have become defective. Moisture, particularly in cases involving dissolved salts, may cause corrosion of reinforcing steel.

Of the six case histories referring to segmentally lined concrete tunnels, four refer to damage resulting from the infiltration of groundwater containing chlorides. In these cases, the chloride contamination of the concrete has caused electrolytic action with the steel reinforcement, causing corrosion and consequent cracking of the surrounding concrete. Corrosion of metallic fixings within the tunnel is also noted.

Rising groundwater tables are apparent in many of the industrialised capitals. Where tunnels were constructed above the water table and no formal provision was made for waterproofing joints between the precast concrete segments, a rising groundwater may enter the tunnel quite freely.

In permeable soil, typically of silts and sands, loss of fines from the surrounding ground into the tunnel may result from high groundwater inflows. In case history J4, the inflow of fines into the tunnel has led to settlement and ovalisation of the tunnel. In case history C1, drainage ducts and pumps have become blocked.

In rail tunnels, where stray currents from the traction supply may occur, the electrolytic action of the moisture may be particularly severe, with the rapid migration of the chloride ions to the steelwork attracting the current. In this respect it may be noted that under wet conditions, the insulation of rails used for current return (in some railway systems) may be severely reduced, increasing the likelihood of stray currents.

Case history UK6 gives details of a site-specific occurrence where the groundwater surrounding a tunnel acted as a medium for the passage of methane into the tunnel. With no particular measures taken for the discharge of the gas from the tunnels, levels of methane were permitted to build up, subsequently leading to an explosion within an adjacent structure. Although this occurred in a tunnel lined with concrete segments, it obviously could occur in any tunnel with a non-watertight lining in appropriate geological conditions.

### *2.6 Segmental Cast-Iron Tunnels*

Similarly to the precast concrete linings, the segmental cast-iron tunnels—including those made from spheroidal graphite iron (SGI)—may exhibit lack of watertightness through seepage at the segment joints.

In case histories UK3, J5 and J6, corrosion of the tunnel lining and fitments is occurring under the action of seepage of sulphuric acid into the tunnel. It is thought that the sulphuric acid is formed by the reaction of the groundwater on the sulphides shown to exist in the sand and clay lenses surrounding the tunnel. Bacteria may play a part in this chemical process.

In case history UK1, coal tar is found to seep into the tunnel from the surrounding ground, causing unsightly marking of the finishes. This problem is site-specific; however, seepage of any substance contained in the groundwater surrounding a tunnel may occur if specific measures are not provided to prohibit this action.

### *2.7 Other Tunnels*

Unlined tunnels have not been included as a category because no case histories have been submitted. It is to be supposed that the ground conditions which permit tunnels to be unlined will not be subject to problems from water.

Two-part linings are becoming increasingly common. The New Austrian Tunnelling Method (NATM) uses a primary lining of sprayed concrete with rock bolts, anchors, lattice girders, etc., to form an active supportive arch within the ground and the primary lining. A secondary lining of reinforced or unreinforced concrete is often added for functional reasons, and this lining frequently is designed to take ground loading in case the sprayed concrete should become degraded.

No case histories of damage to sprayed concrete as a result of water seepage were received. The possibility of such damage is, however, a subject of debate; and in view of its importance to the philosophy of NATM design and durability of linings, it must not be overlooked.

Other two-part linings use segmental concrete rings or extruded concrete as a primary lining. The inner *in-situ* concrete lining is designed to provide durability and watertightness.

No case histories of water-related damage were received.

## 3.0 Repair Methods

### *3.1 General*

When disorders occur, a step-by-step investigation must be made, as described in Figure 1.

After an information-gathering phase, which includes details not only of the lining but also of the surrounding ground and hydrological conditions, the diagnosis allows evaluation of the condition of the structure. This evaluation in turn leads to the definition of a schedule of remedial works, including repair and maintenance works, classified by order of necessity or urgency. This appreciation occurs at the end of the investigation process.

It must always be kept in mind that action may be taken on one or more of the following five zones:

1. The surrounding ground.
2. The interface between ground and supporting structure (lining).
3. The lining mass.
4. The lining intrados.
5. The internal useful spaces of the underground structure.

The intervention may affect only one of these zones, but generally affects several of them. Action may be taken:

- On the surrounding ground, to reduce its permeability by grouting or to collect water by drilling deep borings;
- On the interface between ground and lining, by grouting, in order to fill the voids to strengthen the lining or to push water into the surrounding ground;
- To effect waterproofing repairs, in a manner appropriate to the lining type.

Modern grouting techniques, and especially modern grouts, enable us to seal even considerable water inflows, although the unit cost of hydrophillic and latex grouts (for example) is high. Small leaks are often difficult to seal by grouting alone.

It must be remembered that sealing of leaks does not remove water and harmful chemicals that may have permeated the lining, or chemical deposits that may have been left after evaporation of water. These leaks will continue to affect the lining unless other remedial measures are taken.

If the lining is in very bad condition (e.g., as in case history UK4), partial or complete reconstruction may be necessary; and the new lining must be designed to avoid recurrence of similar or new problems.

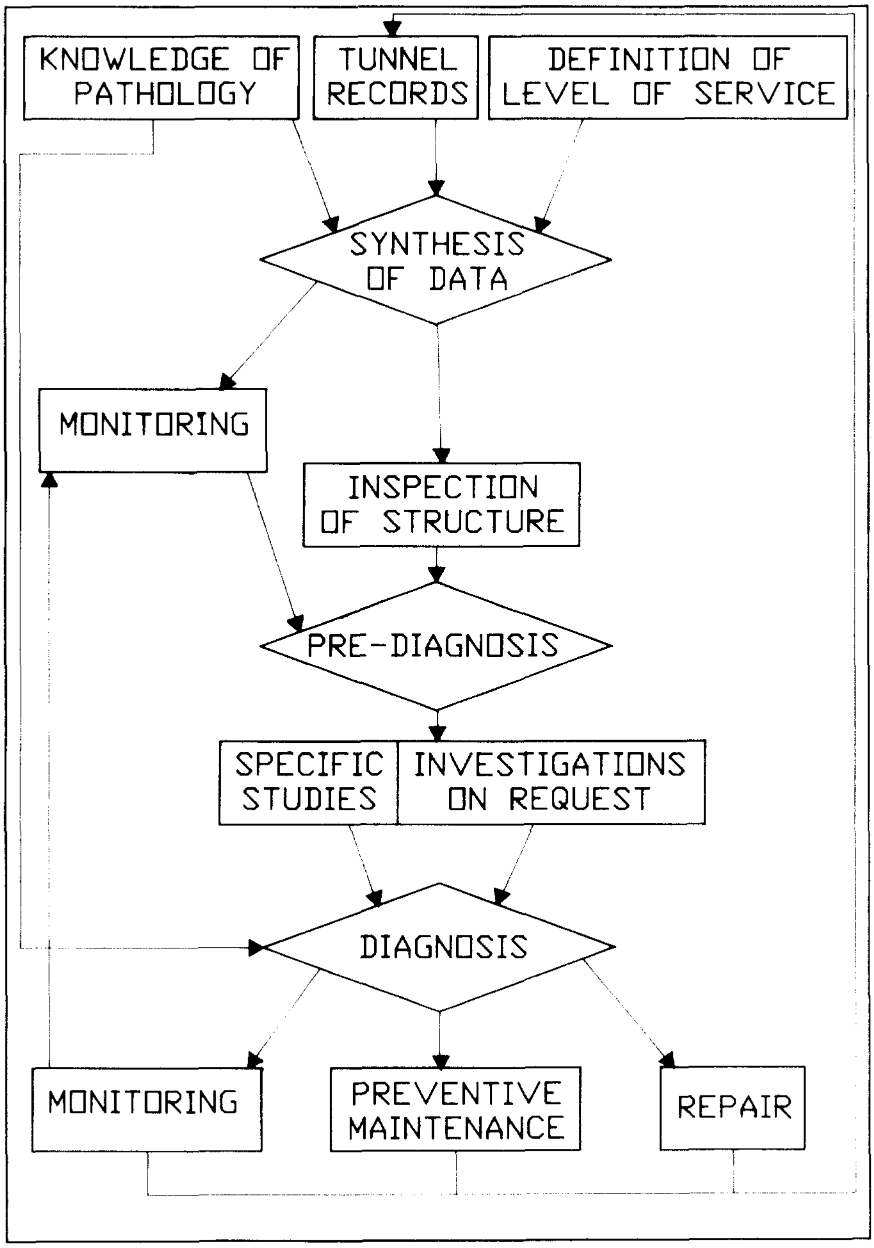


*Figure 1. Step-by-step procedure for investigating tunnel disorders, analysing the evidence, and recommending action on the problem.*

In other situations, partial replacement of the lining—or, if space permits, provision of an inner lining—may be more appropriate. Design of the new lining must take into account any ongoing deterioration of the original lining due to chemical or corrosive action that will not be halted by the new lining.

It is obvious that remedial work operations must not be allowed to cause damage to sound linings; but, for example, excessive pressures used for cleaning joints in masonry could remove more mortar than advisable, leading to overloading of outer brick courses.

Some repair methods from the case histories are noted below. They are not necessarily exclusive to the lining types under which they are described.

### 3.2 Repair of Brickwork Tunnels

Usually these linings are made of several layers of bricks and the defects are often localised on the intrados.

If structural strength remains sufficient, the inner layers of bricks are removed by sections and replaced by shotcrete or poured concrete.

See also the notes on masonry tunnels, below.

### 3.3 Repair of Masonry Tunnels

Usually masonry tunnels have an outer part of ordinary masonry (rubble), surrounded with voids formed during the construction between ground and rubble. The inner part is usually made of one course of ashlars (or, sometimes, of prefabricated concrete slabs).

If the inner course is overstressed, the structure usually is strengthened after jointing, by carefully grouting the voids and the whole masonry. This work has also a temporary effect on the waterproofing, which then must be supplemented by drainage. Repairs by shotcrete or poured concrete can also be used.

To waterproof the lining in the mass, the following methods are available:

1. *Repointing stone or brick.* The following working steps often are necessary before repointing masonry:
   - The deteriorated mortar (in some cases, all of the mortar) is removed using, for example, a high-water-pressure jet.
   - The surface and joints are cleaned by sand-blasting. For dry sand-blasting, quartz-free sand (e.g., granulated blast-furnace slag) is recommended to avoid the silicosis risk. If high-water-pressure jets are used, sand should be added to achieve sufficient wall cleaning.
2. *Grouting open masonries.* However, long-term attack by infiltration of aggressive water is not halted by this measure. To permit grouting, injection holes with diameters between 30 mm and 40 mm and lengths approximately two-thirds of the masonry thickness and with a wooden plug must be placed in the joints. Between two and five boreholes per m$^2$ are drilled, depending on the masonry condition.
3. *Placing a waterproofing system on the intrados,* as for example: repointing supplemented by shotcrete, coats of mortar, mineraliser, or water-repellent resins. If the joints are leaking, they must be repaired first.

If the useful space of the tunnel can be reduced, other methods may be used, such as added inner linings or complete casing with poured concrete, shotcrete, tubbings sleeve or prefabricated sheets supplemented with filling of concrete or mortar case. Because prefabricated inner linings cannot be inspected, their use for this purpose may be only temporary.

To spray an internal shotcrete shell, the damaged area must first be removed until sound material is reached, and the lining must be cleaned and roughened by sand-blasting or high-water shotcrete. Temporary structural support may be needed during this process. Reinforcement bars or wire mesh with a diameter of not more than 8 mm are fastened with steel dowels (anchors) placed at intervals of approx. 0.5-mm. The reinforcement should have a shotcrete cover of about 30 mm. Closely spaced steel dowels are necessary to avoid bond failure and vibration of the reinforcement bars, which cause voids in the shotcrete.

An alternative is a steel-fibre-reinforced shotcrete layer. An additional final layer of shotcrete prevents steel fibre corrosion.

If water drips from any leaks into the tunnel, a drainage layer of foil with naps can be used for repairs. The foil is delivered as webbing or as plate and the overlap is not welded. Spraying an additional shotcrete shell results in a dry tunnel lining. Experience over the last 10 years has proven that the foil possesses sufficient drainage volume between the naps to prevent clogging.

If freezing is likely to be a problem (for example, near tunnel portals), drainage arrangements must be insulated; but this insulation will, in turn, need to be made safe against fire.

### *3.4 Repair of In-situ Concrete Lining*

Only very porous concrete (ca. 30% voids) can be strengthened by grouting. Nevertheless, this method is expensive and slow and is only advisable on structural parts difficult to destroy and rebuild.

Water may be driven away from the lining (low pressure) by grouting of the ground and voids, with subsequent drainage to a radius twice that of the tunnel.

The most frequent method to waterproof such tunnels is to cut or enlarge joints and use them as drainage slits. To prevent water from entering the useful space, pipes and a cover are then provided.

Another commonplace method is to cover the intrados with a waterproof complex—draining sheet + foil + shotcrete or concrete shell. However, this covering will preclude subsequent inspections of the lining. This method is possible only if sufficient useful space is available.

The repair of cracks is a complex task. Efficient methods must take into account many factors: amplitude of joint movements, wetness of the lining, quality of the lining water pressure, water flow. Other properties of the products to be used that must be taken into account are:

- Ability to be laid in the presence of water or only on dry base.
- Type of cleaning and treatment of base required, especially if a bonding agent is required.
- Adhesion to the base.
- Shear strength of products placed at the joint bottom (against water pressure).
- Elasticity of materials, if the joint opens.
- Low-temperature rheology, if frost is likely to be a problem.
- Ability to be placed in a confined atmosphere.

For the user, the installation time, the costs (principally manpower costs), and long-term performance are the criteria for choice of repair method and product.

Generally, satisfactory methods combine the effects of several products. The following steps are the most typical:

1. Careful cleaning of the base.
2. Pre-sealing of the crack bottom.
3. Filling in of the recess by a product sufficiently deformable to prevent any water to pass.
4. A sealing for this filling, so that it does not extrude out of the joint under the action of water and joint narrowing; for instance, by a strip or joint cover.

Efficient systems are expensive.

Grouting of thin cracks is unpredictable in terms of time and cost, because part of the grout may flow into voids and surrounding ground. The zone of penetration of the grout within the cracks is small (generally about 0.6 m), and sealing of the intrados face of the crack will be required.

The repair of cracks one by one must be undertaken only after checking to ensure that long-term movements have ceased (cyclic thermal effects cannot be avoided). If steady time-dependent movements occur, the structural integrity of the tunnel must be restored before waterproofing.

In many cases (e.g., swelling ground, overstressed ground), the construction of an invert is necessary in order to stop movements.

### *3.5 Repairs of Segmental Concrete Tunnels*

Repairs and remedial action to segmentally lined concrete tunnels would generally include:

- The stemming of seepage into the tunnel.
- The removal and repair of damaged concrete.

Of the case histories giving details of problems, repair works have been carried out in just two. For the other cases, the work of carrying out detailed investigation into the causes and extent of the problem is still in hand and is recognised as an important stage in the development of proper remedial action.

The stemming of seepage into a segmentally lined tunnel may be carried out by:

- Tunnel caulking.
- Injecting resin mortar into cracks.
- Forming of an inner lining with proper provision for waterproofing.
- Grouting behind the existing lining.
- Replacing the lining with formal provision for waterproofing.

These methods are discussed in detail in previous sections.

In certain cases of electrolytic corrosion, this action may be halted or greatly reduced by oxygen deprivation (i.e., by an inner airtight lining) or by cathodic protection.

### *3.6 Repair of Segmental Cast-Iron Tunnels*

The stemming of water flows into segmental cast-iron tunnels may be carried out by methods similar to those for segmental concrete. The well-defined joints and straight flanges of the cast-iron segments generally will permit successful caulking of the lining to be carried out, and it is unlikely that inner replacement linings will need to be formed. It would be usual for regrouting of the tunnel to be carried out prior to caulking the tunnel in order to stem water flows as far as possible by sealing leakage paths within the adjacent ground, and to ensure that all voids that may have formed are completely filled.

### *3.7 Other Tunnels*

Case history C1 refers to excessive leakage within an immersed tube tunnel. Remedial action, in this case the repair of the cracks, involved injection of epoxy resins, similar to the methods described in Section 3.3.

For most other forms of tunnels, the methods for repair described above generally will be applicable.

## 4.0 Matters for Consideration in Design, Construction and Supervision of Future Tunnels

### *4.1 General*

Every case history tends to reveal a matter that, in hindsight, could have been improved upon to the benefit of the functional performance and long-term structural integrity of the tunnel. It is not strictly the function of the ITA Working Group on Maintenance and Repair of Underground Structures to study and report on matters relating to design; therefore, the following text deals only with the identification of matters for consideration by the designers.

The second section of the report identified the main problems described in the case histories. In the majority of the cases, the problems and damage related to water have arisen from the inflow of groundwater into the tunnel through the lining. In many cases, this has occurred despite the provision of waterproofing measures. Experience has shown that measures to seal all seepage completely are expensive and need to be justified carefully by designers so that owners are satisfied that the expenditure for waterproofing is appropriate.

Selection of the degree of watertightness of a lining appropriate to the use to which the underground structure is dedicated is outside the scope of this present report. The matter is discussed in many of the references listed at the end of the report. The attitude toward water inflows in structures that have similar uses varies from nation to nation and from owner to owner. Absolute watertightness is seldom achieved in bored tunnels in a wet environment; however, in West Germany, for example, inflows of as little as 0.1 litres per day per square metre of tunnel surface measured over a 10-m tunnel length are specified for frost-endangered sections of traffic tunnels. This is a high standard, and one that is not required in many other countries.

The design engineer often must look further than internal requirements to decide what measures should be taken to offset the potentially harmful effects of water.

The tunnel designer must bear in mind the following points, which are illustrated by case histories:

1. Concrete is not impermeable. Good concrete has a low permeability, and additions to the mix can reduce it, but not to zero. If groundwater is under pressure, it will gradually permeate the concrete lining, and dissolved salts will be diffused into the concrete at the same time. The process may be very slow, but because tunnels are now designed to last for many decades, they may be vulnerable. These effects can be calculated, at least approximately, and appropriate measures taken to eliminate the risk of corrosion.
2. Evaporation can serve to concentrate dissolved salts, depositing them on joint and internal surfaces and transforming a minor and relatively innocuous inflow into a potentially serious corrosion initiator.
3. Chemicals dissolved in the water or in the surrounding ground can be changed from benign to aggressive by reaction with the oxygen which the underground structure provides.
4. Small water inflows can, over long periods of time, carry large quantities of fine material, creating voids in the ground and leading to collapse of the tunnel lining or overlying properties.
5. The tunnel acts as a drain, to a greater or lesser extent; in cohesive soils, this situation can result in changes in water content and consequent consolidation and settlement of foundations, etc.

### *4.2 In-situ Concrete Tunnels*

To prevent subsequent disorders to linings, the designer must take into account as soon as possible the hydrogeological properties of the surrounding ground. Permeability of the ground and chemical compositions of water must be measured during the investigations. Even where testing for permeability is carried out, it must be borne in mind that the excavation of the tunnel may result in changes. In rock, for instance, the loosening created by blasting and the delay before the installation of temporary support increase the permeability of the ground by one or two orders of magnitude.

Hydrogeological zones must be characterised. Consideration must also be given to the operating conditions of the tunnel. Then, the requirements for the type and quality of cement and the granulometry of aggregates are to be specified, with the involvement of the owner.

A forecast of shrinkage must be made and the distance between joints decided according to the above factors. The designer must choose between various solutions for the joints:

- Free draining;
- Enlarged joint with drainage borings;
- Sealing;
- In mountain transit tunnels, protection against freezing must be considered.

If complete waterproofing is required, insertion of a PVC sealing foil gives excellent results and is increasingly popular.

Drainage of the ground around the lining is nevertheless still used in many cases.

### *4.3 Segmental Concrete Tunnels*

Segmental concrete tunnels are generally made watertight by one or more of the following methods:

- Gasketting the radial and circumferential joints;
- Caulking the joints and grommetting the bolts;
- Injecting sealant into a groove in the joints.

Gaskets to precast concrete segments are most commonly used in tunnels constructed below the groundwater table; they may be purely compressible or they may contain material that swells on contact with water. It is of critical importance that the design of the gasket be carried out in concert with design of the tunnel segments, and with a knowledge of the likely forms of construction to be adopted. It is the experience of many tunnellers that the improper specification, positioning or provision of the gaskets can cause significant damage to shield-driven tunnels during their construction, and improper use of gaskets can bring about more problems than they solve.

Although caulking of tunnels is generally carried out during the later stages of construction, it may be undertaken at any time during the life of the tunnel. It is usual for all precast concrete linings to incorporate a caulking groove to the inside of all joints. In conjunction with tunnel caulking, grummetting of all bolt holes will be required to avoid groundwater seepage through the bolt holes of the lining. The design of the grooves must take account of the proposed type and shape of the grummet to ensure adequate sealing.

To prevent the absorption of aggressive groundwater into the segments, the design of coatings to the external faces of the segment must be considered. Such coatings form a lasting barrier to the absorption of the groundwater into the segments. In some situations, a coating may be applied to the reinforcing steel to inhibit corrosion.

In order to permit efficient handling and erection of the precast tunnel segments, it is generally the aim of the designer to minimise their weight. The design may take account of this by the use of high-strength concretes. In some situations, concrete cover to steel reinforcement may be regarded as non-structural and designers may therefore wish to reduce this cover to the minimum. However, such a reduction may well jeopardize the long-term durability of the tunnel.

### *4.4 Segmental Cast-Iron Tunnels*

The methods for providing for watertightness in segmental cast-iron tunnels are identical to those for precast segmental concrete tunnels as described above. In addition, lead caulking may be used. While this type of caulk is more expensive, it is more efficient than many other compounds and is especially valuable in high-flow conditions.

Both SGI and grey cast iron are susceptible to attack by groundwaters containing chlorides. However, the rates of corrosion are much slower than the rates for typical reinforcing steels. Corrosion of the cast iron may also occur under normal tunnel environmental conditions although, again, this occurs at a slow rate.

The design of SGI or cast-iron linings generally incorporates protection coatings of either zinc silicate or bitumen-based products, although in the latter case consideration may need to be given to the possible effects in the event of fire within the tunnels.

Cast-iron tunnel segments are generally lighter than the equivalent concrete segments and the relative ease of handling permits the tunnels to be more easily constructed to high standards with less possibility of defects occurring. Where proper provision is made for waterproofing, it is much easier to provide a high standard of watertightness.

## 5.0 Matters for Further Consideration

The aim in producing this paper has been to provide a comprehensive guide to the damaging effects of water during the working life of tunnels, based on actual case histories. It is realised, however, that the current work falls short of this goal and that further study is required, supported by more case histories. In particular, case histories are required relating to the following aspects:

- External effects (on the surroundings of the tunnels, but not affecting the structure);
- Repairs to segmental tunnels affected by chloride or sulphate attack;
- Problems associated with unlined tunnels;
- Problems associated with tunnel primary linings.

In addition to the above, readers are invited to continue to forward to the Working Group case histories relating to any aspect of the damaging effects of water.

It is proposed that these case histories be stored in a data base, permitting ready access to individual records or groups records relating to particular criteria. In preparing this report, a limited data base file has been formed so that case histories can be readily grouped, for instance, by the classification of defects or by lining type.

In setting up this data base file, it has been found that there is a need for a standardisation of terms used for the description of the lining types, defects, etc., in order for the records to be interpreted and stored accurately. It is proposed that a glossary of such terms be prepared and circulated within the ITA member countries, and that this glossary be used as far as possible in the preparation of future case histories.

The present Report is recognised as being qualitative and lacking in technical data. Therefore, its use is limited to general comparison of types of problems and to guidance as to the type and success of repairs that have been implemented elsewhere. The paper would not give advice, for instance, as to whether groundwater with a certain chloride content is likely to damage the tunnel structure, or whether a particular concrete mix has been found to prevent water egress or to be resistant to attack from de-icing salts. In general, the case histories received to date would not permit a meaningful technical input to the paper, although the benefits of broadening the scope of the paper to include these aspects must be recognised. The contribution of the French Tunnelling Association (AFTES) Working Group (see References) in this context is acknowledged.

Another area where the paper may be expanded includes the success of repair works to tunnels and the cost of these repairs versus the benefits gained. Some of the case histories received thus far have given details of the economics and effectiveness of repairs, but further expansion of the data base is required before meaningful discussion on this aspect can be provided. □

## References

*Note: A more complete bibliography is contained in Reference No. 7.*


1. C.I.R.I.A. (U.K.) 1979. *Tunnel Waterproofing*. London: Construction Industry Research and Information Association.
2. Haack. A. 1986. Wasserundichtigkeiten bei unterirdischen Verkehrsanglagen: Erforderliche Dichtigkeit, Vertragsfragen, Sanierungsmethoden (Water leakages in subsurface traffic facilities: required watertightness, contractual matters, repair methods). *Forschung + Praxis, Unterirdisches Bauen: Erfahrungen – Perspektiven*, Bd. 30.
3. Nozawa, Goto, Yoshida. 1980. Investigation on the effects of water leakage prevention. *Tetsudo-Doboku (Civil Engineering in Railway).*
4. Okada, Kawaguchi. 1980. Countermeasure of icicles in tunnels (adiabatic method). *Tetsudo-Doboku (Civil Engineering in Railway).*
5. Pera, J. and A.F.T.E.S. Working Group No. 14 (Maintenance and Repair). 1984. Recommandation sur les méthodes de diagnostic pour les tunnel revêtus. Recommandation sur les travaux d'entretien et de réparation. Association Française de Travaux en Souterrain, numéro spécial Novembre 1984, 20–68.
6. Pera, J. and A.F.T.E.S. Working Group No. 14 (Maintenance and Repair). 1989. Recommendations for the treatment of water inflows and outflows in operated underground structures. *Tunnelling and Underground Space Technology* 4:3, 343–407.
7. STUVA (Germany). "Damaging effects of water on tunnels during their lifetime: international survey of tunnel maintenance." Draft report prepared for the ITA Working Group on Maintenance and Repair of Underground Structures.
8. Tiedermann, H. R. and Graver, J. 1982. "Groundwater Control in Tunnelling, Vol. 2: Preventing Groundwater Intrusion into Completed Transportation Tunnels" (Report No. FHWA/RD-81/074). Springfield, Va. (U.S.A.): National Technical Information Service.
9. *Tunnels and Water (Los Túneles y el Agua)*. 1988. Proceedings of an International Congress, Madrid, Spain, 12–15 June 1988. Volume II, Section 3: Water in Exploitation. Various important references. Rotterdam: A. A. Balkema.
10. Wanderer, J.; Schaden, K.; Kurzmann, E.; Knoll, P.; and Pö, E. 1985. Abdichtungssysteme in ausgeführten Tunneln (Sealing systems in completed tunnels). *Bundesminsterium für Bauten und Technik, Straßenforschung*, Heft 274.

*Table A1. Reference list of case histories included in the report of the ITA Working Group on Maintenance and Repair of Tunnels.*

| Reference | Country | Location of Tunnel (in or between what town(s)) | Tunnel Use | Type of Lining | Ground Type | Date(s) Built | Damage Class |
|---|---|---|---|---|---|---|---|
| A1 | Austria | Mittersill/Matrei | Road | In-situ concrete | Rock | 1962–67 | BC |
| A2 | Austria | Golling/Werfen | Road | In-situ concrete | Rock | 1962–67 | C |
| A3 | Austria | Bischofshofen/Poham | Railway | Masonry | Rock | 1874 | C |
| C1 | Cuba | Havana Bay | Road | Precast concrete | | 1958 | BC |
| EG1 | Egypt | Ahmed Hamdi | Road | Precast concrete | Rock/clay | 1980 | B |
| UK1 | England | Blackwall | Road | Cast iron | Varied | 1892–97 | C |
| UK2 | England | Southampton | Railway | Masonry | Clay/sand | 1846–47 | BC |
| UK3 | England | Old Street/Moorgate | Light Railway | Cast iron | Clay/sand | 1899–1924 | B |
| UK4 | England | Blisworth | Canal | Masonry | Rock/clay | 1794-05 | B |
| UK5 | England | Dartford/Thurrock | Road | Precast concrete | Rock | 1972–80 | B |
| UK6 | England | Abbeystead | Raw Water | Precast concrete | Rock | 1975–79 | AC |
| D1 | Federal Republic of Germany | Berlin | Road | In-situ concrete | Sand | 1978 | BC |
| D2 | Federal Republic of Germany | Frankfurt | Railway | Masonry | | 1849 | B |
| D3 | Federal Republic of Germany | Frankfurt | Railway | Masonry | Rock | 1849 | B |
| D4 | Federal Republic of Germany | Cologne | Railway | Masonry | Rock | 1910 | BC |
| D5 | Federal Republic of Germany | Cologne | Railway | Masonry | Rock | 1902 | BC |
| D6 | Federal Republic of Germany | Cologne | Railway | Masonry | Rock | 1886 | BC |
| D7 | Federal Republic of Germany | Hanover | Light Railway | RC/Cast iron | Clay/sand | 1976–85 | B |
| D8 | Federal Republic of Germany | Stuttgart | Road | In-situ concrete | Clay | 1958 | B |
| D9 | Federal Republic of Germany | Nuebiberg | Road | In-situ concrete | Cut/cover | 1960–61 | BC |
| D10 | Federal Republic of Germany | Hamburg | Light Railway | In-situ concrete | | 1960 | AB |
| D11 | Federal Republic of Germany | Bochum | Light Railway | In-situ concrete | Rock/clay | 1974–77 | BC |
| F1 | France | Pagny-sur-Heuse | Railway | Masonry | Rock | 1846–51 | B |
| F2 | France | Pagny-sur-Meuse | Railway | Masonry | Rock | 1846–51 | B |
| F3 | France | Marseille | Railway | Masonry | Rock | 1912–14 | B |
| F4 | France | | Canal | Masonry | Rock | 1914–45 | BC |
| F5 | France | Paris | Light Railway | Masonry | Rock | 1941–48 | BC |
| F6 | France | Nice/Digne | Railway | Masonry | Rock | 1880 | BC |
| F7 | France | Sabart | Hydro Gallery | In-situ concrete | Rock | 1929 | B |
| HK1 | Hong Kong | Hong Kong | Light Railway | Precast concrete | Clay | 1980 | BC |
| J1 | Japan | Shimonoseki/Moji | Railway | In-situ concrete | Rock | 1944 | BC |
| J2 | Japan | Shimonoseki/Moji | Railway | In-situ concrete | Rock | 1974 | BC |
| J3 | Japan | Shimonoseki/Moji | Road | PC/In-situ concrete | Rock | 1958 | BC |
| J4 | Japan | Tokyo | Light Railway | Precast concrete | Clay/sand | 1965–76 | BC |
| J5 | Japan | Mikuni | Road | In-situ concrete | Rock | 1959 | B |
| J6 | Japan | Uebonmachi/Nipponbashi | Railway | Precast concrete | Clay/sand | 1970 | BC |
| N1 | Norway | Oslo | Road | In-situ concrete | Rock | 1970 | C |
| CH1 | Switzerland | Basel/Olten | Road | In-situ concrete | Rock/clay | 1963–69 | B |
| CH2 | Switzerland | Simplon/Brig | Road | In-situ concrete | Rock | 1964 | B |
| CH3 | Switzerland | Basel/Olten | Railway | Masonry/concrete | Clay | 1912–16 | BC |
| CH4 | Switzerland | Andeer/Sufers | Road | In-situ concrete | Rock | 1966–69 | BC |
| ET1 | United Arab Emirates | Dubai/Deira | Road | In-situ concrete | | 1972–75 | B |
| US1 | United States of America | Detroit, Michigan | Raw Water | PC/in-situ concrete | Rock | 1948–54 | B |
| US2 | United States of America | Sterling Heights, Michigan | Raw Sewage | In-situ concrete | Silt | 1970–72 | B |
| US3 | United States of America | Sterling Heights, Michigan | Raw Sewage | In-situ concrete | Clay/sand | 1972–73 | AB |
| S1 | Sweden | Stockholm | Rail (Metro) | Shotcrete/unlined | Rock | 1957–58 | BC |
| S2 | Sweden | Jarpen | Hydro | Shotcrete | Rock | 1940 | BC |
| S3 | Sweden | Stockholm | Telecommunications | Shotcrete/unlined | Rock | 1961–75 | C |

*Appendix 1. Case histories of water damage to tunnels.*

| AUSTRIA | | CASE A1 |
|---|---|---|
| **TOWN/TUNNEL:** Mittersill/Matrei Felbertauern Tunnel | PURPOSE OF TUNNEL: Road Tunnel | DATES OF CONSTRUCTION: 1962–67 |

**DIMENSIONS AND SHAPES OF TUNNEL**

Two-lane tunnel, oncoming traffic. Length: 5183 m (see Fig. A1/1); cross-section, see Fig. A1/2. Clearance height: 4.5 m; gradient < 1.7%; semi-transversal ventilation.

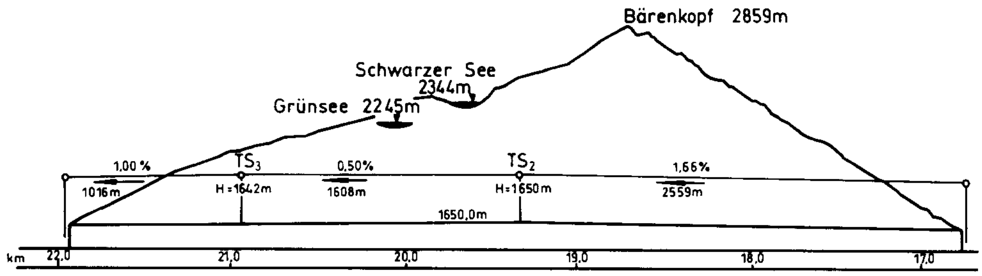


Fig. A1/1 : Profile of the Felbertauern Tunnel

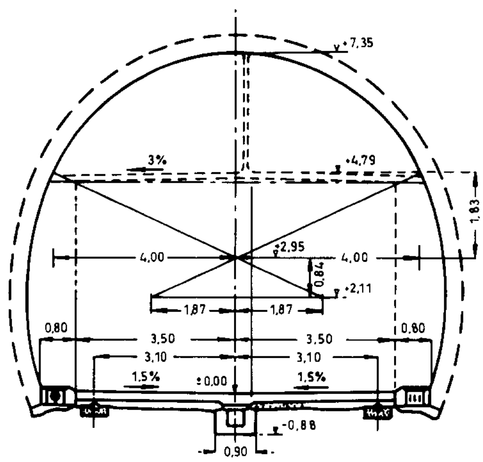


Fig. A1/2 : Cross-section of the Felbertauern Tunnel

**NATURE OF LINING:**

Lining (40 cm thick) consists of concrete (without reinforcement) with a compressive strength of 30 N/sq. mm; block length, 13.5 m; block joints without sealing. Soil water was collected by the Oberhasli method and flows to the bottom drain, which has inspection chambers every 100 m. Ceiling slab (13 cm thick) is made of reinforced concrete.

**GEOLOGICAL AND HYDROLOGICAL CONDITIONS:**

The tunnel is driven through gneiss, amphibolite and green slate.

**NATURE OF INFLOW:**

• Leakage appeared at all ring joints near both portals.
• Many wet surface areas were registered near those places, at which soil water was collected by the Oberhasli method (due to clogged tubes).
• Leakage appeared at construction joints of the ceiling slab.
• The water is not aggressive.

| AUSTRIA | CASE A1 (contd.) |
|---|---|
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Frost damage at repaired concrete areas near the portals. |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | • Icicles at leakages in the whole tunnel during cold days (lowest measured temperature: -12°C in the middle of the tunnel); removal of icicles requires 2 h/day.<br>• Ice film at the side walls on cold days (no ice film on the road surface) up to 800 m from the portal. |
| **METHOD(S) OF CORRECTION:** | Slits (20 cm wide) were made through the concrete lining to the rock (slit total length: 816 m). Relief boreholes were made in the rock at the slits (total bore length: 2268 m). Semi-circular galvanized metal gutters were placed in slits and insulated with 3-cm-thick styropor. The slits were closed with shotcrete. Total cost ca. US$120,000. |
| **REFERENCES:** | • Wanderer, J.; Schaden, K.; Kurzmann, E.; Knoll, P.; Pöhlmann, E. 1985. Abdichtungs systeme in ausgeführten Tunneln (Sealing systems in completed tunnels). Bundesministerium für Bauten und Technik, Straßenforschung, Heft 274, Vienna.<br>• Singer, H. 1966. Der Straßentunnel durch die Felbertauern (Road tunnel through the Felbertauern); Der Bauingenieur 41, No. 4, pp. 140-146.<br>• Minutes of the working group, "Maintenance and operation of tunnels" in the "Research Association of traffic and road engineering," Vienna, 9/18/86. |

| AUSTRIA | | CASE A2 |
|---|---|---|
| **TOWN:** Golling/Werfen; PaßLueg Tunnel | PURPOSE OF TUNNEL: Road Tunnel | DATES OF CONSTRUCTION: 1962–63 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Two-lane concrete road tunnel, oncoming traffic.<br>• Length: 112 m.<br>• Cross-sectional area ca. 52 sq. m. | |
| **NATURE OF LINING:** | Lining consists of 5 cm shotcrete, 30–50 cm filter concrete, and concrete (65 cm thick, compressive strength 25 N/sq. mm). | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The tunnel goes predominantly through limestone, which is very permeable to water. | |
| **NATURE OF INFLOW:** | Water seepage through unsatisfactorily sealed block joints; wet areas on the lining. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | None. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | • Icicles appear at the ceiling slab and an icy surface is noticed on the road on cold days.<br>• Yellow paint on the side walls peels off (cause: water damp pressure).<br>• Corrosion of lighting facilities and metal doors to the air duct was registered (presumably also due to vehicle exhaust gases and thawing salt). | |
| **METHOD(S) OF CORRECTION:** | Leaks were repaired with plaster and paint coat, but results were still unsatisfactory; the next three small tunnels built in this region received a sealing. | |
| **REFERENCES:** | • Wanderer, J.; Schaden, K.; Kurtzmann, E.; Knoll, P.; and Pöhlmann, E. 1985. Abdichtungssysteme in ausgeführten Tunneln (Sealing systems in completed tunnels). Bundesministerium für Bauten und Technik, Straßenforschung, Heft 274. Vienna.<br>Minutes of the working group, "Maintenance and operation of tunnels," in the "Research Association of traffic and road engineering," Vienna, 9/18/86. | |

| AUSTRIA | | CASE A3 |
|---|---|---|
| **TOWN/TUNNEL: Bischofshofen/Pöham Kreuzbergtunnel** | PURPOSE OF TUNNEL: Railway Tunnel | DATE OF CONSTRUCTION: 1874 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Double-track tunnel, 711 m long. | |
| **NATURE OF LINING:** | Masonry. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The tunnel was excavated in limestone, gravel and conglomeratic stone. The depth of cover is small (hillside tunnel). Strong, steady water flows at a rate of at least 5 l/sec from the soil to the bottom drain in the tunnel. | |
| **NATURE OF INFLOW:** | Water dripping from the lining. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Wet tunnel lining. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Icicles (some as long as 200 cm) reduced the clearance width (in wintertime, the icicles had to be removed each day before the first train passed through). | |
| **METHOD(S) OF CORRECTION:** | From 1972–1975, the whole tunnel received a sealing layer (12,000 sq. m):<br>• The masonry was smoothed with shotcrete; then a filter layer, 7 cm shotcrete, wire mesh, and 8 cm shotcrete were applied.<br>• Joints were designed at intervals of 5 m to 8 m. Centre-split pipes were placed in the joints, and the joints were closed with shotcrete.<br>• Both abutments received a bottom drain (Ø 20 cm). | |
| **REFERENCES:** | • Wanderer, J.; Schaden, K; Kurzmann, E.; Knoll, P.; Pöhlmann, E. 1985. Abdictungs systeme in ausgeführten Tunneln (Sealing systems in completed tunnels); Bundesministerium für Bauten und Technik, Staßenforschung, Heft 274; Vienna. | |

| CUBA | | CASE C1 |
|---|---|---|
| **TUNNEL NAME: Havana's Bay Tunnel** | PURPOSE OF TUNNEL: Road Tunnel | DATE OF CONSTRUCTION: 1958 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Immersed tube, 4 lanes, 733 m long. | |
| **NATURE OF LINING:** | Five sections of post-stressed concrete. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | Maximum head of water to the crown is 14 m. | |
| **NATURE OF INFLOW:** | Leakage occurs from cracks and fissures concentrated in the central areas of the tunnel, where settlement occurred during construction. Leakage from some cracks is estimated to be 40 l/hr. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | None noted. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | • Road surface is in poor condition due to intense use and inadequate maintenance.<br>• All electrical and mechanical fittings are in poor condition.<br>• Tunnel drainage ducts are severely obstructed. | |
| **METHOD(S) OF CORRECTION:** | Leakage was stopped by injecting polyurethane resins into the cracks and fissures. Cracks not affected by seepage were injected with epoxy resins. All electrical and mechanical equipment and drainage ducts were replaced and repairs were carried out to the road surface and architectural finishings. | |

| EGYPT | | CASE EG1 |
|---|---|---|
| **TOWN: Ahmed Hamdi Tunnel under Suez Canal near Ahmed Hamdi Village, Egypt** | PURPOSE OF TUNNEL: Road Tunnel | DATE OF CONSTRUCTION: 1980 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Diameter: 10.4 m.<br>• Width of carriageway: 7.5 m.<br>• One lane in each direction. | |
| **NATURE OF LINING:** | Precast reinforced concrete segement with waterproofing flexible pads between segments for protection. The road deck is formed by a system of precast units. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | An overconsolidated stratum of clay and mudstone. Chlorides are present in surrounding waters. | |
| **NATURE OF INFLOW:** | Water passes through some of the joints and through the grout holes in the segments, but within the acceptable design quantity of less than 40 cu. m. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Chlorides and salts have contaminated concrete in areas where the water has passed through, causing rusting of the steel reinforcement of segments near concentrations of chlorides and in the interior face of segments. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | None yet. | |
| **METHOD(S) OF CORRECTION:** | Currently undergoing thorough investigation and monitoring. | |

| UNITED KINGDOM | | CASE UK1 |
|---|---|---|
| **TOWN: First Blackwall Tunnel, U.K.** | PURPOSE OF TUNNEL: Road Tunnel, crossing the River Thames between London Boroughs of Greenwich and Tower Hamlets | DATES OF CONSTRUCTION: 1892–1897 (internally modernized 1967–1969) |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Length between portals: 1.36 km<br>Maximum depth between high water and crown: 17 m<br>Minimum cover to riverbed: 5 m<br>Shape: Circular<br>Diameter (see below): 7.4 m<br>Structure gauge: • Total width— 5.94 m<br>• Height (1) 4.06 m<br>• Height (2) 2.87 m | |
| **NATURE OF LINING:** | • Main length: segmental bolted cast iron.<br>• Approach ramps: brick approx. 0.6 m thick. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | Mixed face of Thames ballast, clay, soft chalk, and sand.<br>Compressed air and deposition of clay blanket on riverbed used as ground water control. | |
| **NATURE OF INFLOW:** | Coal tar: Tunnel driven through ground, contaminated with tar from former Gas Works. Seepages of this fluid enter the tunnel at segment joints.<br>Volume: Rate of flow is small; nevertheless, considerable manpower is expended in removing it.<br>Duration: Since construction. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Nil. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | • Renders secondary lining unsightly.<br>• Causes damages to carriageway surfacing. | |
| **METHOD(S) OF CORRECTION:** | • None until recently: investigations into the precise nature of the material are now proceeding with a view toward some form of chemical treatment.<br>• Weekly "mop-up" operation by maintenance staff using high-pressure hoses and detergent wash accumulations into drainage sump. | |

| UNITED KINGDOM | | CASE UK2 |
|---|---|---|
| TOWN: Southampton Tunnel, U.K. | PURPOSE OF TUNNEL: Rail Tunnel | DATES OF CONSTRUCTION: 1846–1847 |
| DIMENSIONS AND SHAPE OF TUNNEL: | Approx. 7.65 m wide x 6.5 m high x 470 m long. | |
| NATURE OF LINING: | Brick: Arch 600–700 mm.<br>Invert 400–500 mm. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | • Gravel overlying Bracklesham Beds (a widely varying group from clay to sand).<br>• Top of tunnel generally in fairly dense gravel; invert and lower part of tunnel generally in clay, though "fine material" is reported to have "rushed in" during the construction of a refuge.<br>• No direct indication of ground water level, but water flows in through several drainage holes.<br>• No major leaks in upper portion of arch, but tunnel is generally wet; flow increases after rain. | |
| NATURE OF INFLOW: | Ground water (volume varies). Duration: since construction. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | Main arch footings are poor—only some 12–18 in. (300–400 mm) below tops of sleepers; resistance of the main arch to lateral loads is dependent on the stability of invert arch; invert arch is slender and not bonded into springing of the main arch; invert arch is suffering upward deformation (presumably as a result of ground and water pressure) and deterioration (silt and clay are being "forced up" through it).<br><br>Above conditions lead to:<br>• Ground, groundwater pressure deforming and deteriorating invert arch;<br>• Inward movement at springing of main arch;<br>• Potential instability of main arch;<br>• Unacceptable clearances. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | • Waterlogging and clogging of track ballast is leading to increased difficulties with track maintenance.<br>• Reduced clearances leading to speed restrictions, exclusion of certain types of stock, inefficient tunnel use. | |
| METHOD(S) OF CORRECTION: | • Drainage improvements.<br>• Formation of robust reinforced concrete invert slab.<br>• Invert slab.<br>• Relining of main arch with bolted segmental, cast-iron lining. | |
| REFERENCES: | • "Tunnel breaks new ground". In Construction News (June 14, 1984).<br>• "Southampton Tunnel". Pamphlet by B. R. Southern. | |

| UNITED KINGDOM | | CASE UK3 |
|---|---|---|
| **TOWN: Northern Line Old Street to Moorgate** | PURPOSE OF TUNNEL: Metro Tunnel | DATES OF CONSTRUCTION:<br>1899–1901, original<br>1922–1924, enlarged |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Circular: 3200-mm int. diameter, original.<br>3562-mm int. diameter, enlarged. | |
| **NATURE OF LINING:** | Bolted, segmental cast iron. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | • Tunnel constructed through Woolwich and Reading Beds (characteristically variable sands and clays).<br>• Perched water table in the uppermost sand layers of the Woolwich and Reading Beds surrounds the upper half of the tunnel. | |
| **NATURE OF INFLOW:** | • Minor groundwater seepage.<br>• Sulphuric acid seepage. The most likely explanation of this condition is the natural reaction of groundwater and oxygen on the sulphide shown to exist in the sand layer surrounding the tunnel. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | • Corrosion of lining, occasionally to the extent of complete penetration of segment skin.<br>• Deformation of linings caused by the formation of voids in the crown of the tunnel drive due to chemical reaction to formation of sulphuric acid, leading to uneven ground pressure distribution. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Nil. | |
| **METHOD(S) OF CORRECTION:** | Short-term:<br>• Prevention of entry of acid into the tunnel by caulking of segment joints, fitting of grummets to bolts where leakage occurs or can be anticipated.<br>• Strengthening of segment elements by the addition of bolted-on material.<br>• Void filling to crown of tunnels with acid-resistant grout.<br><br>Long-term (provisional):<br>• Segment replacement and chemical grouting. | |

| UNITED KINGDOM | | CASE UK4 |
|---|---|---|
| **TOWN: Blisworth Tunnel, U.K.** | PURPOSE OF TUNNEL: Canal Tunnel | DATES OF CONSTRUCTION:<br>1794–1796 (abandoned)<br>1802–1805 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | 5.5-m-high x 5-m-wide horseshoe x 2.81 km long. | |
| **NATURE OF LINING:** | Brick, four courses thick. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | • The tunnel lies at the interface between the Northampton sandstone and the upper Lias clay: this interface rises above the tunnel at the north end.<br>• The overlying rocks are the Estuarine Series and Blisworth limestone.<br>• There are two independent ground water levels around the tunnel; one, within the Blisworth limestone; the other, in the Northampton sandstone. | |
| **NATURE OF INFLOW:** | Groundwater: tunnel acting as drain lowering the water table in the Northampton sandstone. However, this is not the only cause of the deterioration, which eventually led to renewal of the middle third of the tunnel. Other factors were:<br>• Unmortared joints in the second, third, and fourth courses of the lining;<br>• No headers connecting courses;<br>• Unequal load distribution around the lining. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | • Random flow of water through the brickwork, together with a lack of bonding, resulted in localized bulging, possibly leading to collapse of sections of lining.<br>• Where the crown was in the sandstone, little or no backpacking had been done between extrados and ground. This led to uneven ground and groundwater loading and distortion of the lining. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | No installations. | |
| **METHOD(S) OF CORRECTION:** | Renewal of the middle third (which was most adversely affected) of the tunnel in 6-m internal diameter, reinforced concrete, bolted, segmental lining. | |
| **REFERENCES:** | Tunnels and Tunnelling (November 1983). | |

| UNITED KINGDOM | | CASE UK5 |
|---|---|---|
| **TOWN: Second Dartford Tunnel** | PURPOSE OF TUNNEL: Road crossing of River Thames between Dartford in Kent and Thurrock in Essex | DATES OF CONSTRUCTION: 1972–1980 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Length between portals: 1.44 km<br>Maximum depth between high water and crown: 27 m<br>Shape: Circular<br>Diameter (see below): 9.6 m<br>Structure gauge: • Width: 7.3 m<br>• Height: > 5.1 m | |
| **NATURE OF LINING:** | • For the central mid-river length: segmental, knuckle-jointed, reinforced concrete, 9.54-m internal diameter, with 6-mm-thick mild steel facing plates.<br>• On approach ramps: segmental, bolted, cast-iron, 9.7-m internal diameter. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | • In central mid-river length: pre-treated fissured, water-bearing, upper chalk with flints.<br>• On approach ramps: pre-treated river gravel and silty sand.<br>• Maximum groundwater head, indicated above; groundwater level subject to tidal variation close to river. | |
| **NATURE OF INFLOW:** | Saline groundwater.<br>(Note: de-icing salts are applied in winter to open highway surfaces; tunnel wall washing detergent contains sodium hydroxide having a Ph of 8.5).<br><br>• Volume: 5000–12,000 gals/hr (22,000–54,000 l/hr).<br>• Duration: since construction. Volume appears to vary with the season: high in winter, low in summer.<br>• Location: Through invert segment joints into ventilation void below deck in the length lined with concrete segments. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Nil.<br>The effects dealt with below and certain visual evidence (to which other causes than saline water could be attributable) lead to the suspicion that the structure of the tunnel was affected. Tests carried out thus far have shown that chlorides are present, though not in sufficient proportion to cause concern or definitely to be attributable solely to inflowing groundwater. Further testing at other selected locations is proposed. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | (a) Road Deck<br>The main structural elements are precast reinforced concrete slabs 380 mm thick, 4 m long and some 7.5 m wide. Between main deck units there are 550 mm long in-situ reinforced concrete make-up pieces with:<br>(i) Rebated keys at construction joints.<br>(ii) Conventionally rebated keys on one face and a cast-in-steel hat section coated with bitumen on the other, at movement joints.<br><br>Routine inspection showed transverse cracking at the soffit of the road deck adjacent to several movement joints. Investigation showed chlorides, in zones adjacent and within the in-situ make-up sections, in sufficiently large proportions to warrant remedial action.<br><br>(b) Steel Facing Plates<br>The lining segments above deck level have integral steel facing plates on the inside to provide a substrate for the decorative coating. The plates are non-structural. Groundwater under pressure has found its way between the plates and the face of the segment in isolated locations, causing bulging. | |
| **METHOD(S) OF CORRECTION:** | Reduction of leakage by remedial grouting:<br>• Replace contaminated concrete using water jetting for removal of defective concrete;<br>• Pierce bulges, relieve pressure, drain accumulations; bolt back bulging area, grout residual cavities, or simply fix small-diameter drains to bulge and take to sump. | |
| **REFERENCES:** | Shutter and Bell. "Second Dartford Tunnel". Tunnelling 1979. | |

| UNITED KINGDOM | | CASE UK6 |
|---|---|---|
| **TOWN: Abbeystead** | PURPOSE OF TUNNEL: Water Supply Tunnel | DATES OF CONSTRUCTION: end of 1975–mid 1979 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Circular 2.6-m int. diameter.<br>Length: 6.6 km. | |
| **NATURE OF LINING:** | Concrete (segmental). | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | • Sandstone and mudstone (carboniferous).<br>• Groundwater seeped in—both in the service condition, when the tunnel was filled with water, and during periods of maintenance, when the tunnel was empty. | |
| **NATURE OF INFLOW:** | Groundwater containing dissolved methane of geological origin: on entering the tunnel, a region of less pressure, the dissolved methane is given off, forming bubbles in the tunnel crown. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | None. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | None. However, an explosion, leading to several deaths, occurred on the May 23, 1984, in a valve house associated with the pipeline when an accumulation of methane vented into that chamber. The chamber structure sustained extensive damage. | |
| **METHOD(S) OF CORRECTION:** | • Heightened awareness of the danger in certain types of strata.<br>• Take appropriate action to detect, quantify, etc., during construction.<br>• Make venting arrangements safe in permanent work. | |

| FEDERAL REPUBLIC OF GERMANY | | CASE D1 |
|---|---|---|
| **TOWN: Berlin Tunnel Airport Tegel** | PURPOSE OF TUNNEL: Road Tunnel | DATE OF CONSTRUCTION: 1978 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Outer width: 23.10 m; inner width, 2 x 10.50 m; outer height: 7.0 m.<br>Two-box frame with middle wall. Length: 882 m and 1011 m, respectively.<br>Block length approx. 30 m. | |
| **NATURE OF LINING:** | • Reinforced concrete Bn 250–350; bituminous waterproofing membrane consisting 3 or4 layers;<br>• Reinforcement of the waterproofing membrane in the area of block joints by corrugated special aluminum foil and strips of plastic foil;<br>• Horizontal protective layers of in-situ concrete<br>• Vertical protective layer of masonry;<br>• Average distance between 2 block joints: 30 m.<br><br>Internal outfit:<br>• Floor: floor topping, ceiling with corrugated metal foils, protective asphalt layer, asphalt surface course;<br>• Walls: 7 cm fire protection shell lined with special tiles;<br>• Ceiling: vermiculite plaster with aluminum lining. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | • Middle sand, fine sand, gravel (at depths of 4.2 to 6.7 m).<br>• Hydrological conditions were not specifically investigated.<br>• Immersion depth into groundwater: ca. 2.5 m. | |
| **NATURE OF INFLOW:** | Some joints in the upper wall area as well as in the ceiling are leaking. In general, the leaks are situated above the groundwater table. Therefore, it is a matter of rain and, respectively, thaw water which seeps into the tunnel. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Wetness, corrosion of steel reinforcement in the area of concrete cracks. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Icicles in ceiling and wall areas; ice on the road surface. | |
| **METHOD(S) OF CORRECTION:** | Two leaking joints were excavated. It was shown that the waterproofing membrane was completely torn along the edge of the corrugated aluminum foil. A reason for this damage has not been clarified. The extent of the repair depends on the local and financial possibilities. | |
| **REFERENCES:** | Municipal Authority for Construction and Housing, Berlin. | |

| FEDERAL REPUBLIC OF GERMANY | | CASE D2 |
|---|---|---|
| TOWN: BD Frankfurt/Main Hönebach Tunnel | PURPOSE OF TUNNEL: Railway Tunnel | DATE OF CONSTRUCTION: 1849 |
| DIMENSIONS AND SHAPE OF TUNNEL: | Width: 7.5 to 7.9 m<br>Height: 6.15 m.<br>Cross-section: horseshoe. | |
| NATURE OF LINING: | Arch: brickwork and sandstone masonry (partially with cement plaster).<br>Abutment: limestone masonry. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | • Surrounding rock formation: middle variegated sandstone with imbedded layers of potters' clay and clay shale;<br>• Distinct system of fissures with larger waterflow. | |
| NATURE OF INFLOW: | Water seepage through greater areas of the tunnel lining; concentrated flow through the joints; wet patches in the crown; distinct wetness in the area of the abutments and the niches, causing heavy dripping in some places.<br>The analytic composition of the seepage water is not aggressive for a concrete structure. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | Abutments and niches: corrosion and partial erosion of the joint mortar. An outer waterproofing membrane was installed in the crown area between 1908 and 1911. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | None. | |
| METHOD(S) OF CORRECTION: | • The inner layer of the weathered and damaged masonry was cut in a thickness of 10 to 45 cm section by section.<br>• A 1- or 2-shell reinforced shotcrete lining 7 to 30 cm thick was set. This lining was systematically anchored to the masonry.<br>• Partially shotcrete ribs were formed and reinforced with anchored steel arches.<br>• Ventilation shafts were underpinned, and new steel reinforced concrete shaft linings were constructed (prefabricated concrete rings).<br>• Abutment masonry was grouted with cement mortar and suspension. | |

| FEDERAL REPUBLIC OF GERMANY | | CASE D3 |
|---|---|---|
| TOWN: BD Frankfurt/Main Guxhagener Tunnel | PURPOSE OF TUNNEL: Railway Tunnel | DATE OF CONSTRUCTION: 1849 |
| DIMENSIONS AND SHAPE OF TUNNEL: | Width: 7.8–8.2 m;<br>Height: approx. 6.9 m;<br>Cross-section: horseshoe. | |
| NATURE OF LINING: | Arch: mainly brickwork.<br>Abutment: mainly rubble masonry with sandstone ashlar facing. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | • Surrounded rock formation: middle-variegated sandstone with inbedded compact rock and stable stone benches.<br>• Small and unsteady waterflows. | |
| NATURE OF INFLOW: | • Seeping water, especially through the block joints.<br>• Moist areas in the crown.<br>• Moist and wet patches in the abutments and niches; occasional dripping.<br>• Analytic composition of the water not aggressive for concrete. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | In the abutments, niches and partially in the crown; corrosion and partial erosion of the joint mortar. Between 1910 and 1925, a waterproofing membrane was set in the crown area. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | None. | |
| METHOD(S) OF CORRECTION: | • The inner weathered, damaged and partly scaled layer of masonry was cut in a thickness of up to 45 cm, including the rubble wall area of the abutments.<br>• Grouting and partial backfilling of the abutment masonry.<br>• In special distances, construction of additional shotcrete ribs 50 x 25 cm, reinforced with anchored steel ribs (TH profiles).<br>• In the field between these ribs, a 25-cm-thick anchored shotcrete shell with two layers of reinforcing steel nets was installed, including the abutments.<br>• The tracks were lowered by 20 cm. | |
| REFERENCES: | ETR — Special Edition 1980. "Tunnelsanierung oder Tunnelerneurung" (Bonse/Martinek). | |

| FEDERAL REPUBLIC OF GERMANY | | CASE D4 |
|---|---|---|
| TOWN: BD Cologne | PURPOSE OF TUNNEL: Railway Tunnel | DATE OF CONSTRUCTION: 1910 |

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|---|---|
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Horseshoe with 25 sq. m cross-section.<br>• Single track.<br>• 1087 m long. |
| **NATURE OF LINING:** | Sandstone masonry in cement-lime-mortar; one-half of the tunnel length is lined with bolted invert, the other half with subsequently installed concrete floor. |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The tunnel is driven through different rock formations of the early Devonion Period; headwaters above the tunnel; 8 springs in the floor area. |
| **NATURE OF INFLOW:** | Water seeps through the masonry of the crown and the invert into the tunnel. |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Moisture penetration through the masonry; mortar gets washed out. |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Alluviation of cohesive soil material leads to clogging of the drainage system and contaminates the ballast. This causes insufficient dewatering of the tunnel and unstable bedding of the tracks. |
| **METHOD(S) OF CORRECTION:** | Because the concrete plaster partially sprayed onto the crown lining displaces only the water, the method is not satisfactory. In the future, sprayed concete mortar will no longer be used; instead, the joints will be closed with special mortar and the seepage water will be drained along the lining. The ballast as well as the drainage system will have to be cleaned every 30 years. |
| **REFERENCES:** | German Federal Railway. |

| FEDERAL REPUBLIC OF GERMANY | | CASE D5 |
|---|---|---|
| TOWN: BD Cologne | PURPOSE OF TUNNEL: Railway Tunnel | DATE OF CONSTRUCTION: 1902 |
| DIMENSIONS AND SHAPE OF TUNNEL: | Horseshoe with 50 sq. m cross-section; 570 m long. Double-track tunnel; currently, only one track operating. | |
| NATURE OF LINING: | Masonry of greywacke in cement-lime-mortar. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | The tunnel goes through rock formations of the early Devonion Period and through stable clay slate; heavy water inflow in the northern section; 36 spring intercepting structures in the tunnel (water supply for a residential area). | |
| NATURE OF INFLOW: | Water seeps through the masonry. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | The masonry is moist all the time, causing the mortar to be washed out. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | Icing of the contact wire. | |
| METHOD(S) OF CORRECTION: | Setting of a 12-cm reinforced and anchored shotcrete shell with imbedded plastic split hoses for drainage stopped the tendency toward icing; however, the lining is still moist. Repair is possible by setting a new inner lining, but the costs are relatively high. | |
| REFERENCES: | German Federal Railway. | |

| FEDERAL REPUBLIC OF GERMANY | | CASE D6 |
|---|---|---|
| **TOWN: BD Cologne** | PURPOSE OF TUNNEL: Railway Tunnel | DATES OF CONSTRUCTION: 1886 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Horseshoe with 25 sq. m cross-section; single track; 1050 m long. | |
| **NATURE OF LINING:** | Rubble wall with trass mortar. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | Inclined greywacke schist, partly hard, partly weathered and fissured, water-bearing. | |
| **NATURE OF INFLOW:** | Seepage water out of the covering layers. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Moisture penetration, efflorescence, washing out of the mortar. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Icing. | |
| **METHOD(S) OF CORRECTION:** | A sprayed plaster with screen wire was set in 1935. The tunnel lining is dry in most sections, but the unlined niches are wet. Details of the execution of the former repair works are not known. In general, the repair measures can be considered to be positive. | |
| **REFERENCES:** | German Federal Railway. | |

| FEDERAL REPUBLIC OF GERMANY | | CASE D7 |
|---|---|---|
| TOWN: Hanover | PURPOSE OF TUNNEL: Light Railway Tunnel | DATES OF CONSTRUCTION: 1976–1985 |
| DIMENSIONS AND SHAPE OF TUNNEL: | 14.2 km light-railway tunnel; predominantly double-track tunnel; multi-box rectangular cross-section. | |
| NATURE OF LINING: | • Reinforced concrete tunnel (exception: shield-driven tunnel with cast iron lining elements, GGG 50).<br>• Approx. 50% of the tunnels are sealed with multi-layered bitumen waterproofing membranes; 50% consist of watertight concrete.<br>• The joints between the cast iron lining elements are sealed with neoprene profiles. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | Approx. 6–12 m sand and gravel, chalk-clay underneath; groundwater level 3–5 m beneath the surface. | |
| NATURE OF INFLOW: | After the tunnel was taken into operation, approx. 33 leaks were observed in the whole tunnel system (14.2 km), each with a maximum inflow of water of 10 l/24 h. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | None. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | None. | |
| METHOD(S) OF CORRECTION: | • 15 places were grouted with synthetic resin; in the remaining places, which are observed occasionally, there is little inflow of water.<br>• In one major damage case (Raschplatz), the bituminous sealing was partially removed and repaired before construction was finished. | |
| REFERENCES: | Municipal Authority of the City of Hanover. | |

| FEDERAL REPUBLIC OF GERMANY | | CASE D8 |
|---|---|---|
| TOWN: Stuttgart | PURPOSE OF TUNNEL: Road Tunnel | DATE OF CONSTRUCTION: 1958 |
| DIMENSIONS AND SHAPE OF TUNNEL: | • Two-lane tunnel, oncoming traffic; 824 m long.<br>• Internal width: 10 m.<br>• Clearance height: 4.5 m (external); 5.5 m (in the middle).<br>• Varying cross-section forms, partly standing ellipse.<br>• Fresh air supply duct below; exhaust air duct above. | |
| NATURE OF LINING: | Internal shell of reinforced concrete, walls faced with tiles; bituminous sealing between external and internal shell. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | Overlying ground approx. 25 m; gypsum keuper (marl, clay-stone and gypsum), including locally positioned components (anhydrite) heavily swelling in contact with water; only slight inflow of water during the construction phase. | |
| NATURE OF INFLOW: | Wet areas in the roof, in the middle of the tunnel; fissure in the internal shell, presumably caused by swell lifting in the gypsum keuper. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | None. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | None. | |
| METHOD(S) OF CORRECTION: | Fissure injection intended, if swell lifting settles down. | |
| REFERENCES: | Municipal Authority of the City of Stuttgart. | |

| FEDERAL REPUBLIC OF GERMANY | | CASE D9 |
|---|---|---|
| TOWN: Neubiberg | PURPOSE OF TUNNEL: Road Tunnel | DATES OF CONSTRUCTION: 1960–61 |
| DIMENSIONS AND SHAPE OF TUNNEL: | • Highway tunnel (München–Salzburg), 327 m long, crossing under an airfield.<br>• Two box-frame cross-sections; block length 33–51 m. | |
| NATURE OF LINING: | Steel-reinforced concrete. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | Backfilling (cut-and-cover method). | |
| NATURE OF INFLOW: | Drenching of transversal fissures in ceiling slab, in frame walls having direct contact with soil; seepage of surface water into block joints. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | Transversal fissures in the ceiling slab and frame walls having direct contact with soil, because the block length is too great. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | Icing. | |
| METHOD(S) OF CORRECTION: | Proposed: renovation by total sealing against surface water. | |
| REFERENCES: | Obserste Baubehörde im Bayerischen Staatsministerium des Innem. | |

| FEDERAL REPUBLIC OF GERMANY | | CASE D10 |
|---|---|---|
| TOWN: Hamburg | PURPOSE OF TUNNEL: Urban Underground Railway Tunnel | DATE OF CONSTRUCTION: 1960 |

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| **DIMENSIONS AND SHAPE OF TUNNEL:** | Rectangular cross-section; double-track tunnel.<br>Width: 8.5 m; height: 5.7 m. |
| **NATURE OF LINING:** | Steel-reinforced concrete lining with external bitumen sealing.<br>Waterproofing of the floor: 4 layers R500N (ragfelts).<br>Waterproofing of the walls: 3 layers R500N (ragfelts). |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | Groundwater level: upper edge of the tunnel ceiling. |
| **NATURE OF INFLOW:** | On a tunnel length of approx. 50 m, toluol seeped on the side of one wall and bitumen dissolved by toluol seeped through the holes of the spacers. |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | No effects inside the tunnel. After removing the soil from the external wall it was recognized that all of the bitumen of the wall sealing and part of the bitumen in the floor sealing was dissolved and carried away by the ground water stream. |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Irritating odor in a nearby station. |
| **METHOD(S) OF CORRECTION:** | • Floor:<br>Auxiliary adit tunnels 2.5 m wide were built under the tunnel; damaged sealing was removed and replaced by 3 layers R500N (ragfelts) and 1 additional layer of 0.1-mm-thick corrugated copper foil; all layers were glued with minerally filled bitumen mass. Subsequently the auxiliary adit tunnels were closed with bricks.<br><br>• Walls:<br>Damaged sealing was removed and renewed with 3 layers R500N and 1 additional layer of 0.1-mm-thick corrugated copper foil; all layers were glued with minerally filled bitumen mass. A sheet of 0.4-mm-thick copper was fitted as an external protection layer.. The joints were soldered with a standing fold. |
| **REFERENCES:** | Municipal Authority of the City of Hamburg. |

| FEDERAL REPUBLIC OF GERMANY | | CASE D11 |
|---|---|---|
| TOWN: Bochum | PURPOSE OF TUNNEL: Light Railway Tunnel | DATES OF CONSTRUCTION:<br>1974–1977<br>In operation since 1979 |
| DIMENSIONS AND SHAPE OF TUNNEL: | • Double-track, mouth cross-section.<br>• Constructed by underground excavation method.<br>• Width: 9.2 m; height: 8.4 m.<br>• Excavation cross-section: 66 sq. m. | |
| NATURE OF LINING: | Double shell lining:<br>• External shell: 25 cm shotcrete<br>• Internal shell: 30 cm in-situ concrete, B 35, watertight. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | • Ground conditions: 0 – 1.5 m fill material<br>1.5 m – 2.5 m medium till coarse silt<br>2.5 m – 10.5 m marl, semihard to hard<br>> 10.5 m rock formation (upper Carboniferous)<br><br>• Ground water level at -5.0 m. | |
| NATURE OF INFLOW: | Leakage appeared at the block joints (block length approx. 8 m) constructed as expansion joints and sealed with water stops (32 cm wide). Medium to strong water emergence, depending on the groundwater level. Furthermore, fissures appeared in the concrete of the internal shell near the crown. These fissures caused wet surfaces and dripping water in the tunnel. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | Up to now, no severe effects on the tunnel structure. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | The contact wires show corrosion. Lime sedimentation led to the danger of an electrical contact between the contact wire suspension and the contact wire itself. Because of the temporary water seepage and the very high air humidity, the sleepers, which are made of soft wood, could decay. | |
| METHOD(S) OF CORRECTION: | The leaks at the expansion joints, as well as the fissures in the concrete of the internal shell, were grouted from inside the tunnel with a polyurethane (PU) foam and subsequently with a 2-component synthetic resin. These works were very successful. The PU foam reacted immediately after contact with the very humid air. This reaction sometimes prevented the injection of fissures. For this reason, fast working up of PU foam is essential for successful work. | |
| REFERENCES: | Municipal Authority of the City of Bochum. | |

| FRANCE | | CASE F1 |
|---|---|---|
| **TOWN: Pagny-sur-Meuse Foug-tunnel** | PURPOSE OF TUNNEL: Railway Tunnel | DATES OF CONSTRUCTION: 1846–1851 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Twin track tunnel, 1123 m long.<br>• Semi-circular arch, radius 3.70 m; side walls 2.30 m high; width 7.40 m.<br>• Electrification in 1961. | |
| **NATURE OF LINING:** | • Masonry from bedded limestone rubble, 1 m thick on average for walls and arch.<br>• From 1.00 m up to 1.85 m above the springings, the vault has an extra thickness of about 0.50 m to support dry-stone blocks which form a filter. The water drained from the vault by this arrangement was originally carried away by drain pipes incorporated into the wall. There is no invert; water is collected and carried off the two lateral ditches and a central collector. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The tunnel was excavated in the spurs of the calcerous plateau (calcerous formation of the Upper Oxfordian Period). The rock mass—crossed at its base by the tunnel—consists in its upper part of Corallian limestones; in the middle, of alternating sandy marls and siliceous limestones; and at the bottom, of sandy marls turning to clays which are very sensitive to water. The strata dip slightly westward.<br><br>The Corallian limestone formations and the alternating strata of marls and silicified limestones form the base of a water-bearing stratum, which causes significant water in-flows through the walls.<br><br>Some water collected in the tunnel provides the water supply for the nearby town. | |
| **NATURE OF INFLOW:** | Considerable wetness throughout the whole structure. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | • Weathering of the masonry walls, particularly cracking and scaling of the facing rubble stones due to freezing.<br>• Thinning of the vault lining, caused during the electrification, which could have long-term effects on the performance of this part of the structure.<br>• In the crown, detaching of the waterproofing coat placed during the electrification works.<br>• Failure of bonding in the masonry at the springings.<br>• Partial dislodging of walls, resulting from the works involving lowering of the track bed during electrification.<br>• Mud rising up through the crack bed must be cleared away. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | None. | |

| FRANCE | CASE F1 (contd.) |
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**METHOD(S) OF CORRECTION:**

- For the tunnel crown (see Fig. F1/1):
– Refurbishment of the blocking masonry through injection.
– Filling of voids resulting from the thinning of the lining during electrification.
– Provision of a reinforced shell of shotcrete.

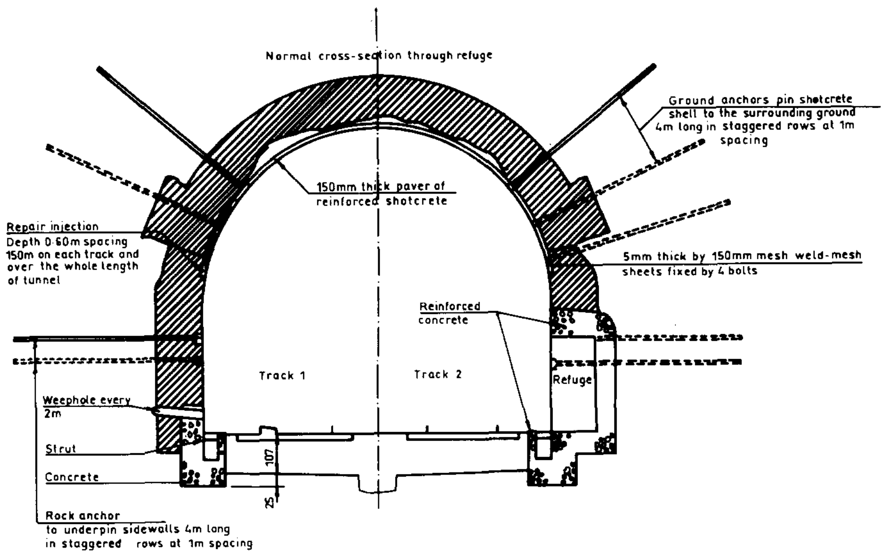



Fig. F1/1 FOUG TUNNEL
SITUATION AFTER RENOVATION

- For the walls and track bed (see Fig. F1/2):
– Underpinning of walls to mitigate the effects of their disturbance and to allow reconstruction of the track bed while providing clearances required for a maximum speed of 140 km/h;
– Achievement of a flexible reconstruction after lowering of the track bed.

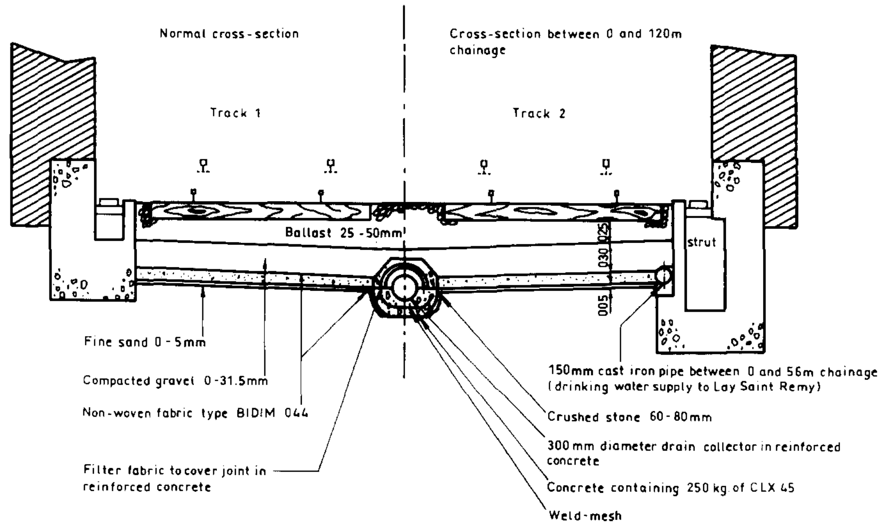



Fig. F1/2 FOUG TUNNEL
TRACK BED DRAINAGE BLANKET
(Heavy type)

**REFERENCES:**


Lesot, M. "Restauration of the SNCF Railway Tunnels at Foug and Pagny." Report for the ITA Working Group on Maintenance and Repair, Warsaw 1983.

| **FRANCE** | | **CASE F2** |
|---|---|---|
| **TOWN: Pagny-sur-Meuse**<br>**Pagny-tunnel** | PURPOSE OF TUNNEL: Railway Tunnel | DATES OF CONSTRUCTION:<br>1846–1851 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Twin track tunnel, 572 m long; semi-circular arch, radius 3.70 m; side walls 2.30 m high; electrification in 1961. | |
| **NATURE OF LINING:** | Masonry from bedded limestone rubbles, thickness 1 m on average for walls and arch; from 1.00 m up to 1.85 m above the springings, the vault has an extra thickness of about 0.50 m to support dry-stone blocks which form a filter. The water drained from the vault by this arrangement was originally carried away by downpipes incorporated into the wall. There is no invert; water is collected and carried off by two lateral ditches and a central collector. | |
| **GEOLOGICAL AND HYDROLCGICAL CONDITIONS:** | • The tunnel was excavated in the spurs of the calcareous plateau constituting the Hauts de Meuse (calcareous formation of the Upper Oxfordian Period).<br>• In Pagny, the upper part of the rock mass consists of a thick stratum of Corrallian colitic limestone above a stratum of saccharoidal limestone; the lower part—crossed by the tunnel—consists of marl-limestone presenting various facies (marly limestone, sandy marls, ferruginous colitic limestones, crinoidal limestone).<br>• All beds are fractured and permeable. | |
| **NATURE OF INFLOW:** | Considerable wetness in the whole structure. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | • Weathering of the masonry walls, particularly cracking and scaling of the facing rubblestones due to freezing.<br>• Thinning of the vault lining, caused during the electrification, which could have long-term effects on the performance of this part of the structure.<br>• In the crown, detaching of the waterproofing coat placed during the electrification works.<br>• Failure of bonding in the masonry at the springings.<br>• Partial dislodging of walls as a result of the works of lowering the track bed during electrification.<br>• Mud, rising up through the track bed, which must be cleared away. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | None. | |
| **METHOD(S) OF CORRECTION:** | • For the tunnel crown:<br>– Refurbishment of the blocking masonry through injection;<br>– Filling of voids resulting from the thinning of the lining during electrification;<br>– Provision of a reinforced shell of shotcrete (see Figs. F2/1-3). | |

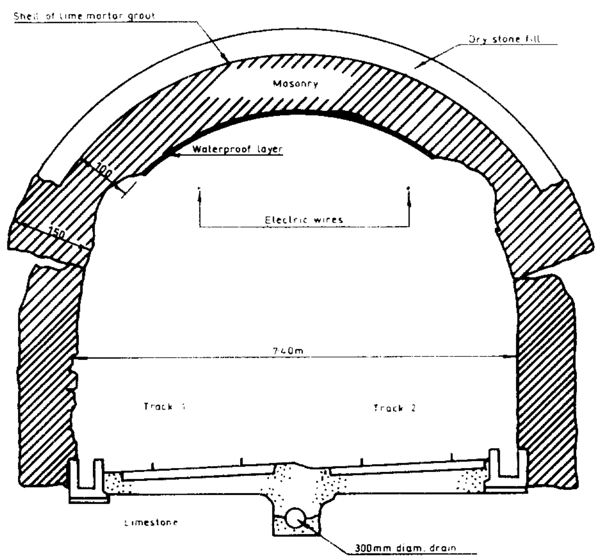


Fig. F2/1 PAGNY SUR MEUSE TUNNEL
SITUATION BEFORE RENOVATION

| FRANCE | CASE F2 (contd) |
|---|---|

**METHODS OF CORRECTION: (contd.)**

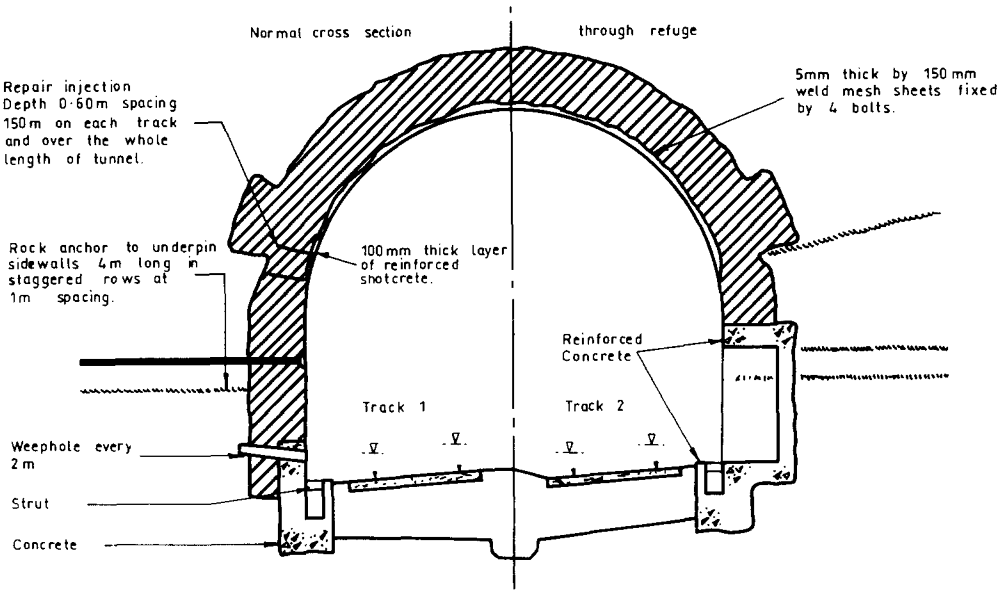



Fig. F2/2 PAGNY SUR MEUSE TUNNEL SITUATION AFTER RENOVATION

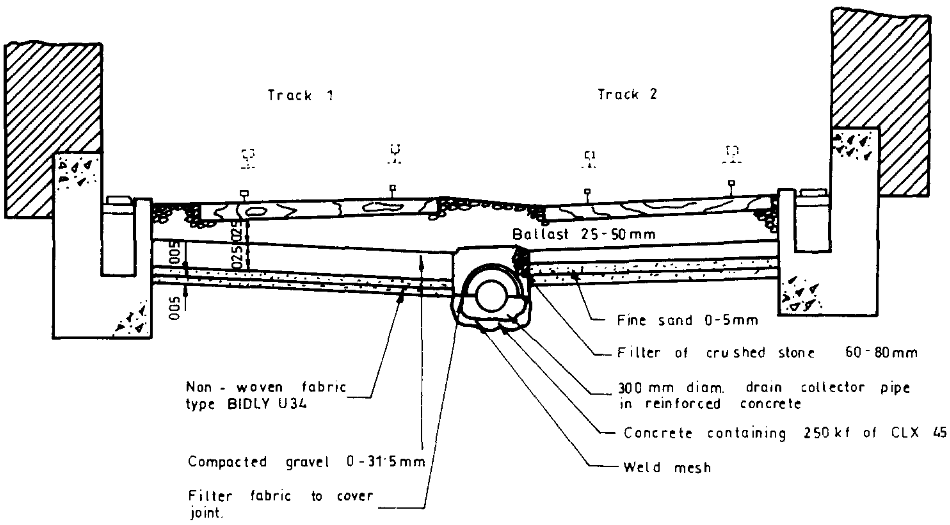



Fig. F 2/3 PAGNY SUR MEUSE TUNNEL TRACK BED DRAINAGE BLANKET (Light type)

- For the walls and track bed:
  - Underpinning of walls to mitigate the effects of their disturbance and to allow reconstruction of the track bed while providing the clearances required for a maximum speed of 140 km/h;
  - Achievement of a flexible reconstruction after lowering of the track bed..

**REFERENCES:**


Lesot, M. "Restauration of the SNCF Railway Tunnels at Foug and Pagny." Rep r for the ITA Working Group on Maintenance and Repair of Tunnels." Warsaw 1983.

| FRANCE | | CASE F3 |
|---|---|---|
| **TOWN: Marseille Rio Tinto Tunnel** | PURPOSE OF TUNNEL: Railway Tunnel | DATES OF CONSTRUCTION:<br>1912–1914 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Length: 631 m, i.e., 2 tunnels connected by a vaulted cross-gallery, 29 m long, with windows in the downward sidewall when crossing the Assiette Vale.<br>• Platform width: usual double track.<br>• Direction: nearly east-west.<br>• Cross-section: almost circular.<br>• Opening: at springs 8.60 m; on platform level 8.00 m; key height 6.10 m. | |
| **NATURE OF LINING:** | Limestone quarrystones, dressing coursed, rough case with lime mortar. The lining is generally 0.45–0.60 m thick. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | • Lithology of the surrounding ground: dolomite limestone with breccia inclusions of Portlandian, SW-dip;<br>• Structure of surrounding ground: belongs to the south flank of the Nerthe's anticlinal, thus leading to noticeable fracturation. Seepage water circulates in diaclassis and small crevices of the limestone rock, which is slightly karstified near the tunnel.<br>• Overburden height varies considerably, from a maximum of 54 m, with a chemical works at the eastern part (production and storage tanks of basic products and water). The production is not varied: methyl chloride, sulfuric acid, sodium sulphate, hydrochloric acid, etc. Old wastes have been dumped in a ravine and an old quarry and along the works platform. | |
| **NATURE OF INFLOW:** | As rain water has percolated through the old and more recent deposits, the deposits have become loaded with sulfate and finally have percolated into the cracks of the rock massive above the tunnel. Because the deposits are quite old, the whole rock massive is impregnated, both with cracks and with limestone pores. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | The disorders recorded in zones of profuse inflows rich in minerals result from:<br>• A chemical process: binders are attacked by the strongly selenitic water;<br>• A physical process: crystallization of sodium sulphate with increased volume in pores of quarry-stones and lime mortar in the intrados.<br><br>Considering the very high concentrations observed, this results in a quick disorganization of the masonry, as evidenced by:<br>• The deep decomposition of mortar;<br>• Falling down of large scales from quarry stones after disjoining, and marked hollow sounds at hammer soundings;<br>• Occurrence of large deposits of whitish sulphate.<br><br>Two tunnel areas located east of the Assisette Vale have been mainly affected by this damage up to the recent past:<br>• From MP 200–290, under the Beaume Christine Vale where cleaning water is concentrated;<br>• At the eastern portal, MP 620–638, directly bored in chemical waste (sodium grouts). | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | None. | |

| FRANCE | CASE F3 (contd.) |
| --- | --- |

**METHOD(S) OF CORRECTION:**

To combat such damages, in addition to an action undertaken many years ago by the works' managers in order to improve the tightness of the production equipment and storage tanks, supporting works have been performed several times in the structure, since 1937, when the first sulphate deposits appeared in the gallery.

The treatment consisted (at least for the most recent damages) essentially of rebuilding the lining, intercalating a waterproofing device, in materials resistant to chemical agents:

1. Oversilicated acid-resistant bricks, rough-cast with HTS Lagarge cement mortar and siliceous sand, sandwich-type tightness in bitumen over steel sheet (compound acid-resistant) in 1961. In 1972, partial repairs were performed on MP220–240 and 250–254.

The 1972 repairs comprised:
- The careful demolition, under the protection of ribs, of the parts to be repaired in the vault and sidewalls;
- The re-cutting of the ground, to adapt the profile;
- The construction of a concrete pre-vault, 400 g of cement, 0.10 m thick, provided at its base with a longtitudinal drain (perforated semi-pipe) and weep holes;
- The rebuilding of the lining with oversilicated acid-resistant bricks, rough-cast, or oversilicated cement mortar, 600 kg/cu. m of siliceous sand, 0.44 m thick, intercalated between vault and pre-vault a compound acid-resistant layer (3-cm-thick bitumen on 15/10-mm steel sheet, 1.50 x 0.75 m).

The steel sheets were placed as horizontal lines and assembled by means of a hot-welded acid-resistant tightness joint. Then the masonry was built upwards and the pre-vault concrete cast downwards progressively, by steel sheet line heights.

It should be noted that in 1961, the bitumen layer was cast in-situ between the brick masonry and the steel sheets, which had been previously assembled and wedged, and the concrete pre-vault between the achieved layer and the re-cutting bottom.

2. Reinforced concrete with application of polyurethane elastomer compound on the extrados (fabricated outside the tunnel) in 1974–1975: MP 619–624 (Estaque portal), as total repair.

These works involved:
- The excavation of an armoured trench in the embankments under the tunnel up to the vault and along the existing sidewalls;
- The demolition, under the protection of ribs, of the tympanum wall and tunnel masonries;
- The rebuilding in reinforced concrete (350 kg/cu. m) of the vault (0.50 m thick) and sidewalls, then tympanum wall, by lengths of 2 m high for this latter;
- The installation on the vault extrados of a polyurethane tightness (two-compound) including:
  - — A slightly diluted prepolymeric polyurethane resin layer, for impregnation and saturation of the support;
  - — A full layer, undiluted and tight, of the same product;
  - — A two-layer protection with two-element MEP S polyurethane resistant to various chemical agents, with Ph ranging from 5 to 9;
  - — Covering the whole, before packing with neutral materials, with a triple BIDIM sheet, and a double bedding of thick sand and 15/25 gravels, acting as a drain up to the longitudinal gutters in the spring.

| FRANCE | F3 (contd.) |
|---|---|

**METHOD(S) OF CORRECTION:**

3) B1 concrete, unreinforced, and shotcrete with intermediate tightness by PVC 20/10 film from SETR, laboratory tested (CEMEREX) in 1980—1981: MP 195—290.
In this latter case, to hinder the effects of lateral spreading of loaded water, the tunnel had been injected on the whole length, and collecting chambers with radiating collecting 10 m—long boreholes have been built on both sides of the re—built zone and in this zone itself.

Have been integrated into a project of re—cutting the profile to the electrification gauge on the whole tunnel length:
— a lowering of the rock platform;
— the sidewall underpinning after partial demolition of their base and construction of longitudinal stringer—gutters anchored on both sides into the surrouding ground, replacing the central drain;
— The installation on the bed—rock or base layers for flexible draining (compacted coarse crushed slag, min. thickness 0.15 m, calibrated coarse alluvial gravels 0–31.5, thickness 0.10 m).

The works specifically aimed to remedy the disorders resulting from highly loaded seeping water on the tunnel structure consisted of:

• right up to the fully constructed area (MP 195–290) and its immediate vicinity:
— the demolition of vault and sidewall masonries, by successive lengths, under the protection of a gantry, using a hydraulic rock—breaker for the vault and explosives for the sidewalls;
— the installation — wet process — of a shotcrete shell reinforced by 2 mats of welded wire—mesh, thickness 0.18, 28 days—resistance 300 bars, addited with 6% sodium silicate, acting as a pre—vault;
— the making of the lining itself, in cast—in—situ, unreinforced B1 concrete (400 kg CLK cement/m3) on the vault and sidewalls, thickness 0.40 m, supported by the longitudinal reinforced concrete girder—gutters previously installed;
— the excavation on the mountain side at MP 192, 293, 315 and 330, on both sides of the repaired zone, of 4 collecting chambers, width 3 m, depth 5 m, supplemented at their bottom by an aureole of 5 radiating collecting boreholes, 100 mm, under a vertical plan length 15 m, provided with strainered tubes.

The first 4 operations described above were performed in 2 months, with operation totally stopped.

• in the remaining length of the tunnel, supplementing this treatment:
— filling up and watertightness grouting on the extrados, after rejointing of masonries, in two passages, from 15 lines of 51 mm- boreholes, 1 m spaced, distance between boreholes alternated from one line to the other: 4 m, stable grout consisting of 50 kg of CLK cement, 50 kg sand, 5% of bentonite for 50 litres of water (minimum compression strength 10 MPa);
— drilling of drainage boreholes arranged in aureole, integrating into the lining with radiating collecting 2.50 m—long boreholes, every meter in the vault, fitted with strainered PVC tubes, in the wettest parts between the re—built zone and the tunnel exit (installed at MP 357, 372, 376, 554, 599, 607, 615, 617);
— making of subhorizontal drains, also fitted with strainered PVC tubes, 63, in the sidewalls, every 2.50 m.

At present, in spite of local wet parts, the tunnel is free from inflows of chemical products in the sidewalls: also, the 4 draining recesses properly concentrate the water loaded with sodium sulphate seeping from the rock.

**REFERENCES:**

French National Railways (S.N.C.F.)

| FRANCE | | CASE F4 |
|---|---|---|
| TOWN: | PURPOSE OF TUNNEL: Navigation Tunnel | DATES OF CONSTRUCTION:<br>Vault: 1914<br>Upper part of sidewalls: 1945<br>Structure out of operation until 1963<br>Lower part of sidewalls: 1963–65 |
| DIMENSIONS AND SHAPE OF TUNNEL: | • Three-centre vault; sidewalls slightly battering to the inside, 6.25 m high.<br>• Width reserved for boats: 6.50 m.<br>• Width between sidewalls : 9.50 m (on water level), leaving two side platforms (anchored to sidewalls) for pedestian circulation.<br><br>Section involved: 350 m at the northern tunnel portal. | |
| NATURE OF LINING: | Vault: brick masonry, consisting of, from the intrados to the ground:<br>• 2 brick rails, bullheader-laid, rough-cast with lime mortar;<br>• 1 wear-resistant layer of mortar, 2–5 cm thick;<br>• 1 waterproofing device, consisting of an assembly of zinc plates;<br>• Dry brick rubble. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | Lithology of surrounding ground:<br>• Grey chalk, including beds of large silex from Later Turonian.<br>• White silex chalk from Earlier Senonian.<br><br>Structure of surrounding ground:<br>• Subhorizontal layers.<br><br>Overburden: 20 m.<br><br>Hydrology:<br>• Watertable of Senonian and Turonian chalk lowered by the tunnel at sidewalls level;<br>• Ground drips through cracks at roof level.<br><br>From 1970 to 1975, a plant installed on the overburden has discharged bleach into a trench located in the axis of the north portal. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | The zinc plate has been attacked by bleach (Javel water), and the zinc plate is pierced through. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | Inflows in the vault, disturbing traffic. | |
| METHOD(S) OF CORRECTION: | Bentonite-cement grouting in the dry bricks rubble. | |
| REFERENCES: | French Ministry of Transportation. | |

| FRANCE | | CASE F5 |
|---|---|---|
| **TOWN: Paris** | PURPOSE OF TUNNEL: Metro Tunnel | DATES OF CONSTRUCTION: 1941–1948<br>Interruption for more than 1 year between 1943 and 1945 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Structures behind station (terminal): opening from 10.45–13.00 m.<br>• Structures with continuous radius of curvature with invert. | |
| **NATURE OF LINING:** | • Vault: masonry of millstone quarries — vesicular limestone with siliceous skeleton — rough-cast with cement mortar.<br>• Sidewalls: thickness ranging from 1.10–1.50 m, and invert: ballast concrete.<br>• Overall coating of intrados in cement mortar. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | From the ground surface (0:00) the geological layers are the following:<br>• from (0.00) to (-5.00) : filling;<br>• from (-5.00) to (8.70) : pholadomite marls;<br>• from (-8.70) to (-10.70) : Monceau sand;<br>• from (-10.70) : Saint-Ouen limestone.<br><br>Average watertable level during works : (-9.70).<br><br>Utmost levels of extrados:<br>• vault (-6.00);<br>• invert (-15.00).<br><br>Average level of tracks : (-12.20). | |
| **NATURE OF INFLOW:** | Water inflows are gathered and transported up to a dewatering structure. The analyzed water has been sampled in the receiving tank of this structure.<br><br>Water nature: industrial waste water, highly acid (sulphuric acid) and very rich in salts predominant with lime and aluminum; also copper, chromium and nickel in measurable quantities. The volumes of aggressive effluents could not be measured. Inflows were diffuse, but localized on one sidewall in an area of about 100 m.<br>Hydrogen potential (pH) of analyzed water :<br>— November 1966 : pH 2.5;<br>— January 1968 : pH 1.4;<br>— March 1968 : pH 1.9;<br>— July 1968 : pH 1.5;<br>— April 1969 : pH 4.5. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | The analysis shown that the lime of the mortars dissolved, after which carbonate of lime appeared, along with sulphate of lime. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | The coatings in cement mortar have been damaged in the same way as in masonries.<br>A part of the steel ducts of the draining installation has been excessively corroded. | |
| **METHOD(S) OF CORRECTION:** | In addition to the works performed in the industrial plant which produced the acid effluents, regeneration works of the masonry have been undertaken. A total quantity of 291.5 t of CLK cement has been grouted under low pressure (0.1–0.2 MPa) into the masonry of the concentrated area (one sidewall and a part of the vault 97 m long). Moreover, the damaged ducts of the draining installation have been replaced. | |
| **REFERENCES:** | Régie Autonome des Transports Parisiens (R.A.T.P.). | |

| FRANCE | | CASE F6 |
|---|---|---|
| **TOWN: Route between Nice and Digne** | PURPOSE OF TUNNEL: Rail, Metro Railtrack Tunnel | DATE OF CONSTRUCTION: ca. 1880 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Length : 1,195 m.<br>• Platform width : 4.50 m.<br>• Key height : 5.50 m.<br>• Cross-section : horseshoe. | |
| **NATURE OF LINING:** | • Completely built with clayey limestone quarry stones, which are rather soft, and therefore likely to split on the surface.<br>• Joints in lime mortar.<br>• Quarry stones assembled as irregular mosaic (except for the three unbroken key courses). Quarry stones are most irregular, heterometric, with a marked pyramid shape to the inside. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | Lithology of the surrounding ground:<br>• Schistosized and fractured black marls from the Aptian Cenomanian, alternating with limestone banks about 20 cm thick.<br><br>Presence of 10–15% sodic montmorillonite.<br><br>Overburden: The 150 m section in which the corrosion problems have occurred are located in the western part of the tunnel, in a zone where the low overburden has a swampy aspect on the surface.<br><br>Structure of the surrounding ground:<br>• Layers dip of 25°–35° to the horizontal;<br>• In the concerned area, tunnel built according to the direction. | |
| **NATURE OF INFLOW:** | Inflows from the surface are loaded with melted salt:<br><br>pH 8 $Ca^{++}$ 150 mg/l $Na^{+}$ 150 mg/l $Mg^{++}$ 50mg/l $SO_4$ — 500 mg/l | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | • Noticeable disjointing, softening and creep of joint mortar.<br>• Large profile deformations: sidewalls closing up, vault lifting.<br>• Scales.<br>• Broken quarry stones, weathered mortar.<br>• Cracks.<br>• Efflorescences of Na SO (thenardite).<br>• Presence of expansive thaumasite (about 10%) in the joint weathering products. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | The drainage gutter is blocked by the joint weathering products. | |
| **METHOD(S) OF CORRECTION:** | • Drainage and removal of running water on the overburden.<br>• Repair of gutters.<br>• Systematic rejointing on about 30% of the total surface of the concerned area, using CLK cement.<br>• Localized reconstruction of lining.<br>• Extrados and regeneration groutings in the masonry and the construction of an invert are planned in a second works phase. | |
| **REFERENCES:** | Société des Chemins de Fer de Provence. | |

| FRANCE | | CASE F7 |
|---|---|---|
| TOWN: Sabart | PURPOSE OF TUNNEL: Hydroelectric Gallery | DATE OF CONSTRUCTION: 1929 |
| DIMENSIONS AND SHAPE OF TUNNEL: | • Diameter: 3.00 m.<br>• Horseshoe-shaped.<br>• Cross-section: 6.5 sq. m.<br>• Length: 13,800 m. | |
| NATURE OF LINING: | Cement concrete. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | Granite from MP 0 to MP 9,500.<br>Limestone from MP 9,500 to MP 13,800. | |
| NATURE OF INFLOW: | Design flow = 15.5 sq. m/s. Snow-melt water pH 5. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | Dissolution of binder and even calcareous aggregate—heavy leakages (about 16 l/s/). | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | None. | |
| METHOD(S) OF CORRECTION: | In 1959 and 1963–65, the damaged concrete areas were repaired with a concrete of a proportion of 300 kg of CLK cement per cu. m, and laying of an aluminous cement coating (600 kg/cu. m) and 0/4 sand on the whole gallery length. Since these repairs were performed, the tunnel has performed well, with only a slight evolution of leakages (4 l/s in 1982). | |
| REFERENCES: | Electricité de France (E.D.F.). | |

| HONG KONG | | CASE HK1 |
|---|---|---|
| **TOWN: Hong Kong Mass Transit Railway** | PURPOSE OF TUNNEL: Metro Tunnel | DATES OF CONSTRUCTION:<br>Early 1980s |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Circular 5.6-m internal diameter.<br>• Reinforced concrete.<br>• Approx. 10 km long. | |
| **NATURE OF LINING:** | Precast reinforced concrete, bolted, segmental. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | Marine clays and completely decomposed granite. | |
| **NATURE OF INFLOW:** | Saline ground water. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Corrosion of reinforcing bars in the segments leading to straining, cracking and the loosening of lumps of concrete from the segments. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Similar to those in lining with likelihood of quicker deterioration of the track "bed" concrete by the action of stray currents. | |
| **METHOD(S) OF CORRECTION:** | Obtain accurate information about magnitude of problem and rate of deterioration, principally by chloride sampling.<br><br>Investigate methods of contaminant, or correction by:<br>• Removing affected material and creating low chloride, high alkalinity conditions by careful selection of repair materials and procedures;<br>• Creating nil-oxygen conditions;<br>• Cathodic protection;<br>• Rebuilding damaged linings. | |

| JAPAN | | CASE J1 |
|---|---|---|
| **TOWN: Shimonoseki/Moji Kanmon Tunnel** | PURPOSE OF TUNNEL: Railway Tunnel | DATE OF CONSTRUCTION: 1944 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Two single-track subaqueous tunnels.<br>• Varying cross-section forms; partly circular and partly rectangular.<br>• Length: 3.6 km (length of undersea section, 1.1 km).<br>• Gradient ≤ 25%. | |
| **NATURE OF LINING:** | Steel-reinforced concrete. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The tunnel was constructed in the Mesozoic Kanmon Strata, consisting of irregular igneous, sedimental and metamorphic rocks. The minimum overburden depth (tunnel roof to sea bottom) is 10 m. Sea depth is approx. 20 m. | |
| **NATURE OF INFLOW:** | Leakage appears at many parts of the tunnel lining. Table J1/1 (on following page) shows the amount of leakage at different tunnel sections. The leakage water has nearly the same salinity as the sea water. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | • Concrete of the lining was neutralized in 10–40 mm depth in deteriorated concrete. The strength of the concrete was reduced.<br>• Cracks are developing in the concrete track-slabs and cement asphalt mortar is deteriorating. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | The leaked sea water is splashed, thereby forming a mist caused by the suction effect of trains. This results in the progressive erosion not only of the rails, but also of the electric facilities at the ceiling. The main salt-related damages due to water leakage are:<br>• Rust-like pockmarks 1–1.5 mm deep are generated on the entire surface of the rails.<br>• Fastenings and other attachments of rails are corroded progressively.<br>• Salt water adheres to the insulator of the feeder line, ruining the insulation.<br>• The lighting facilities are also ruined, e.g., through the corrosion of metals and demolition of lamps.,<br>• Corrosion of stainless steel attaching bolts of the drain pipes.<br>• Clogging of the drain pipes (drainage system is shown in Fig. J1/1). | |

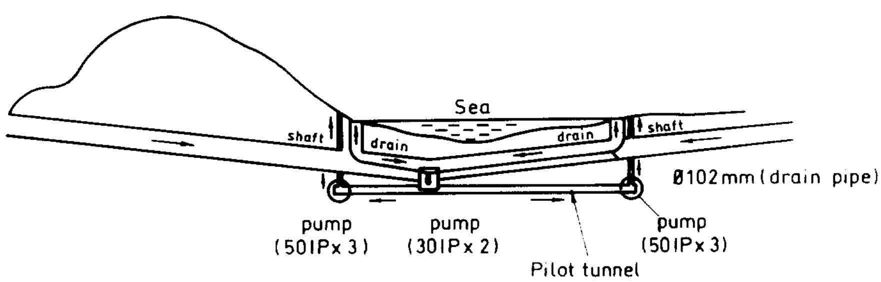



Fig. J1/1: Drain system for the Kanmon Tunnel

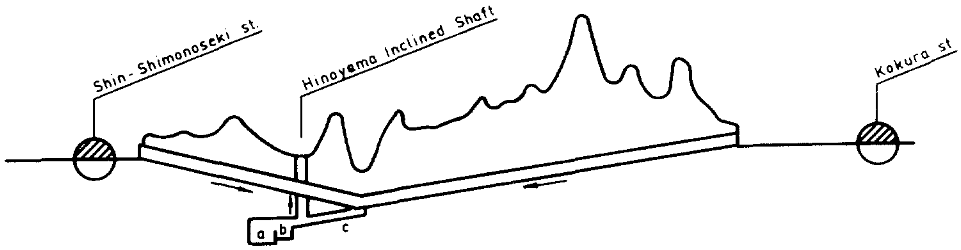
| JAPAN | CASE J1 (contd.) |
|---|---|
| METHOD(S) OF CORRECTION: | A 10-year program of water leakage prevention measures has been carried out since 1979; 10740 m are being treated with cut-off works. The measures applied involve the placing of drain pipes and coating concrete linings with a sealing agent called Hydeck-K-11, which is composed of special permeable chemicals such as cement particles and resin emulsion. These compounds are mixed with water and coated on the concrete surface. After coating, these permeable compounds react with the isolated lime of the concrete to attain crystallization and, consequently, fill up the capillary void of the concrete, thereby resulting in a sealing effect.<br><br>The rails are replaced every 5.8 years. Alloyed steel rails tentatively have been placed in the undersea section, and their effectiveness is being analyzed. For other materials, corrosion prevention measures such as replacing and cleaning of the fastening devices are carried out. A periodic coating of silicon resin is applied to the insulator, and titanium alloyed bolts for the drain pipe attachments are employed as well.<br><br>A summary of the maintenance costs over a 10-year period is shown in Table J1/2, below. |
| REFERENCES: | Korehide Miyaguchi. 1986. "Maintenance of Kanmon Railway Tunnels". Tunnelling and Underground Space Technology 1: 3/4, 307–314. |

*Table J1/1. Leakage in the Shin-Kanmon Tunnel.*

| Type of Leakage | Shimonoseki-end Shore | Sea | Moji-end Shore | Pilot Section | Total |
|---|---|---|---|---|---|
| Down-line (cu. m per day) | 290 | 74 | 53 | 358 | 783 |
| Up-line (cu. m per day) | 204 | 62 | 94 | 148 | 508 |
| Sum (cu. m per day) | 502 | 136 | 147 | 506 | 1291 |
| (%) | 39 | 11 | 11 | 39 | 100 |
| (cu. m/min x km) | 0.25 | 0.078 | 0.099 | 0.27 | – |

*Table J1/2. Compilation of repair costs for the Shin-Kanmon Tunnel.*

| Year | Lining Repair and Prevention of Leakage | Water Supply Equipment Repair for Washing Away Mud | Drain Cleaning | Other | Total |
|---|---|---|---|---|---|
| 1973 | 4960 | 287 | 658 | 348 | 6253 |
| 1974 | 2879 | 258 | 1324 | 980 | 5241 |
| 1975 | 2624 | 1158 | 704 | 1833 | 6329 |
| 1976 | 2227 | 10528 | 3082 | 2913 | 18750 |
| 1977 | 1753 | 10827 | 1246 | 605 | 14431 |
| 1978 | 1205 | 149 | 1515 | 395 | 3264 |
| 1979 | 22500 | 638 | 1963 | 776 | 25857 |
| 1980 | 24750 | 0 | 3238 | 118 | 28106 |
| 1981 | 18400 | 250 | 1452 | 15360 | 35462 |
| 1982 | 19923 | 0 | 787 | 780 | 21490 |
| 1983 | 8976 | 817 | 216 | 0 | 10009 |
| Unit: thousand yen. | | | | | |

| JAPAN | | CASE J2 |
|---|---|---|
| **TOWN:** **Shimonoseki/Moji** **Shin-Kanmon Tunnel** | PURPOSE OF TUNNEL: Railway Tunnel | DATE OF CONSTRUCTION: 1974 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Double-track subaqueous tunnel.<br>• Varying cross-section forms: circular (inner diameter 10.1 m) in undersea tunnel section; horseshoe shaped in section built in underground excavation method; and rectangular in section built by cut-and-cover method.<br>• Length: 18.7 km (length of undersea portion, 0.88 km).<br>• Gradient ≤ 18%. | |
| **NATURE OF LINING:** | Steel-reinforced concrete. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The tunnel was excavated in the Mesozoic Kanmon Strata, which consists of irregular igneous, sedimentary and metamorphic rocks. The minimum overburden depth (tunnel roof to sea bottom) is 20 m. Sea depth is approx. 20 m. | |
| **NATURE OF INFLOW:** | Leakage appears at many parts of the tunnel lining. Table J2/1 (on following page) shows the amount of leakage at different tunnel sections. The leakage water has nearly the same salinity as the sea water. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Cracks are developing in the concrete track-slabs and cement asphalt mortar is deteriorating. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | The leaked sea water is splashed, thereby forming a mist caused by the suction effect of high-speed trains (which run at 210 km/h). This results in the progressive erosion not only of the rails, but also of the electric facilities at the ceiling. The main salt-related damages due to water leakage are:<br>• Rust-like pockmarks 1–1.5 mm deep are generated on the entire surface of the rails.<br>• Fastening and other attachments of rails are corroded progressively.<br>• Salt water adheres to the insulator of the feeder line, spoiling the insulation.<br>• The lighting facilities are also spoiled, e.g., through the corrosion of metals and demolition of lamps.<br>• Corrosion of stainless steel attaching bolts of the drain pipes.<br>• Clogging of the drain pipes (Fig. J2/1 shows the drainage system).<br><br><br>a. Storage Tank 552 $m^3$<br>b. Sedimentation Tank 360 $m^3$<br>c. Inspection gallery 4051 $m^3$<br>Fig. J2/1: Drain system for the Shin-Kanmon Tunnel | |

| JAPAN | CASE J2 (contd.) |
|---|---|
| METHOD(S) OF CORRECTION: | In the Shin-Kanmon Tunnel, which has a total of 1307 joints, drain pipes are attached along 406 placing joints of arch concrete and 558 joints of side wall, totaling 4855 m in length.<br><br>Corrosion prevention measures such as replacing and cleaning of the fastening devices are carried out. A periodic coating of silicon resin is applied to the insulator, and titanium alloyed bolts for the drain pipe attachments are also used.<br><br>Further measures involve the placing of drain pipes and replacement of rails.<br><br>A compilation of the maintenance costs from 1975 to 1983 is shown in Table J2/2, below. |
| REFERENCES: | • Korehide Miyaguchi. 1986. "Maintenance of Kanmon Railway Tunnels". Tunnelling and Underground Space Technology 1:3/4, 307–314.<br><br>• Kretschmer, M./Fliegner, E. 1987. Unterwassertunnel in offner und geschlossener Bauweise (Undersea tunnels). Ernst & Sohn Verlag, Berlin. |

*Table J2/1. Leakage in the Shin-Kanmon Tunnel.*

| Type of Leakage | Shimonoseki-end Shore | Sea | Moji-end Shore | Total |
|---|---|---|---|---|
| Sum (cu. m/day) | 4608 | 5904 | 6912 | 17424 |
| Percent (%) | 26 | 34 | 40 | 100 |
| (cu. m/min x km) | 0.78 | 3.60 | 0.36 | – |

*Table 2/2. Compilation of repair costs for the Shin-Kanmon Tunnel.*

| Year | Lining Repair and Prevention of Leakage | Cleaning of Water Reservoir (side drain, etc.) | Other | Sum |
|---|---|---|---|---|
| 1975 | 0 | 1800 | 5000 | 6800 |
| 1976 | 0 | 0 | 4700 | 4700 |
| 1977 | 8300 | 3900 | 8500 | 20700 |
| 1978 | 5900 | 0 | 11100 | 17000 |
| 1979 | 51800 | 7900 | 25800 | 86500 |
| 1980 | 60800 | 1200 | 24600 | 86600 |
| 1981 | 8200 | 27600 | 12800 | 48600 |
| 1982 | 26100 | 28000 | 15600 | 69700 |
| 1983 | 46500 | 21000 | 7200 | 74700 |

Unit: thousands yen.

| JAPAN | CASE J3 |
|---|---|

| TOWN: | PURPOSE OF TUNNEL: | DATE OF CONSTRUCTION: |
|---|---|---|
| **Shimonoseki/Moji Kanmon Highway Tunnel** | Road Tunnel | 1958 |

**DIMENSIONS AND SHAPE OF TUNNEL:**

- Two-lane subaqueous highway tunnel; 3461 m long (see Fig. J3/1).
- Cross-section: circular for the undersea section; horseshoe-shaped for the land section (see Fig. J3/2).
- Gradient ≤ 4%,

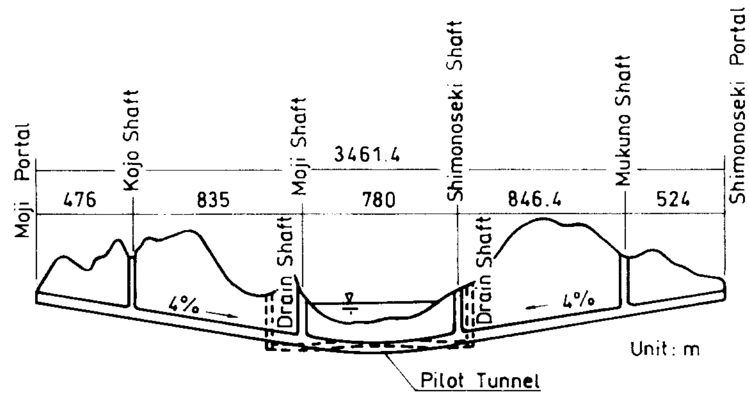



Fig. J3/1: Longitudinal profile of the Kanmon Highway Tunnel

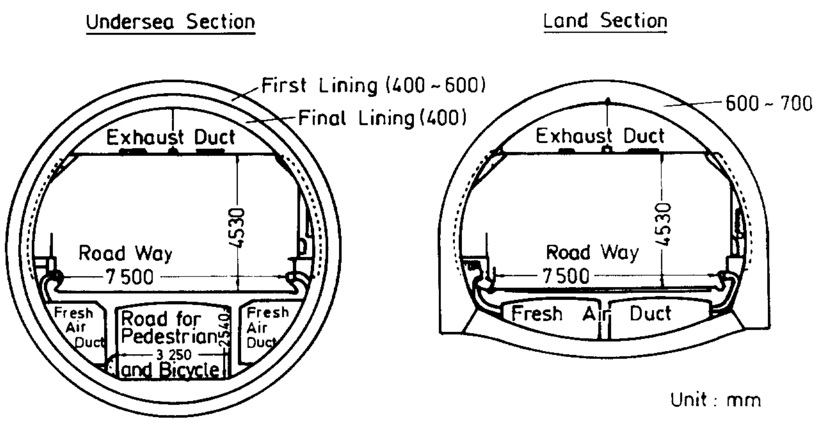



Fig. J3/2: Cross-section of the Kanmon Highway Tunnel

**NATURE OF LINING:**

Reinforced concrete:
- Lining of undersea section consists of an inner and an outer shell (total wall thickness, 0.8–1 m).
- Lining of land section consists of a single concrete shell (wall thickness, 0.6–0.7 m).

**GEOLOGICAL AND HYDROLOGICAL CONDITIONS:**

The tunnel was driven through strata consisting of diorite, porphyrite and hornfels with geological faults. The minimum overburden depth (tunnel roof to sea bottom) is 20.7 m. Sea depth is approx. 20 m.

| JAPAN | CASE J3<br>(contd.) |
|---|---|

**NATURE OF INFLOW:**

Sea water leakage appears at many parts of the tunnel.

**EFFECT(S) ON STRUCTURE OF TUNNEL:**

• Corrosion of the reinforcement bars in the roadway slab concrete and spalling of the concrete. 413 m of the undersea tunnel section was seriously damaged (1979).
• More than 900 m of the ceiling plate concrete (6 cm thick) in the undersea section and part of the land section of the tunnel had deteriorated seriously (Fig. J3/3).

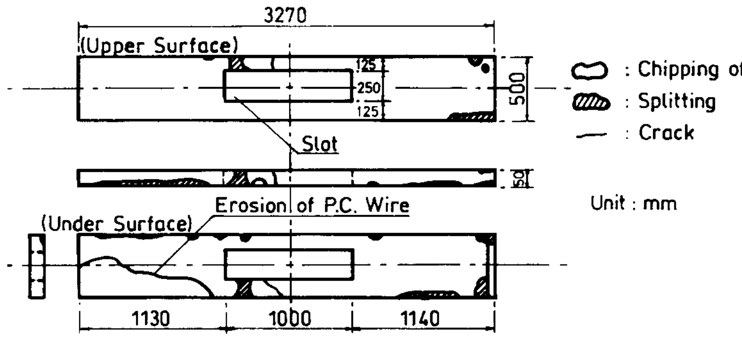



Fig. J3/3: Damages to the ceiling plate of the Kanmon Highway Tunnel

**EFFECT(S) ON INSTALLATION IN TUNNEL:**

• Corrosion of the drain pipes.
• The frame of the front glass and the attachment metals of the lighting facilities were seriously corroded.
• In six year's time, the thickness of fan blades corroded approx. 1.5 mm.

**METHOD(S) OF CORRECTION:**

• The renovation works of the road slab concrete were as follows:
– The design load was increased from T-20 to TT-43.
– The side wall thickness was increased to balance with the sectional inertia and also to ensure the fresh air duct area, resulting in a reduction in the width of the sidewalk.
– The covering of reinforcement bars was ensured at 50 mm on the surface of the slab, and 40 mm on the other parts.
– The dimension of the lower part of the vertical side wall, where the leakage water was apt to collect, was increased to protect the reinforcement bars from corrosion by the sea water, and further drainage ditch of plain concrete was placed on the fresh air duct side.
– The distance between the joints of the concrete was increased from 18 to 63 m, because the joint becomes the structural weak point.

• Renovation of the ceiling plates is planned in the near future.
• The drain pumps were replaced with stainless steel pumps.
• Lighting facilities are replaced over a 13-year period.
• Fan blades were replaced after 14 years in service.

**REFERENCES:**


Wada, Kanji. 1986. "Maintenance and Control of Kanmon Highway Tunnel". Tunnelling and Underground Space Technology 1:3/4, 315–322.

| JAPAN | | CASE J4 |
| --- | --- | --- |
| **TOWN: Tokyo Underground Tunnel** | PURPOSE OF TUNNEL: Road Tunnel | DATES OF CONSTRUCTION: 1965–1972 1968–1976 |
| **NATURE OF LINING:** | Steel-reinforced concrete segments. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The tunnel was constructed beneath the central area of Tokyo, in diluvial and alluvial strata consisting of sand, clay and gravel. At the time of planning, the underground water table was several metres underneath the tunnel as a result of pumping throughout a period of high economic growth. The water level has been restored since 1971. However, because of administrative restrictions against pumping, the present tunnel is completely under the groundwater table. The underground water is salty and ferric. | |
| **NATURE OF INFLOW:** | The tunnel lacks an inner concrete lining in the sections where a high water level was not anticipated at the time of planning. Soon after inauguration of service, it became apparent that the watertightness of segment lining of these sections was unsatisfactory. Leakage occurred in joints of the lining segments of the whole structure, including the subgrade. The inflow to the tunnel spurted out and included a large amount of soil under unbalanced water pressure as the groundwater and soil entered. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | • Joint bolts and steel frames of the segments were seriously damaged by corrosion.<br>• Damage to the joint bolts of a key segment, if advanced, makes it impossible to maintain the cylindrical configuration of the tunnel.<br>• The tunnel is assumed to lose side support as the discharge of ground soil advances.<br>• Track irregularity has been generated due to the water pressure beneath the invert. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | • Increasing expenditure for sewer rates and sewage disposal.<br>• Corrosion of steel installations such as rail fastenings, handrails and gratings. | |
| **METHOD(S) OF CORRECTION:** | Emergency countermeasures for damaged sections have been initiated by water interception treatment of the joint bolts and by injection of watertightening material. The inner concrete lining was completed to a length of 340 m by live work, and another 660 m is to be constructed two years hence. Gap-tightening work between the invert and the lining will be carried out thereafter. | |

| JAPAN | | CASE J5 |
|---|---|---|
| **TOWN: Mikuni National Route 17** | PURPOSE OF TUNNEL: Highway Tunnel | DATES OF CONSTRUCTION: Opened in 1959 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • 7.6 m wide (at base).<br>• Shape of tunnel: Gothic arch (egg shape with three radii).<br>• 1218 m long, with a 0.6% grade throughout. | |
| **NATURE OF LINING:** | • In-situ concrete lining of three different thicknesses, (250 mm, 300 mm, and 500 mm), depending on geology.<br>• Under-drainage of invert provided by 300- to 600-mm pipes. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | New sedimentary rock of the Miocenii-Neogene period, consisting mainly of hard shales, with intrusion of quartz-diorite porphyrite, diorite porphyrite, and liparite. Volcanic area with sulphur mines in adjacent mountains. Groundwater is highly acidic. | |
| **NATURE OF INFLOW:** | Water inflow throughout most of the length of tunnel, with spouting water from joints, has occurred since construction. Total inflow 50–100 l/sec. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | • Ice on the road surface, icicles hanging from the tunnel ceiling.<br>• Acidic water attack of the concrete lining, causing degradation and spalling. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | None noted. | |
| **METHOD(S) OF CORRECTION:** | Trial back-grouting with acid-resistant materials was first tried, but because of the extent of voids and the length of tunnel, this measure was considered uneconomical. In 1959, an inner 300-mm sprayed mortar lining was placed with back drainage strips at 7–8 m centres, connected longitudinally with V grooves intercepting areas of leakage. The sprayed lining was effective for four years, after which time water seepage began to reappear and spalling of the mortar began to occur under the action of the frosts. Acid degradation also continued.<br><br>In 1968, investigations were carried out to determine the extent of lining degradation and the quantity and acidity of the seepage. Remedial action following this study consisted of a new in-situ concrete inner lining reinforced with steel H section. A synthetic rubber waterproofing membrane was placed between the new and existing linings to completely cut off the acidic water inflows, and existing drainage measures were sealed. The new lining was designed to withstand the expected earth and water pressures in itself. | |
| **REFERENCES:** | Suzuki, Michio and Yoshio Sawa. "Mikuni Tunnel—Erosion of Placed lining Concrete due to Acidic Water Flow in Mikuni Tunnel and Countermeasures." | |

| JAPAN | | CASE J6 |
|---|---|---|
| **TOWN: Uebonmachi–Nipponbashi Tunnel, Namba Railway Line, Kinki-Nippon Railway Co.** | PURPOSE OF TUNNEL: Rail Tunnel | DATES OF CONSTRUCTION: Opened for service in 1970 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Overall length: 1407 m.<br>Circular 10-m outside diameter. | |
| **NATURE OF LINING:** | • 1390 m lined with reinforced concrete segments.<br>• 17 m lined with steel segments.<br>• Inner shotcrete lining 100 mm thick to section totaling 370 m. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | Upper diluvial sand/gravel layers and anticline of marine clay and sand layers in alternate bedding. At one location, tunnel passes through sand layers with direct surface water infiltration and containing significant groundwater. | |
| **NATURE OF INFLOW:** | Inflows of acidic groundwater (pH value 4.7) were occurring where the tunnel ran through the anticlinal sand lens (160 m length of tunnel). The condition had existed since construction. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | After 15 years of service, a core sample taken from the lining indicated neutralization extending to a depth up to 5 mm from the outer surface of the segment. The lining concrete generally retained a compressive strength of 670 kg/sq. cm. The structure was therefore considered sufficiently stable. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | • Severe corrosion of the rails and P.C. tie fastenings.<br>• Deterioration of cables in side wall ducts.<br>• Deposition of red-brown matter on the lining.<br>• Deposition of brown matter on insulator surfaces, requiring frequent cleaning and replacement of insulators.<br>• Electrical arcing on the pantograph.<br>• Staining of the rolling stock. | |
| **METHOD(S) OF CORRECTION:** | Chemical grouting of the ground adjacent to the tunnel was carried out as follows:<br>1. LW-1 grouting (grout/soil ratio of 50%) to a 0.5 m/thick layer as a void filler, followed by suspension-type micro-fine cement (at ratio of 32%) to 1.5-m-thick annulus.<br>2. Grouting pressure of 3.0 kg/sq. cm with gel time of 90 seconds.<br><br>The grouting significantly reduced the seepage and consequently caused a rise in the water table in the anticline sand lens, preventing further oxidation of the iron pyrites and, thus, the formation of acidic groundwater. | |
| **REFERENCES:** | • Kawamura, Takeski and Masahiro Yamada. "Seepage Control of Shield Tunnel in Namba Line at Kinki". Nippon Railway Co.<br>• Inchihara, Minaru. "Marine Clay of the Osaka Formation and Freshwater Clay". Yuko Ichihara. | |

| NORWAY | | CASE N1 |
|---|---|---|
| **TOWN: Oslo**<br>**Bryn Tunnel** | PURPOSE OF TUNNEL: Road Tunnel | DATE OF CONSTRUCTION: 1970 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Two two-lane tunnels, each 9.50 m wide.<br>• Length: 200 m. | |
| **NATURE OF LINING:** | • Single-shell, in-situ concrete lining, block length 6 m.<br>• Joints with rubber waterstops.<br>• No waterproofing protection. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The tunnel was constructed in solid rock (rock cover 5–20 m); drainage is accomplished by the gravity flow system. | |
| **NATURE OF INFLOW:** | The watertightness of the lining soon proved to be unsatisfactory. Leakages occurred in cracks and construction joints, especially after periods of heavy rainfall. In the winter, this situation resulted in icicles on the ceiling and lumps of ice on the walls and roadway. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | None. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | The icing necessitated routines for systematic tunnel inspections and maintenance activities in the form of ice removal. These activities were most intensive after thaws or rainy periods, followed by frost. | |
| **METHOD(S) OF CORRECTION:** | The amount of maintenance work led to repairs for one of the two-lane tunnels in 1974; and for the other, in 1976. Pipes were installed along the leaking cracks and joints to lead the leaking water to the drainage system. The pipes were supplied with a thermostat-regulated electric heating wire to avoid icing. The result of the repair was fairly good, but leakages still create a need for some ice-removal activities during the winter.<br><br>The repair and maintenance costs (especially heating) were all converted to the year of opening and compared to the construction cost. The construction cost could have been increased by 14%–29% (depending on interest rates), assuming the result would have a watertight tunnel. | |
| **REFERENCES:** | Taugbol, T. 1986. "Maintenance and economical consequences of water leakages in the Bryn Tunnel". In Proceedings of a Conference on Low Cost Road Tunnels, Vol. 2. | |

| SWITZERLAND | | CASE CH1 |
|---|---|---|
| **TOWN: Basel/Olten Belchentunnel** | PURPOSE OF TUNNEL: Road Tunnel | DATES OF CONSTRUCTION: 1963–1969 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Two two-lane tunnels.<br>• Length: 3180 m.<br>• 7 crosscuts between the tunnels.<br>• 3 ventilation shafts.<br>• Excavation cross-section ≥ 79 sq. m.<br>• Gradient ≤ 1%. | |
| **NATURE OF LINING:** | • External shell: shotcrete (10–20 cm thick), anchors and steel arches.<br>• Sealing: PVC sealing foil, 1 mm thick; longitudinal drainage (hoses at 5 cm) for water at the sealing base.<br>• Internal shell: ca. 30-cm-thick concrete (without reinforcement); joints spaced at 12-m intervals.<br>• Ventilation shafts: concrete lining, no sealing or drainage. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The tunnel goes through strata consisting of clay, marl, lime, dolomite and gypsum keuper. | |
| **NATURE OF INFLOW:** | • Leakage at many joints of the lining (due to sealing damages caused through the face formwork of wood at the joints and sharp edges of the shotcrete surface).<br>• Water seepage at the first crosscut and at the tunnel lining in gypsum keuper (due to lining deformations caused by swelling of gypsum). | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | At one ventilation shaft, the concrete lining had softened so much that it could be removed only by hand (presumably this condition was caused by using an inadequate cement, instead of lime-free aggregates). The reinforcement was severely corroded. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Unknown. | |
| **METHOD(S) OF CORRECTION:** | • Damaged concrete areas were removed and replaced by new concrete. A surface sealing was applied.<br>• Water seepage places were injected. This measure was not satisfactory. Slits were then cut into the lining and connected with the bottom drain; this measure also had no permanent success.<br>• It is planned to cover the surface of the ceiling slab with plastic foil and let the dripping soil water flow through pipes to the bottom drainage. | |
| **REFERENCES:** | Wanderer, J.; Schaden, K.; Kurzmann, E; Knoll, P.; Pöhlmann, E. 1985. "Abdichtungssysteme in ausgeführten Tunneln" (Sealing systems in completed tunnels). Bundesministerium für Bauten und Technik, Straßenforschung, Heft 274, Vienna. | |

| SWITZERLAND | | CASE CH2 |
|---|---|---|
| **TOWN: Simplon/Brig Kulmtunnel (Kaltwasser)** | PURPOSE OF TUNNEL: Road Tunnel | DATE OF CONSTRUCTION: 1964 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Approx. 700-m-long highway tunnel. | |
| **NATURE OF LINING:** | Shotcrete; soil water is collected by the Oberhasli method and flows to the longitudinal drainage (concrete pipes ≈ 20 cm) under the sidewalk. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The hillside tunnel was excavated in rock strata bearing large amounts of water. | |
| **NATURE OF INFLOW:** | • Leakage and wet surfaces at the circular joints at 6-m intervals. Icicles and leakage necessitated improvements in 1977.<br>• In April 1979, all of the water in the drainage at the portal was frozen and the backflow caused water inflow at the lining (especially the hillside tunnel wall). | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Freezing and backflow of water caused and widened cracks in the lining. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Unknown. | |
| **METHOD(S) OF CORRECTION:** | • In the enlarged joints, centre split pipes were fastened, insulated and closed with plaster.<br>• On the vault lining, 6 cm shotcrete, a filter layer (SAPE foil), wire mesh, and 6 cm of shotcrete were applied.<br><br>Wet surface areas (but no dripping water) still appear after these improvements. A composite structure of sealing lining and first shotcrete lining does not exist (gap of ca. 2 mm). | |
| **REFERENCES:** | Wanderer, J.; Schaden, K.; Kurzmann, E.; Knoll, P.; Pöhlmann, E. 1985. "Abdichtungssysteme in ausgeführten Tunneln" (Sealing systems in completed tunnels). Bundesministerium für Bauten und Technik, Straßenforschung, Heft 274, Vienna. | |

| SWITZERLAND | | CASE CH3 |
|---|---|---|
| **TOWN: Basel/Olten Hauenstein—Basistunnel** | PURPOSE OF TUNNEL: Rail Tunnel | DATES OF CONSTRUCTION: 1912–1916 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Twin-track tunnel; 8.1 km long; cross-section, see Fig. CH3/1. | |

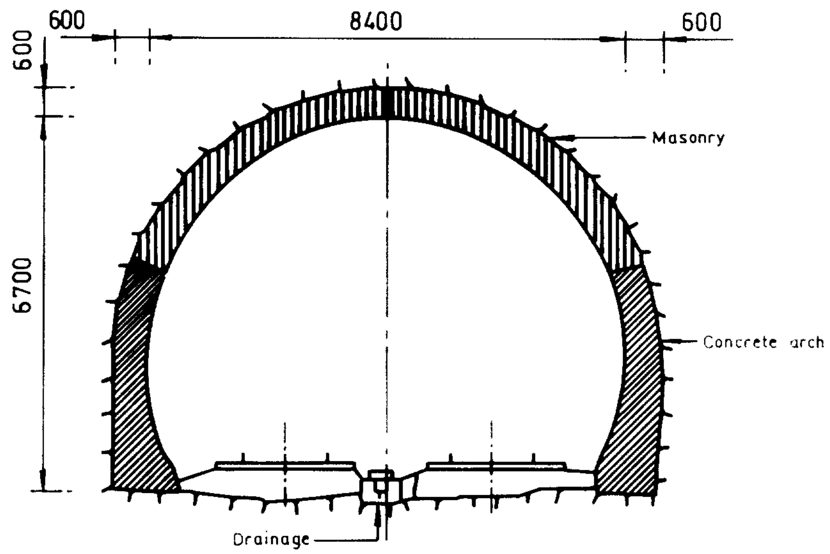
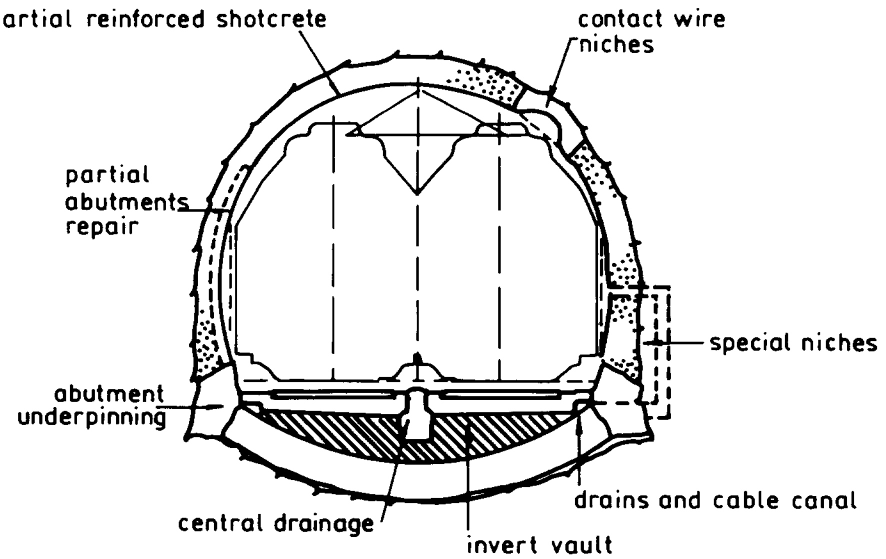
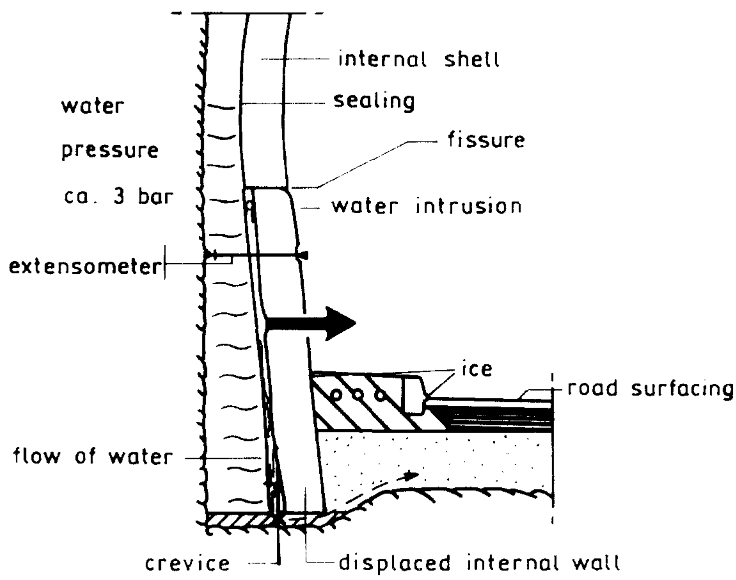



Fig. CH3/1: Cross-section of the Hauenstein-Basistunnel before repair

| | |
|---|---|
| **NATURE OF LINING:** | The crown lining consists of masonry, the side walls and abutment of concrete; average thickness ca. 0.6 m. |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The north and south part of the tunnel were excavated in hardly water-permeable, marly clay soil with swelling characteristics (swelling pressure 20–200 N/sq. cm). The middle part of the tunnel was constructed in water-permeable, limey marly soil (water inflow during the construction period ca. 30 l/s; water temperature 28°C). |
| **NATURE OF INFLOW:** | Considerable wetness in the whole structure; wetness in the invert; water has somewhat high concentrations of lime and sulfate. |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | • Drainage defect, because of lime sedimentation and swelling soil.<br>• Clearance height reduced, because swelling soil lifts rails.<br>• Mud rising up through the track bed. |

| SWITZERLAND | CASE CH3 (contd.) |
|---|---|
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | • Corrosion of the electric facilities on the vault.<br>• Anchoring of the electric facilities deteriorates.<br>• Rail position is inaccurate and train velocity has to be decreased in the tunnel. |
| **METHOD(S) OF CORRECTION:** | The following improvements were necessary:<br>• Construction or replacement of invert vaults.<br>• Replacement of the invert drainage, construction of drains and cable canals at the side walls,<br>• Sealing of the wet vault areas.<br>• Replacement of the tracks and electric facilities.<br>• Lowering of the invert for a larger clearance profile, etc. (see Fig. CH3/2)<br><br>Modernization work on the tunnel last from the end of 1980 until the spring of 1987. The overall costs for this project amounted to about 190 million DM.<br><br><br><br><br>Fig. CH3/2: Cross-section of the Hauenstein-Basistunnel after repair with details of improvements carried out. |
| **REFERENCES:** | Etterlin, A. 1986. Rekonsstruktion Havenstein-Basistunnel, Luzern. |

| SWITZERLAND | | CASE CH4 |
|---|---|---|
| TOWN: **Andeer/Sufers Rofla Tunnel** | PURPOSE OF TUNNEL: Road Tunnel | DATES OF CONSTRUCTION: 1966–1969 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | Two-lane tunnel, oncoming traffic<br>Length: 995 m.<br>Horseshoe-shaped cross-section.<br>Gradient: 5.6 %. | |
| **NATURE OF LINING:** | Internal shell of 30-cm-thick concrete; plastic sealing between internal and external shell. (see Fig. CH4/1). | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | Overlying ground ca. 150 m; tunnel was excavated in stable, hard rock strata of porphyr; only slight inflow of water through rock fissures during the construction period. | |
| **NATURE OF INFLOW:** | Water leakage through block joints and horizontal fissures (approx. 1.5 m above the escape route) of the internal concrete shell (Fig. CH4/1).   Fig. CH4/1: Water leakage in the Rofla-Tunnel | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Fissures in the internal shell. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Icy road and escape route. | |

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| **METHOD(S) OF CORRECTION:** | The following measures were carried out (see Fig. CH4/2):<br>• Drainage bore holes every 5 m;<br>• Two mortar anchors every meter to secure the abutment;<br>• Sealing of the wall sides (the sealing foil leads the water to the thermal insulated drains under the escape route); thermal insulation of the sealing prevent the formation of ice during the winter (see Fig. CH4/3); protection of the insulation with lining planks. |

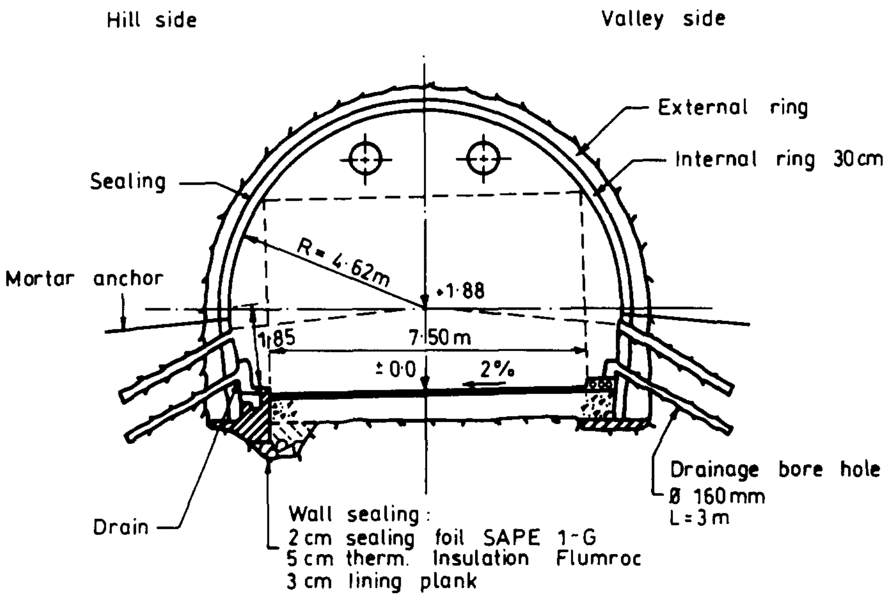


Fig. CH4/2. Renovation in the Rofla - Tunnel (34m Tunnel test section)

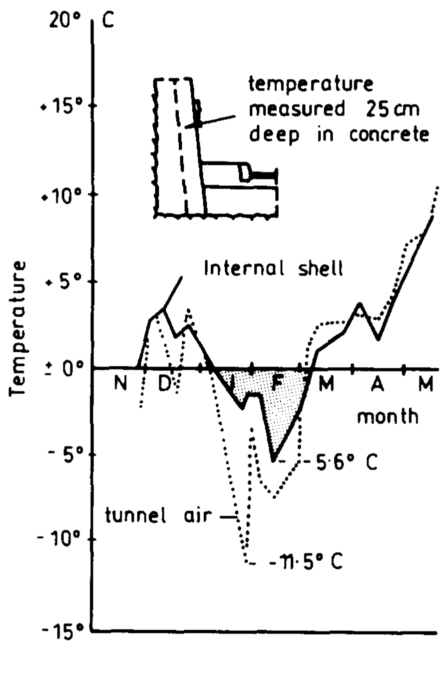


Fig. CH4/3. Temperature measurement results of the tunnel air and 25cm deep in the lining between 10. 1985 and 5. 1986.

| | |
|---|---|
| **REFERENCES:** | Mettler, R. 1987. "Sanierung der Tunnel Mont la Schera, Versasca und Rofla". Paper given at Symposium Sanierung von Tunnelbauwerken, München. Tunnel (Sonderheft), 1987, 58–63. |

| UNITED ARAB EMIRATES | | CASE ET1 |
|---|---|---|
| **TOWN: Dubai/Deira** | PURPOSE OF TUNNEL: Road Tunnel | DATES OF CONSTRUCTION: 1972–1975 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | • Four-lane subaqueous road tunnel.<br>• Width of each lane: 3.65 m.<br>• Length: 560 m.<br>• Rectangular cross-section. | |
| **NATURE OF LINING:** | 9-m-long reinforced concrete blocks with a wall thickness of 1 m. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | The invert is 15 m below high water level. | |
| **NATURE OF INFLOW:** | Leaking joints and seepage of salty water through the structure. Cause of the leaks has been traced to the inadequate quality of the local limestone aggregate for the concrete and the excessive hardness of the joint insets made of bituminized cork. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Damages to the reinforced concrete (high levels of chloride were measured in the concrete). | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Unknown. | |
| **METHOD(S) OF CORRECTION:** | • After a thorough cleaning of the tunnel and removal of defective concrete, approx. 23000 litres of epoxy resin will be injected into some 33,000 bore holes. The brittle cork will be removed from the joints and will be replaced with flexible Neoprene packing.<br>• The costs of repair have been estimated at £11 million. | |
| **REFERENCES:** | • 1986. Plugging Dubai's leaking road tunnel. Tunnels & Tunnelling 18 (11), 9.<br>• Kretschmer, M. and Fliegner, F. 1987. Unterwassertunnel (Subaqueous Tunnel). Ernst & Sohn Verlag, Berlin. | |

| UNITED STATES OF AMERICA | | CASE US1 |
|---|---|---|
| **TOWN: Detroit, Michigan Northeast Raw Water Tunnel** | PURPOSE OF TUNNEL: Raw Water Tunnel | DATES OF CONSTRUCTION: 1948–1954 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | 10 ft. inside diameter; cylindrical. | |
| **NATURE OF LINING:** | • Primary lining: 16-inch-thick precast concrete, O'Rourke blocks (7 segments).<br>• Secondary lining: cast-in-place non-reinforced concrete; nominal thickness: 16 inches. | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | • Bedrock at a depth of 130 ft.<br>• Overlying the bedrock, tough lodgement glacial till (called hardpan) consisting of very dense sands and silts with relatively high clay contents.<br>• The hardpan is overlain by fine-grained glaciolacustrine deposits and/or recent glacial outwash containing bands of nested boulders and moraine.<br>• Tunnel primarily runs through fine-grained lacustrine at a depth from 90 to 100 ft. below the surface.<br>• Water pressure in the tunnel corresponds to an elevation head of 50 ft. | |
| **NATURE OF INFLOW:** | The inflow to the tunnel consisted of groundwater with small amounts of soil, under unbalanced water pressures of 3–5 psi. The infiltration occurred initially at shrinkage cracks near the springline between the two concrete pours. It is theorized that approximately 55 cu. yds. of material were piped into the tunnel over a period of 32–38 years. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | As the groundwater and soil piped into the tunnel, the tunnel lost bottom and side support. When loss of support occurred beneath the invert, the resulting loading caused the structure to crack circumferentially. Further, the loss of soil from the invert allowed the tunnel to settle. The maximum settlement noted was approximately 30 inches. When the loss of support occurred at the springline, the resulting loading caused a pattern of longitudinal cracking and spalling. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | None. | |
| **METHOD(S) OF CORRECTION:** | Several access shafts were drilled to investigate possible distress of the tunnel. After the distressed area was identified, the tunnel was refilled with water and divers were utilized to place inflatable bulkheads in the tunnel, effectively isolating the distressed portion. The area between the bulkheads—a distance of approximately 300 ft.—was then stabilized by filling it with a cement and flyash mixture.<br><br>A program of high-pressure grouting using a cement-flyash mixture was undertaken outside the filled tunnel. Fifty-five cu. yds. of grout material was placed around the tunnel. The tunnel was then dewatered, the bulkheads deflated, and the cement stabilized flyash removed by hand mining.<br><br>Structural steel ribs were installed on 2.5-ft. centers and expanded to within 2 inches of the tunnel walls during the mining operations. A 10-inch-thick layer of steel-fiber-reinforced shotcrete containing micro-silica is to be placed over the ribs to complete repair work. | |
| **REFERENCES:** | Neyer, Jerome C. 1983. Soft Ground Tunnel Failures in Michigan. | |

| UNITED STATES OF AMERICA | | US2 |
|---|---|---|
| **TOWN: Sterling Heights Corridor Interceptor** | PURPOSE OF TUNNEL: Raw Sewage | DATES OF CONSTRUCTION: 1970–1972 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | 12-ft. 6-in. inside diameter; cylindrical. | |
| **NATURE OF LINING:** | • Primary lining: steel ribs and timber lagging.<br>• Secondary lining: monolithic poured non-reinforced concrete (nominal thickness: 16 inches). | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | This tunnel was bored primarily in a horizon of compact silt, over a horizon of very compact fine sand, and capped by a very stiff silty clay. The tunnel invert, within the study area, is at depths ranging from 50 to 60 ft. below the ground surface.<br><br>The groundwater level at the project ranged from 35 to 44 ft. below the ground surface. Due to the impermeable glaciolacustrine clays over the silt and sand, these horizons are under slight artesian pressure at some locations, and effectively free groundwater table conditions at other locations. | |
| **NATURE OF INFLOW:** | The inflow to the tunnel consisted of groundwater with small amounts of soil, under water pressures of 4 to 8 psi. The infiltration occurred initially at cracks in the concrete liner, primarily at construction joints, and shrinkage cracks. The main inflows occurred at locations below the springline of the tunnel. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | As the groundwater and soil were piped into the tunnel, the tunnel lost bottom and side support.<br><br>When loss of support occurred beneath the invert, the resulting loading caused the structure to crack circumferentially. When the loss of support occurred at the springline, the resulting non-uniform loading caused a pattern of ovalling, longitudinal cracking, and spalling. In addition, the tunnel section settled vertically into the voids below the invert, causing additional distortion and distress in the liner. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | None. | |
| **METHOD(S) OF CORRECTION:** | Initially the soil was frozen to prevent further collapse. The flow was diverted and permanent repair accomplished by jacking 9-ft. inner diameter reinforced concrete pipe through the distressed areas. The annular space between the new pipe lining and the old tunnel was filled with cement grout. In addition, an extensive program of grouting outside the original tunnel was undertaken. | |
| **REFERENCES:** | Neyer, Jerome C. 1983. Soft Ground Tunnel Failures in Michigan.<br>Neyer, Tiseo and Hindo Ltd. 1982. Summary Report on Emergency Repairs of Corridor Interceptor.<br>U.S. Army Corps of Engineers. 1980. 15-Mile Road/Edison Corridor Sewer Tunnel Failure Study, Detroit Area, Michigan. | |

| UNITED STATES OF AMERICA | | CASE US3 |
|---|---|---|
| TOWN: Sterling Heights<br>Romeo Arm Interceptor | PURPOSE OF TUNNEL: Raw Sewage Tunnel | DATES OF CONSTRUCTION:<br>1972–1973 |
| DIMENSIONS AND SHAPE OF TUNNEL: | 11-ft. inside diameter; cylindrical. | |
| NATURE OF LINING: | • Primary lining: steel ribs and timber lagging.<br>• Secondary lining: unreinforced monolithic concrete lining placed as the mining progressed (nominal thickness: 14 inches). | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | The tunnel was bored largely along the contact between an upper unit of heavily overconsolidated clay and a lower soil unit of very compact gray fine sand. The tunnel invert ranged from approximately 55 to 70 ft. below ground surface. The groundwater level at the project ranges from 35 to 40 ft. in depth. Due to the impermeable glaciolacustrine clays over the fine sand, this horizon is under artesian pressure. The tunnel was under gravity flow with flow depths ranging from 18 inches to 6 ft. | |
| NATURE OF INFLOW: | The inflow into the tunnel consisted of groundwater with major amounts of soil, under water pressures of 4 to 8 psi. The infiltration occurred initially in the removal of soil fines from uncontrolled pumping during the construction of a proposed shaft next to the interceptor. Several thousand cubic yards of material flowed into the tunnel, blocking the flow and filling it with sand and silt. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | As the groundwater and soil were piped into the tunnel, the tunnel lost bottom and side support. When loss of support occurred beneath the invert, the resultant loading caused the structure to crack circumferentially. The tunnel then settled in segments into the voids beneath the invert leading to a progressive failure in a downstream direction from the initial inflow point. Sufficient amounts of soil were transported into the tunnel, essentially filling the inside with soil materials. A large and extensive settlement trough occurred over the centerline of the tunnel, settling a two-lane road by as much as 3 ft. over a distance in excess of 1000 ft. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | None. | |
| METHOD(S) OF CORRECTION: | An emergency bypass of the failed section was installed by the contractors retained by the City of Detroit Water and Sewerage Department.<br><br>In order to stop inflow of soils into the ruptured tunnel, a program of dewatering and grout injection was initiated. Preliminary soil boring results indicated that it would take at least several weeks to lower the level of the groundwater to a point below the tunnel. Pumping of cement-based grout, however, proved effective in halting the progressive collapse of the system within 7 days.<br><br>Due to the extensive quantities of soil within the tunnel, the filled tunnel section was abandoned and a new tunnel section constructed around the failed section. | |
| REFERENCES: | • Neyer, Jerome C. 1983. Soft Ground Tunnel Failures in Michigan.<br>• Neyer, Tiseo and Hindo, Ltd. 1979. Summary Report of Emergency Repairs of Romeo Arm Interceptor. | |

| SWEDEN | | CASE S1 |
|---|---|---|
| **TOWN: Stockholm Underground Railway (Sweden)** | PURPOSE OF TUNNEL: Metro Rail Tunnel | DATES OF CONSTRUCTION: 1957–1988 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | 25–70 sq. m. | |
| **NATURE OF LINING:** | Shotcrete or partly unlined (rock). | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | • Granite gneiss.<br>• Tunnel located beneath ground water level. | |
| **NATURE OF INFLOW:** | Locally large inflow or leakage. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | Frost damage, calcareous precipitation, discoloration. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Corrosion, weathering. | |
| **METHOD(S) OF CORRECTION:** | Grout injection, frost isolation, heating. | |
| **REFERENCES:** | "Technical Description of the Stockholm Underground". April 1964, Stockholm. | |

| SWEDEN | | CASE S2 |
|---|---|---|
| TOWN: Tail Race Tunnel (Jarpen, Sweden) | PURPOSE OF TUNNEL: Hydro Power Plant Outlet Tunnel | DATES OF CONSTRUCTION: 1940; Reparations—1985, 1986 |
| DIMENSIONS AND SHAPE OF TUNNEL: | 105 sq. m. | |
| NATURE OF LINING: | (Shotcrete) concrete arches locally. | |
| GEOLOGICAL AND HYDROLOGICAL CONDITIONS: | • Graywacke schist, phyllite.<br>• Tunnel located beneath ground water level. | |
| NATURE OF INFLOW: | Pulsating hydro-dynamic loads. | |
| EFFECT(S) ON STRUCTURE OF TUNNEL: | Erosion, oxidation, rockfalls. | |
| EFFECT(S) ON INSTALLATION IN TUNNEL: | Corrosion of concrete cast in-situ, weathering. | |
| METHOD(S) OF CORRECTION: | Shotcrete, rock bolting. | |
| REFERENCES: | Benedik, Rasa. "Damages and Repair of Tail Race Tunnel at Järpströmmen water power plant after 40 years in operation." In Proceedings of a Conference on Large Underground Openings, Florence, Italy, 8–11 June, 1986, Vol. 2, pp. 37–45. | |

| SWEDEN | | CASE S3 |
|---|---|---|
| **TOWN: Tyrens, Sundyberc** | PURPOSE OF TUNNEL: Telecommunications Tunnels | DATES OF CONSTRUCTION: 1961–1975 |
| **DIMENSIONS AND SHAPE OF TUNNEL:** | 7 sq. m–20 sq. m; 33 km long. | |
| **NATURE OF LINING:** | Shotcrete, mostly unlined (rock). | |
| **GEOLOGICAL AND HYDROLOGICAL CONDITIONS:** | • Granite gneiss.<br>• Tunnel located beneath ground water level. | |
| **NATURE OF INFLOW:** | Normally 5–10 l/min/100 m in areas where no pre-grouting was performed; some inflow in grouted areas. | |
| **EFFECT(S) ON STRUCTURE OF TUNNEL:** | None. | |
| **EFFECT(S) ON INSTALLATION IN TUNNEL:** | Corrosion on steel details, holes in floor asphalt (from dripping). | |
| **METHOD(S) OF CORRECTION:** | Extra drains installed after tunnel was completed. | |
| **REFERENCES:** | Tenne, Hats. "Maintenance and repair of underground structure programme for maintenance—examples from Stockholm". In Proceedings of a Rock Mechanics Meeting in Stockholm, Sweden, 1984 (Stockholm: Swedish Rock Engineering Research Foundation). | |