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INTERNATIONAL TUNNELLING ASSOCIATION

STUDY OF METHODS FOR REPAIR OF TUNNEL LININGS

ETUDE DES METHODES POUR LA REPARATION DES REVETEMENTS DES TUNNELS

BY

Working Group No. 6 Maintenance and Repair

Groupe de Travail n° 6 Entretien et Repair

Reference: Report and documents, final edition June 2001

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CHAPTER 1

INTRODUCTION

In 1991 the International Tunnelling Association Working Group No. 6 on Maintenance and Repair of Underground Structures published a report on the damaging effects of water on tunnels during their working life, in the journal Tunnelling and Underground Space Technology [1]. Case histories, gathered for that report from various nations, illustrated the wide range of problems, which result from water inflows, and demonstrated the need for reliable methods of intervention to reduce or eliminate these problems.

The Working Group has accordingly followed up this earlier work by undertaking a study of methods of repair of water leakage. This work has involved collecting, classifying and reviewing case histories of leak sealing operations, and this present report incorporates the results of that work. Although water leakage represents the major problem with respect to repair and maintenance of underground structures and is the principal subject of this Study, the scope of the Study and this report was extended to cover methods of dealing with other types of problems such as inferior construction, ageing, humid environments, frost damage, operational damage, etc in order to present an overview of all types of repairs.

The causes of damage to tunnel linings may represent a failure in tunnel design or construction, or possibly a failure or degradation of the waterproofing arrangements as designed, or the incorrect specification of construction materials. However, it is not the main purpose of this Study to suggest ways to improve the design, but rather to consider the remedial measures, which have to be undertaken during the service life of a tunnel. It should be noted that, here and throughout the rest of this report, any reference to tunnels should be interpreted as including all types of man-made underground structures or facilities.

In Chapter 2, the objectives of the repair works are discussed bearing in mind that the repairs must be technically adequate and cost effective. This is particularly important with respect to the sealing of leaks; requirements for watertightness will vary depending upon tunnel use and the nature of the surrounding ground and groundwater. Total elimination of water flows can prove costly in some circumstances, and it is wise to undertake a careful assessment of requirements in terms of watertightness, so that a cost-effective remedial programme can be selected. This chapter also contains notes on the inspection of tunnels and the investigations required to assess damage and select appropriate remedial measures.

In Chapter 3, categories of leak sealing processes and repair methods are defined, depending upon their relationship to the tunnel structure and its surroundings. This chapter is intended only to facilitate classification and discussion of the various repair methods applicable.

Chapters 4, 5, 6 and 7 describe the processes and materials, which are appropriate to the categories defined in Chapter 3. These chapters include valuable additional remarks based on the individual and collective experience of Group members. The experience of the tunnel operators in the repair and strengthening of the tunnel linings are also noted and discussed.

Concluding remarks are made in Chapter 8, which is followed by a summary of all of the case histories, which have been reviewed by the Group and form the basis of the Study.

The Study has taken a number of years to complete and the members of the Working Group have changed during this period. The principal members, who have made major contributions to the Study, and to whom special acknowledgement and appreciation of their contributions is given, are as follows:

Name	Country
Dr A Haack (Tutor)	Germany
Mr A Howard (Previous Animateur)	United Kingdom
Mr M Julien	France
Mr N Kotake	Japan
Mr R Machon (Vice Animateur)	Germany
Mr M Marec	France
Mr G Posgay	Hungary
Mr J Richards (Animateur)	South Africa
Mr H Russell Jr	United States Of America

The Executive Council of the ITA is also thanked for their support of Working Group No. 6 in carrying out the Study. Lastly, thanks are extended to all those people, organisations and ITA Member Nations for providing case histories of water leakage and repairs of damage in tunnels, which formed a valuable data base for the Study.

References:

[1] Tunnelling and Underground Space Technology (Vol 6. No 1, pp 11- 76).

CHAPTER 2

OBJECTIVES OF REPAIR WORKS

There are two principal objectives of any repair process:

(i) To re-create an environment within the tunnel appropriate to the use of the tunnel; and
(ii) To preserve the structural competence of the tunnel and to safeguard the external environment.

These objectives are considered in turn in the following sections.

2.1 Environment Inside the Tunnel :

Changes in the tunnel environment are principally related to water leakage. There are two main factors:

- The overall permeability of the tunnel lining, as measured by the total amount of water which enters or exits the structure; and
- The nature, magnitude and position of individual sources of leakage.

Overall permeability is usually expressed as the flow through the lining per day per unit area, measured over stated reference lengths; for instance 0.2 litres per day per square metre (0.2 *l*/day/sq.m) measured over any 10 metres of tunnel. Frequently the allowable maximum permeability is reduced as the reference length increases; for example, corresponding to the above, the maximum flow might be set at 0.1 *l*/day/sq.m over a reference length of 100 metres.

The permeability requirements will vary from tunnel to tunnel depending upon operational criteria and the options of the individual owners. This is exemplified by Table 2-1, which lists permissible leakage rates for various metro railway systems. As can be seen, the specified acceptable leakage standards vary significantly and a number of factors require to be considered in establishing these standards.

Underground Railway Systems	Short Section		Long Section	
	Leakage Rate [*l*/day / sq.m]	Reference Length [m]	Leakage Rate [*l*/day / sq.m]	Reference Length [m]
Washington (USA)	10.7			
San Francisco (USA)			0.9	80
Atlanta (USA)			0.9	80
Boston (USA)			1.8	35
Baltimore (USA)	5.3	3.5	0.7	35
Buffalo (USA)	0.4	10	0.2	1000
Melbourne (Australia)	0.25	10	0.1	1100
Antwerp (Belgium)	0.25	10	0.1	100

Table 2-1 : Examples of permissible daily leakage rates[1]

For example, individual sources of leakage may not cause a breach of the overall leakage requirements but may, because of their nature or position, result in damage to the internal structures or fittings, to the tunnel structure itself, or to the surrounding environment. The presence of water, albeit only drops, can cause unsightly staining and, because of their persistence, can result in erosion or corrosion, and in some circumstances the formation of icicles, ice and ponding of water, which interfere with the use or with the safety of users or the personnel in the tunnel. Drops may also be completely unacceptable, if they can fall on members of the public or their vehicles, thereby causing an unnecessarily high level of concern on the part of the public with regard to personal safety. Furthermore, leakage cannot be tolerated in any form in areas where there is water sensitive electrical, electronic, or special operational equipment.

The nature and composition of the flow are also important, and chemical or biological contamination can create a need for remedial work even though flow levels are otherwise acceptable.

It is useful for reference purposes to be able to specify different classes of watertightness for different operating conditions, particularly in cases where the owner is responsible for the operation of an extensive network of tunnels. An example of this is the German Railway Company, Deutsche Bahn AG, the operating company for 746 tunnels in their network. Included in this number are 491 "old-constructed" tunnels built in the years between 1840 and 1940. The classes of water-tightness and respective acceptable water leakage rates are shown on Table 2-2.

Tight-ness Class	**Moisture Characteristics**	**Use of Tunnel**	**Definition**	**Acceptable leakage rate (*l*/day/sq.m) at the reference length**	
				10m	**100m**
1	Completely dry	Stores, workrooms, rest rooms	The wall of the lining must be tight so that no moist patches are detected on the intrados	Nil	Nil
2	Substantially dry	Frost-endangered underground sections	The wall of the lining must be tight so that only slight, isolated patches of moisture can be detected on the intrados, e.g. result of discolouration. After touching such slight moist patches with a dry hand, no traces of water should be detected. A sheet of blotting paper placed on a patch, should not discolour as a result of absorbed moisture.	0.2	0.05
3	Capillary moisture penetration	Underground sections and rooms which do not require class 1 or class 2.	The wall of the lining must be tight so that only isolated, locally restricted patches of moisture are to be seen. Restricted patches of moisture are areas at which a penetration of moisture could be registered. A sheet of blotting paper will discolour as it is soaked with water, but no trickling water is to penetrate the intrados.	0.4	0.1

Table 2-2 : Classification of watertightness by DEUTSCHE BAHN AG for their underground facilities[2].

It is not the purpose of this Study to define or recommend acceptable standards of water-tightness. It must be pointed out, however, that elimination of all leakages during the operating phase of a tunnel can be a lengthy and expensive process, and before proceeding with this work, the detailed requirements should be reviewed in relation to the needs of the tunnel environment, so that a reasonable objective can be defined. This may not be the same as the water-tightness criterion set at the design stage.

It is important in referring to leakage, to standardise on terminology to avoid misunderstanding. In this report, we have used the recommended definition of descriptive terms proposed by the UK Construction Industry Research and Information Association (CIRIA), in their 1979 Report on Tunnel Waterproofing with one additional term, "Past Moisture". These terms are listed and defined in Table 2-3. The term, "Past Moisture", was considered appropriate for inclusion to describe the circumstances where previous leakage is evident by staining of the tunnel lining or fittings. The stopping of the leakage may be the result of only a temporary change in the external environment of the tunnel and in such circumstances, it would be important to monitor the situation to ensure that the leakage does not recur. In some circumstances, the classification may need further expanding to accommodate for example, water entering under high pressure.

Leakage Description Term	Definition
Past Moisture (additional term – see Section 2.1)	Staining arising from former moisture
Damp Patch	Discolouration of part of the surface of a lining, moist to touch
Seep	Visible movement of a film of water across the surface
Standing Drop	A drop of water, which does not fall within a period of one minute.
Drip	Drops of water which fall at a rate of at least one drop per minute. (Note: one litre per day is three to four drops per minute)
Continuous Leak	A trickle or a jet of water. (Note: drops become a continuos trickle when they fall at a rate of about 300 drops per minute.)

Table 2-3 : Recommended definition of descriptive terms from CIRIA, London[3].

2.2 Structural Competence of the Tunnel and the External Environment

Water inflow can affect the tunnel structure and the surrounding environment in a number of ways. For example:

- By transportation of fine solids from the ground into the tunnel, causing blocked drains and, more importantly, voids around the tunnel and in the ground which could develop into serious lining support problems;
- By introducing chemical contaminants into the tunnel lining (sodium chloride is a common example), causing corrosion and degradation of the lining material; and
- By lowering the ground water table around the tunnel, resulting in consolidation of soils and settlement, affecting structures and utility services above and close to the tunnel.

The competence of the tunnel lining can also be affected or compromised by factors other than water leakage including:

- Sub-standard workmanship resulting in voids or laminations in the lining material or reduced cover to the steel reinforcement;
- Ageing and overall deterioration of the tunnel lining;
- Deterioration of the lining surface due to operating environments such as humidity and high traffic volumes and related exhaust fumes;
- Changes in stress in the tunnel lining due to changes in loadings; and
- Damage to the lining during erection causing cracking or spalling, which may lead to accelerated deterioration and potential failure.

If any of the above conditions exist, the objective of remedial work must be to eliminate them or to reduce their impact to safe and acceptable limits, but not before inspection, investigation and definition of the problem. It is clear that, in order to ensure that the structural integrity of the tunnel and the safety of the tunnel users are not compromised in anyway, a thorough definition of the problem, its causes and effects, must be established before a course of remedial action is decided upon.

This will require a careful inspection to be carried out by engineers who are familiar with the type of lining and usage of the tunnel in question and the possible effects of the leakages and/or degradation of the lining. Experienced personnel are required, so that the urgency of action can be properly assessed, the severity and consequences of a leak or lining damage can be evaluated, and proper action is implemented in a timely manner. The magnitude of the leakage may not always be indicative of the degree of damage to the liner, which can occur. For instance, a small continuous leak in a crack penetrating a concrete reinforced liner will cause extensive damage to the reinforcing over time. The deterioration of the lining formed by such a leak can be accelerated by the presence of stray electrical currents or salts in the groundwater. It should be noted that leakage into the liner may not be clearly visible from the interior of the lining. Therefore, linings should be inspected routinely as part of a well-planned inspection and preventive maintenance programme to detect any need for lining repairs.

This routine inspection may indicate the need for additional investigation and non-destructive testing. In this respect, the Report by the Working Group on Non-Destructive Testing Methods [4] will provide useful information.

A report on the inspection, investigation and testing should include the following information under the respective headings:

2.2.1 *General location of problems*

Plans and sections of the tunnel showing locations relative to topography, geological features, tunnel portals, and access shafts.

2.2.2 *Tunnel construction data*

Geology, groundwater, construction methods, problems experienced and any other pertinent construction related information.

2.2.3 *Details of tunnel lining*

Type of lining, dimensions, materials and specification, and waterproofing measures incorporated in the construction works (waterproof membranes, grouting etc.).

2.2.4 *Location and classification of damage.*

Record of visual surveys presented in a standardised format indicating position, nature and severity of damage, and if appropriate, a suggested method of repair. A useful standardised classification of leakage has been developed by CIRIA of the UK. This is referred to and expanded upon in Section 2.1 and Table 2-3. Depending upon the type of lining, leaks may occur at joints, cracks, honeycombing, spalling and in the case of unlined tunnels, at rock fissures etc., or by percolation through the mass of the lining. Such information should be carefully recorded. If joints or cracks are involved, widths and affected lengths should be recorded in each case. In the same way, boundaries of areas of percolation should be noted.

2.2.5 *Analysis of Damage*

In the case of leakage, chemical and biological analyses of the water or fluid by a laboratory should be undertaken. In some cases, including those not associated with leakage, it may be necessary to assess the overall competency of the lining by taking samples of the lining material and/or the application of non-destructive testing methods[4]. Damage to the lining caused by the development of uneven or excessive ground pressures will require reference to the original design and/or a structural analysis of the capacity of the in-situ lining; in some cases, both references are useful.

2.2.6 *Origin of Leakage*

This may seem obvious (e.g. ground water), but a leaking sewer, water main or underground storage tank may be responsible. This can usually be established from the chemical and biological analysis of the fluid.

2.2.7 *Effects of Leakage and Degradation*

The following may be involved:

- Staining, build-up of salts;
- Corrosion of fittings, including electrical and mechanical equipment;
- Erosion of internal structures;
- Degradation of tunnel lining due to erosion and corrosion of metallic elements, crystallisation of salts in lining mass, deterioration of the cementitious mortar in concrete and stone masonry or brick linings, and reduction in the strength or integrity of the lining;
- Transportation of solids (blocking of drains, forming of voids behind the lining);
- Lowering of the groundwater table (consolidation of ground, settlement of adjacent structures); and
- Frost damage arising from leakage.

The investigation report will typically consider all possible causes of the damage or defect with the overall objective being to assist in the choice of remedial methods and materials.

References:

[1] ITA Report, A. Haack, 1991: Water Leakages in Subsurface Facilities: Required Watertightness, Contractual matters, and Methods of Redevelopment, TUST, Vol. 6, No. 3, pp 273 – 282.

[2] DS 853, 1993. Eisenbahntunnel planen, bauen und instandhalten [Planning, building, and maintenance of Railway Tunnels], Karlsruhe: Deutsche Bahn AG.

[3] CIRIA, 1979. Report on Tunnel Waterproofing, London: CIRIA

[4] A. Haack, J. Schreyer, G. Jackel, 1995. State-of-the-Art of Non-Destructive Testing Methods for Determining the state of a Tunnel Lining. TUST Vol. 10, No. 4, pp. 413 – 431.

CHAPTER 3

CATEGORIES OF REPAIR METHODS

3.1 Introduction

The purpose of categorising repair methods for treating leakage or damage not related to leakage is to provide an easy point of reference for analysing the various case histories of repairs and/or prescribing appropriate methods of repair. In the case of leakage, the categories refer directly to the type of repair method adopted, while in the case of damage other than leakage, the categories refer to the use of the tunnel. The reason for the different approaches in categorisation is due to the different primary factors involved.

In the case of leakage a primary differentiating factor in treating the leakage is the method of repair rather than the intensity of the leakage. For example a standing drop in a tunnel containing sensitive electrical/electronic equipment may require to be treated in the same way as a continuous leak in a railway tunnel; both may require lining reinstatement. The type of repair may therefore not be related to the intensity or type of leakage.

In the case of defects other than leakage, the cause of the damage and the type of repair appropriate is to a large extent related to the use of the tunnel, which becomes the primary differentiating factor.

This is further elaborated upon in the following sections.

3.2 Leak Sealing Methods

Leakage into a tunnel is the principal cause for the deterioration of tunnel liners and its proper control is paramount in the protection of the tunnel structure. The following four categories of the methods of repairs required to control or eliminate the leakage are presented:

Surface Sealing Methods: Applied to the inner surface of the tunnel lining, becoming a part of the lining surface.

Conduction Methods: Applied at the intrados of the tunnel lining, where it is acceptable to allow controlled drainage or channelling of the water towards the tunnel invert and along the tunnel towards a sump for disposal.

Lining reinstatement: Measures taken to establish or re-establish the impermeability of the tunnel lining.

Elimination at Source: Measures undertaken outside the tunnel lining, within the surrounding ground mass.

It is recognised that the categories of methods defined above may sometimes be used in conjunction with one another and additional methods, developed for specific conditions, may not be fully identified with one category or another. Leak sealing methods will also vary depending upon the type of lining. The categorisation, however, will facilitate the process of selection of appropriate remedial measures by providing a point of reference.

An additional category relating more to the prevention rather than the repair of damage caused by water intrusion comprises the use of heat to reduce thermal activity and thereby reduce or eliminate frost damage.

Surface sealing methods are only appropriate to the sealing of very low rates of leakage. They typically involve the simple application of proprietary products, albeit in strict accordance with the manufacturer's specifications. The other three categories of repair methods are more intricate in their application, requiring significant skill and expertise; these are considered in some detail in later sections of the report.

3.3 Repair Methods for Damage Other Than Leakage

In analysing the case histories provided by the Member Nations of ITA, it was apparent that there were typical types of damage related to the various operational uses of the tunnel. For example, in road tunnels and in newly built concrete lined rail tunnels, carbonation of the concrete lining is a major source of damage; in older rail tunnels ageing is a major consideration; while in water tunnels, scouring and corrosion of the lining is prevalent.

Therefore in consideration of damage caused other than by leakage, rather than categorising the repair methods, the case histories were categorised in terms of operational use of the tunnel and type of lining. From this it is possible to draw conclusions on the effectiveness of various repair methods.

Notwithstanding, it is obvious that damage to the structures of tunnels and similar underground facilities are aggravated by the presence of water of any kind in the surrounding ground mass of the structure under investigation. In cases where leakage becomes the predominant concern, the categorisation of the repair method would be in terms of the leak sealing method selected and as described in Section 3.2.

CHAPTER 4

CONDUCTION OF WATER LEAKAGE ON LINING SURFACE AND DISPOSAL

4.1 Introduction

This method of repair involves the treatment of leakage through a tunnel lining by channelling, drainage and disposal of the water. It can be used where the overall integrity of the lining is not compromised by the leakage and the operational effectiveness of the tunnel is not unduly affected by the installation and maintenance of the waterproofing system.

In the consideration of this repair method, by which water leakage is conducted in a controlled manner towards the invert, where it is channelled to a sump for disposal, twenty-four case histories have been taken into account. The case histories have been divided into three homogenous types:

Type A	**Channelling of Leakage Water** 9 Cases : CU1, F5, I4, I8, J1, J2, J3, J4, J22
Type B	**Inner Shell** 10 Cases : F1, F4, F6, F7, F11, F12, I9, J18, J27, US12
Type C	**Sprayed Membrane or Inner Lining** 5 Cases : I3, I6, J20, US3, US 7

Each of these types of treatment are described and analysed in the following sections and are illustrated in diagrams at the end of each of the respective sections. The Study assesses the general and specific characteristics, qualities, cost and precautions that must be taken into account for each type to determine the most appropriate repair measure.

In all of these types of surface treatment, attention should be given to the following:-

- Protection of the waterproofing system against damage caused by vehicle impact and/or vandalism;
- Protection in case of fire such that at least those systems, which cannot be easily accessed for repair, remain efficient;
- The avoidance of fire spread and production of noxious gases in cases of combustion of unsuitable waterproofing materials (e.g. PVC) is provided for; and
- Insulation against cold of those installations subject to freezing temperature, which may cause the drained water to freeze, giving rise to unacceptable pressure and weight build-up in the system, and ultimate collapse.

Each of the types of treatment requires the use of techniques, machinery or materials not generally used on civil engineering construction sites. It is therefore recommended that trained and experienced personnel are used, perhaps utilising a specialist company. Effective good quality control procedures should also be enforced. Experience has shown that in circumstances where these criteria are adequately provided for and where the installations are well maintained, the waterproofing systems are efficient and long-lasting.

4.2 Type A : Channelling of Drainage Water Leakage

4.2.1 *General Characteristics*

The technique involves the installation of strips of drains and gutters of various materials (steel, fibreglass, flexible or rigid PVC) at leaking cracks or joints in the tunnel, to create a channel to collect the water and conduct it to the drains at the tunnel invert. The sealing of the edges of the waterproofing drains and gutters is achieved either by mechanical compression and caulking compounds or by the use of adhesives. The joints in the channel are sealed by resin or welding as appropriate. It should be noted that PVC and similar materials give off toxic gases when burned and cannot be recommended; their use in a number of countries is prohibited. In those countries, where their use is permitted, it is highly recommended that the approval of local fire protection and safety authorities is obtained prior to their installation underground.

4.2.2 *Special Characteristics*

Cases I4 and J22 incorporate radial drainage pipes drilled through the lining into the surrounding ground and provided with strainers to filter the water and prevent blockage of the drain. The collected water is conducted into the tunnel through the lining. This method is applicable only to tunnel structures where the primary waterproofing is provided by the concrete lining itself and a waterproofing membrane has not been installed.

4.2.3 *Construction*

These techniques can be installed without major difficulty, providing the areas to be treated are localised. The selection of which system is to be used is site specific and depends on the availability of suitable materials and acquired experience and expertise. These installations can be performed usually without interfering significantly with the tunnel use; often the work is performed during night-time hours, when the highway or transit system can be shut down with minimal interference to the public.

4.2.4 *Effectiveness*

The effectiveness of the system is primarily dependent upon the competency of the sealing of the gutter and drain joints and edges. The difficulty is to quantify the extent of the water inflows, which may not be seen in their entirety at any time due to seasonal variations. It is generally necessary to carry out numerous inspections over a period of one to three years and adding additional gutter and drain installations as required. These channels are well suited for the treatment of radial cracks and joints, but are not suitable for horizontal or acutely inclined cracks,and which should be grouted. The channels may become blocked as noted in Section 4.2.5.

4.2.5 *Durability*

The materials used are non-oxidising, corrosion-free and are stable, and therefore are durable and long lasting. Dependent upon the quality and sediment content of the drained water, the channels may become obstructed by fines or calcitic deposits. In these cases, provisions must be made for larger channels with a larger flowing cross section. At the base of the sidewalls, the gutters and drains are often unprotected and may be subject to impact damage from vehicles in road tunnels.

This method of drainage is particularly susceptible to damage from cold weather and fire. In the case of installations exposed to freezing temperatures, the water in the drains and gutters may freeze, causing uplift or bursting; insulation of the installation will be necessary. In a severe fire, it can be expected that the installation will be destroyed and require to be replaced. Careful consideration should be given to the use of materials, which produce noxious gases in cases of fire. Such materials should be avoided in underground installations open to the public and wherever personnel admittance is possible.

Adhesives used for securing the edges of the drainage channels can be subject to water vapour uplift (seasonal breathing through brickwork and pores in concrete), which may cause the channels to come adrift. In these circumstances supplementary or alternative attachment by mechanical means, along with caulking and sealing, is recommended.

4.2.6 *Inspection and Maintenance*

Generally these gutters and drains cannot be removed for inspection and maintenance unless the installation comprises a mechanical assembly designed for this purpose. It should be noted that Case J22 uses drains provided with an inner permeable geotextile (inner sock) as a strainer or filter, on which concretions crystallise; this sock can be removed and replaced easily. Case J4 provides for a channel with a cleaning hole equipped with a sealing plug for inspection and cleaning purposes.

It is recommended that the channels and their access ports should be of sufficient diameter to facilitate maintenance operations. The German Railway Company, Deutsche Bahn AG, specifies that the channels or ducts should have a diameter of 100mm or more and, at a height of 1.5m, a T-piece with a plug of a minimum diameter of 100mm should be installed for inspection and maintenance of the system[1].

4.2.7 *Aesthetics*

The gutters and drains protrude from the inner tunnel shell. They are generally highly visible and spoil the overall appearance of the tunnel structure, particularly in public areas. In addition, they impede sidewall cleaning operations in transport tunnels. The only exception to this is Case I4, where the drain is installed in a channel formed in the surface of the lining.

4.2.8 *Cost*

The cost effectiveness of waterproofing a tunnel with this system increases as the ratio of the length of cracks to be treated compared to the total surface of the liner decreases. In France, the average cost is about US$ 150 to 200 per linear metre, while in the United States typical costs vary from $75 to $250 per linear metre (based on 1990 costs). It should be noted that the unit cost per metre is dependent on the site access, type of materials, work schedule restraints and the local labour market. Therefore, cost comparisons of alternative repair methods should be made for each project and evaluated on an individual basis.

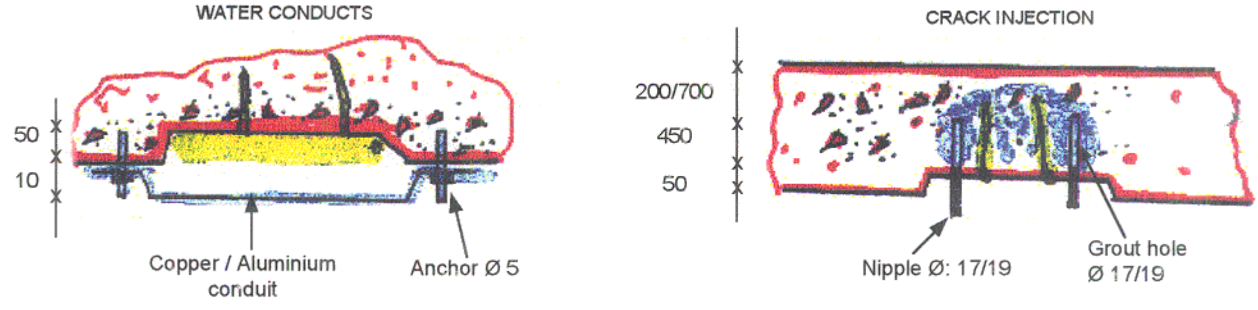
4.2.9 *Conclusions*

In general, the application of these techniques is simple and without any major difficulty, provided that the gutter and drain specifications are observed. The efficiency of the system can be improved by:

- Proper sizing of channel cross sections to provide for the buildup of concretions (calcitic deposits) and the sedimentation of solids in the drain water;
- Suitable selection of materials and location of the gutter and drains for the conditions encountered;
- Providing for easy maintenance of the drain for long term effectiveness;
- Limiting the use of gutters and drains in horizontal locations; and
- Consideration of the use of radial drains through the tunnel liner where leakage through the liner walls is encountered.

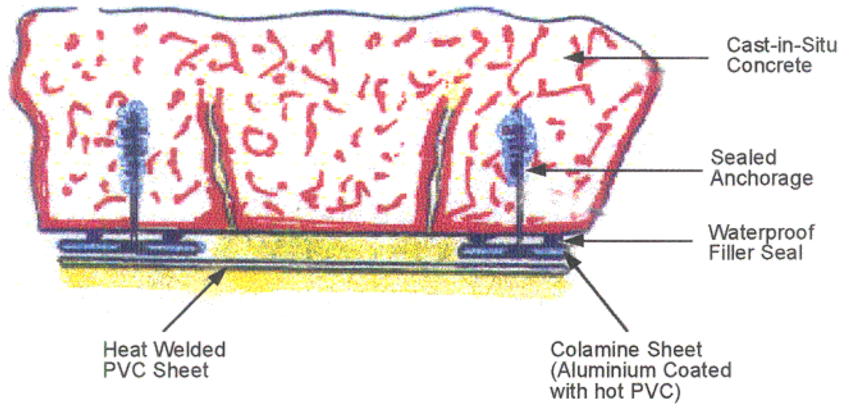
For further information on this method of water proofing, please refer to the following diagrams showing examples of installations for Type A, Channelling of Leakage Water.

TYPE A - CHANNELLING OF LEAKAGE WATER



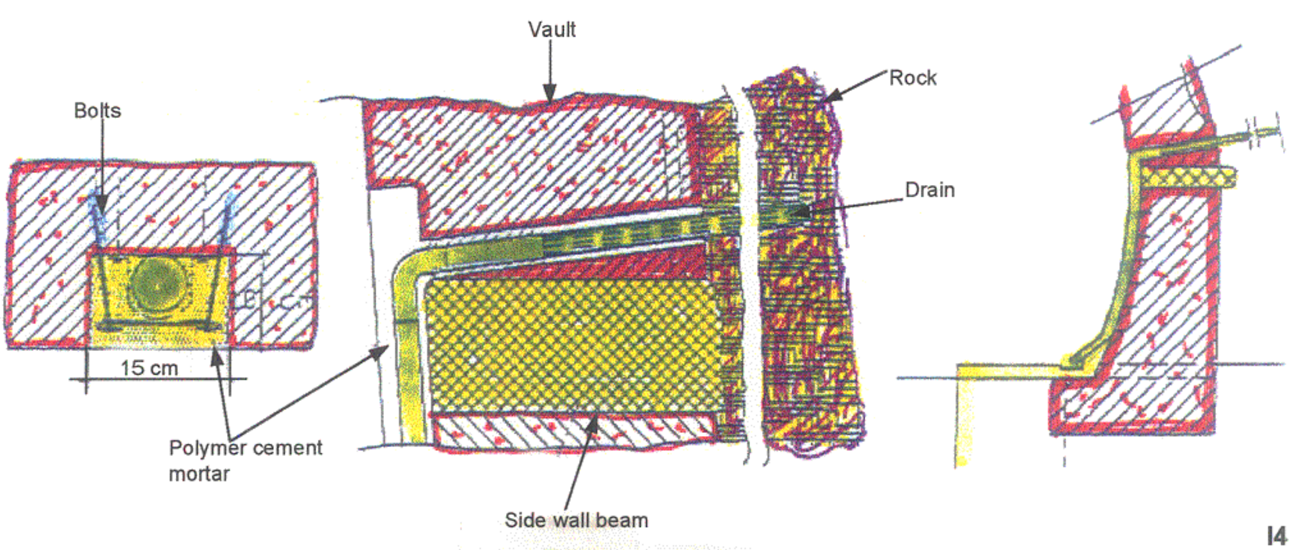
(All dimensions are in millimetres and are not to scale)

CU1



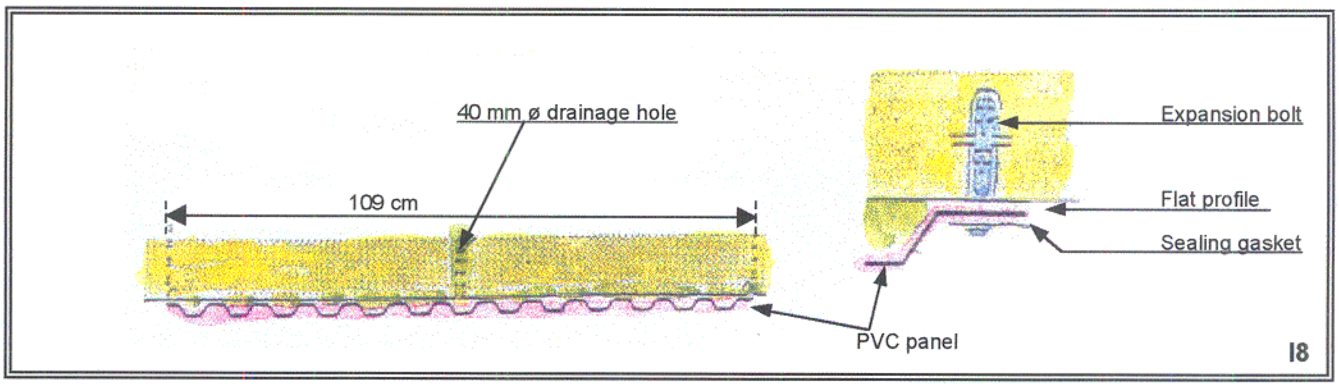
BRS Patent

F5

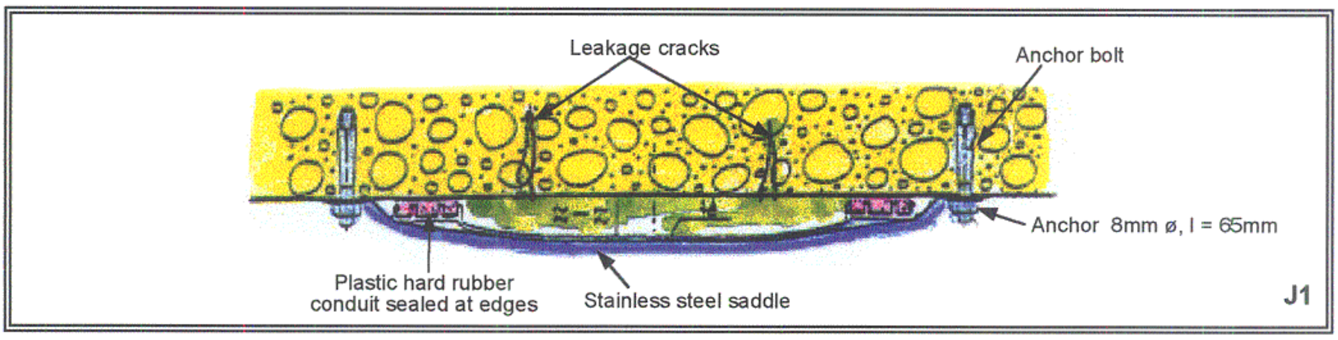


I4

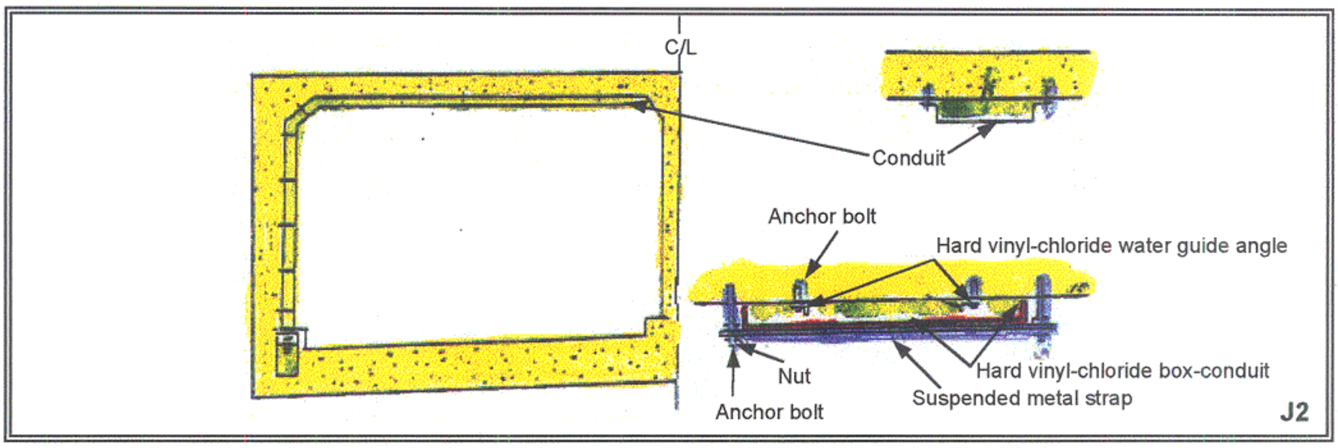
TYPE A - CHANNELLING OF LEAKAGE WATER



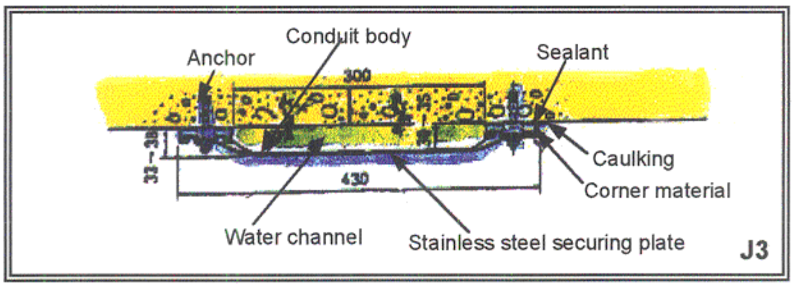
I8



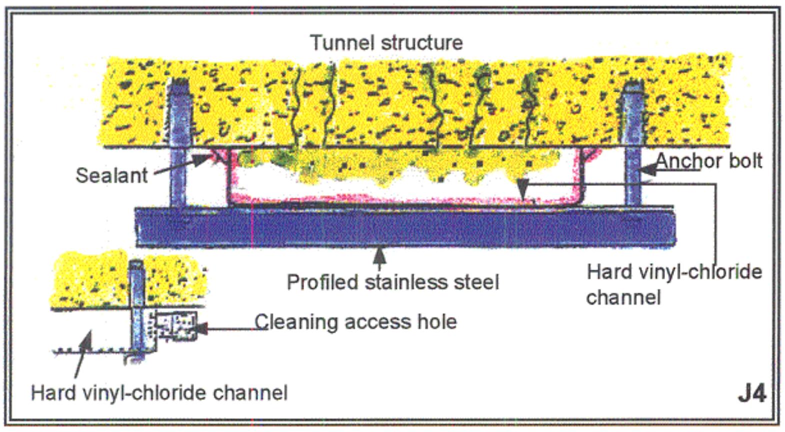
J1



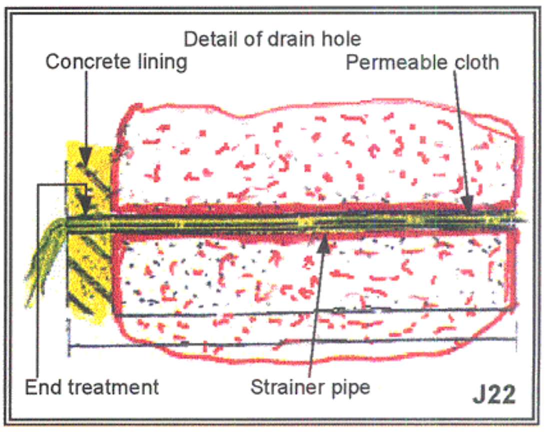
J2



J3



J4



J22

4.3 Type B : Inner Shells

4.3.1 *General Characteristics*

This technique uses a waterproof sheet membrane fixed to the existing intrados (rough rock, shotcrete, masonry or in-situ concrete), which is subject to leakage through a network of dripping cracks or joints; the waterproof membrane drains the water towards the tunnel invert and the collecting system. The synthetic membrane made of PVC, HDPE or latticed foam (the lattice foam additionally provides thermal insulation to prevent ice from forming behind the waterproofing) is somewhat fragile and must be protected against mechanical damage (e.g. vehicle collision and vandalism) and thermal effects (fire –-frost). The protection is provided by means of an interior shell, comprising in-situ cast concrete, shotcrete or a prefabricated shell. In cases of exposure to severe frost, an insulation sheet should also be incorporated into or fixed to the waterproof membrane system.

4.3.2 *Special Characteristics*

The US12 case utilises a corrugated synthetic or sheet metal material placed around the excavation in elements similarly to tiles on a roof, in order to guide water towards the base of the sidewall. This technique raises difficult maintenance problems (brittleness – corrosion) and has poor aesthetics; its use should be reserved for small rural tunnels with light traffic.

4.3.3 *Construction*

PVC or HDPE waterproofing membrane should be fixed onto the intrados without perforating, which may otherwise give rise to subsequent leakage. This can be achieved (as for the construction of new tunnels) by heat-welding the sheet onto synthetic washers, the latter being fixed onto the tunnel intrados by mechanical nailing prior to installing the membrane.

If latticed or semi-rigid foams are used, they may be fixed by anchors passing through the membrane, provided the waterproofing is maintained at each perforation by a mechanical device or sealing of attached elements. These operations are complex and require skilled workers and a high standard of workmanship.

The material for construction of the inner protective shell must address the following issues:-

- *Shotcrete :* It is difficult to achieve good bond between the shotcrete and the synthetic sheet forming the shell. The shotcrete must be rapid setting using accelerators and/or special rapid hardening cements and must be applied with a high degree of expertise.

- *Frame Structures :* The minimum thickness of concrete frames are about 40cm, which may lead to an unacceptable loss of tunnel clearances in existing tunnels. In addition, the high cost of a temporary heavy steel framework is not cost effective for tunnels less than 300 to 400m in length. Lastly, the installation of this framework requires the closing of at least one lane of traffic, which is often not possible in urban environments where diversion of traffic cannot be provided for in the tunnel. Frame structures are usually unacceptable for rail tunnels due to the strict requirements for operating clearances for the rolling stock, and the general lack of alternative routes for the rail traffic.

- *Prefabricated Concrete Elements* : Prefabricated or precast concrete elements provide excellent quality control during fabrication and provide very high strength permanent liners. These elements require heavy construction equipment to handle and are difficult to install in the typically restricted construction window provided by most tunnel operators, during which time total closure of the tunnel is required. This system is best performed with total tunnel closure for the entire construction period, with no returning of the tunnel to service until the project is complete. The cost of this method is very high due to the requirements for setting up of a prefabricating plant, tunnel closure, heavy construction equipment, and extensive measures for diversion of traffic.

4.3.4 *Effectiveness*

These systems are very efficient for the whole drained surface, provided that the waterproofing membrane is not perforated accidentally during installation and provided that adequate quality control measures are implemented, particularly with respect to the sealing and heat-welding of the elements of the membrane. These systems must be protected from fire, depending on the flammability of the membrane materials used. The best method of protecting the membrane from fire is to use a cementitious material to provide an acceptable fire rating, as determined by the appropriate authorities.

Dependent upon the quality of the drained water, settlements and solutes could block the drainage collector system. Refer to Sections 4.3.5 and 4.3.6 in this regard.

4.3.5 *Durability*

When materials are used, which are able to withstand the operating environment in road tunnels, this technique offers a good guarantee of long time durability. Efficiency will be enhanced by placing a porous material (e.g. alveolar geotextile) between the membrane and the existing intrados, which provides an ample cross-sectional area for water drainage. The same effect can be achieved by using a membrane fitted with studs, which act as spacers and form channels for the water to flow through. Various heights of the studs can be specified to accommodate different water inflow conditions.

The drains, collecting the water from the water proofing membrane, may become obstructed by a build-up of calcitic deposits and sediment. The cross-section of the drains should make allowance for this and provision should be made for cleaning and maintenance.

The waterproof membranes are susceptible to damage from fire and protection must be provided. Refer to Section 4.3.4 in this regard.

4.3.6 *Inspection and Maintenance*

These systems, with the exception of the water collecting and disposal system (refer to 4.3.5), cannot be inspected and require minimal maintenance. The drainage collector system is generally placed under the sidewalk at the footwall, or in an equally accessible location which, can be inspected and maintained without difficulty, if they are designed and installed properly. However, it should be noted that in many cases in the past the collector design has not provided for maintenance and the drainage system has become blocked and ineffective.

4.3.7 *Aesthetics*

These techniques generally provide an aesthetically pleasing geometrical and smooth internal lining. Furthermore, the complete waterproofing system avoids staining and deposits associated with drips and general water ingress.

4.3.8 *Cost*

The cost varies significantly dependent upon the particular site conditions, the measures to be implemented to maintain traffic flow during installation, the importance of providing a surface with a good aesthetic appearance, operating conditions to be catered for, etc. The cost for France can range from US$ 250 to US$ 500 per sq.m (1998 prices). Consequently, the installation conditions must be carefully assessed before deciding to use these techniques. The technique is generally cost effective for tunnels with heavy traffic and with widespread cracking and water ingress.

4.3.9 *Conclusions*

For these techniques to be effective, they must be meticulously applied with appropriate specifications and proper supervision and inspection during the installation. The selection of the proper system is site dependent and must satisfy the requirements of the operator and the physical environment of the tunnel. In addition to the treatment of water inflows, this technique improves the tunnel appearance and the comfort of the users.

4.3.10 *Innovative Experiences*

These are the new F11 and F12 cases. After experimentation on prototypes, strength test and various research works, CETu, in co-operation with manufacturers and contractors, has developed a concept of a thin, waterproof, free-standing and independent shell, which provides:

- A total waterproofing system (with or without reinforced thermal insulation) protected by a heat-welded sheet protected by shotcrete;

- A total shotcrete or sprayed concrete thickness of the shell of between 10 and 30cm, depending on the application. This allows, in lined tunnels, a limited reduction in the cross-section of the tunnel. In unlined tunnels with significant overbreak, the shotcrete or concrete quantities can be limited to an absolute minimum requirement, while retaining joints and voids that will improve thermal insulation and provide passage for inspection of the extrados of the shell through access hatches;

- A lining with a controlled geometry which will improves the tunnel appearance; and

- Minimal tunnel closure and maintenance of traffic flow to one lane, when it is impossible to close the tunnel during the installation.

The basic principle is the construction of a shotcrete or sprayed concrete shell, which is adequately reinforced and supported, so that it is free standing and able to support the dead load of the uncured shotcrete without deformation.

This shell provides primary support to the waterproofing system, comprising an outer layer made up of an impermeable membrane sheet or latticed foam reinforced on both sides by plant-thermosealed synthetic felt, which serves as a surface on which the shotcrete is sprayed. These structures, which are easily damaged by collision from vehicles, are placed on reinforced concrete, shock-resistant substructures of about 2m in height, which have on their outer side, waterproofing and drainage facilities to collect and transport water to a drain collector system under the sidewalk.

Two different methods for controlling leakage have been applied in French tunnels since 1994, viz:

i) Case F11: the structure is made of lattice girders and conventional steel reinforcement, assembled outside the tunnel in 8 to 10m long modules. These modules support the waterproofing system fixed on the extrados. The modules are transported inside the tunnel, attached to the concrete substructures and to each other and shotcrete is then sprayed onto the inside surface.

   This method allowed for a relatively unrestricted traffic flow during the work. The tunnel was closed for only a part of the night for transporting and placing the modules.

ii) Case F12: the structures is made of three dimensional latticed reinforcing panels reinforced by pre-compressed micro-girders, which are either supported on the existing tunnel intrados or on specially designed concrete abutments in areas of significant overbreak.

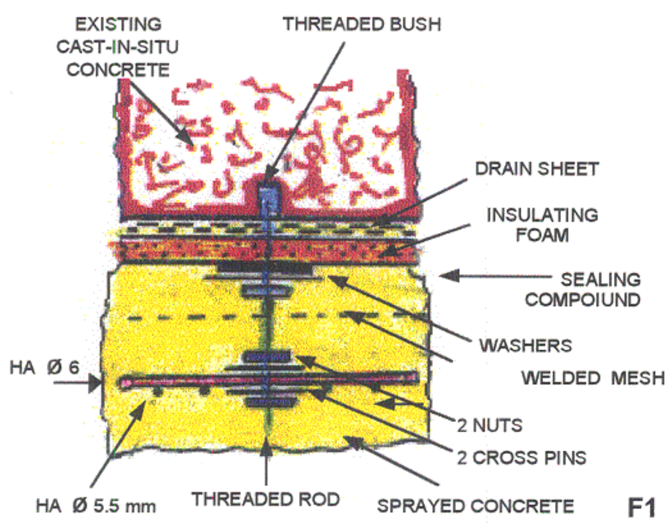
   The waterproofing system is placed on the outside of these structures. The low weight of the various elements, manufactured to the required thickness and curved according to the required intrados profile, allows them to be placed in the tunnel on a formed concrete substructure by means of a travelling gantry which makes it possible to maintain traffic flow in one lane. Once erected the structure is shotcreted.

   This method allowed a tunnel to be waterproofed with minimal traffic diversion, allowing the passage of lorries (width for traffic passage was 4.30m), where closure of the tunnel was not possible.

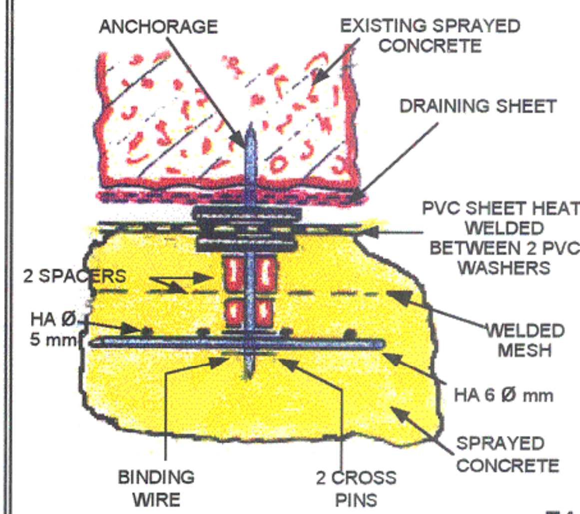
In both these cases, the thin shells were quite effective. The cost for lengths under 150m is about US$200 per sq. m, which is up to 50% of the cost for the reinforced concrete shell (refer to Section 4.3.8).

For further information on these repair systems, including both the application to the tunnel intrados and the free standing shell, please refer to the following diagrams for Type B – Inner Shell.

TYPE B - INNER SHELL



F1



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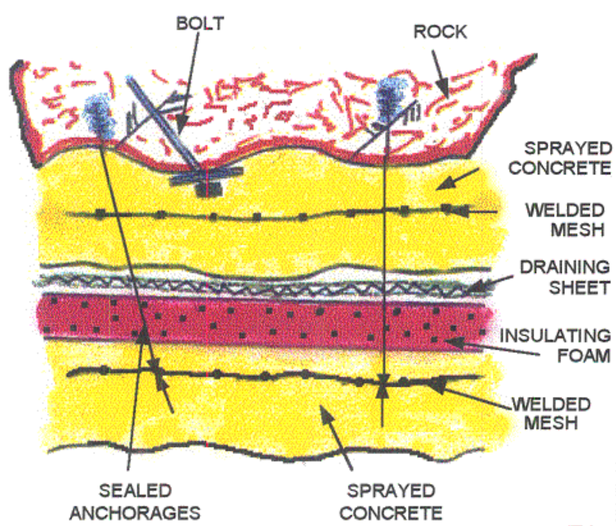

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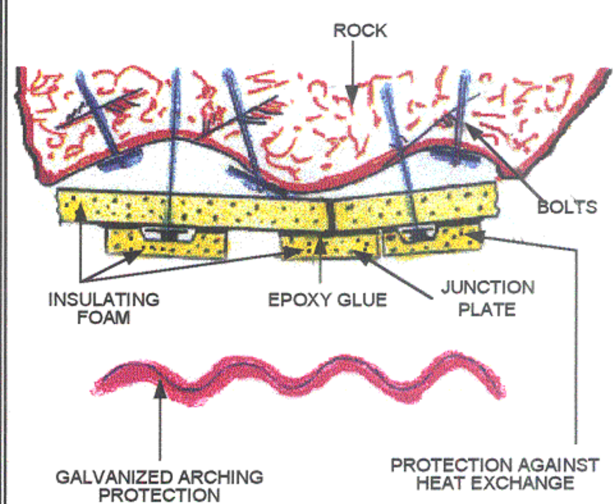

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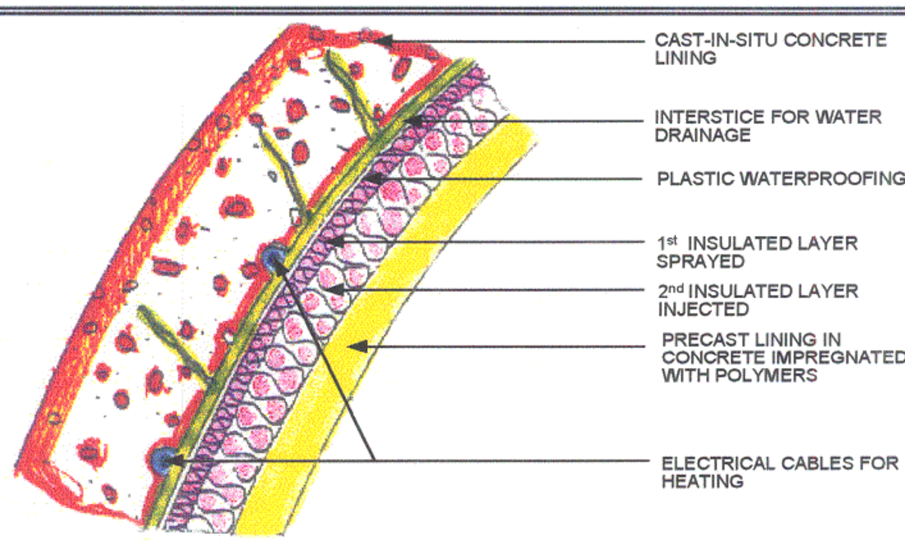

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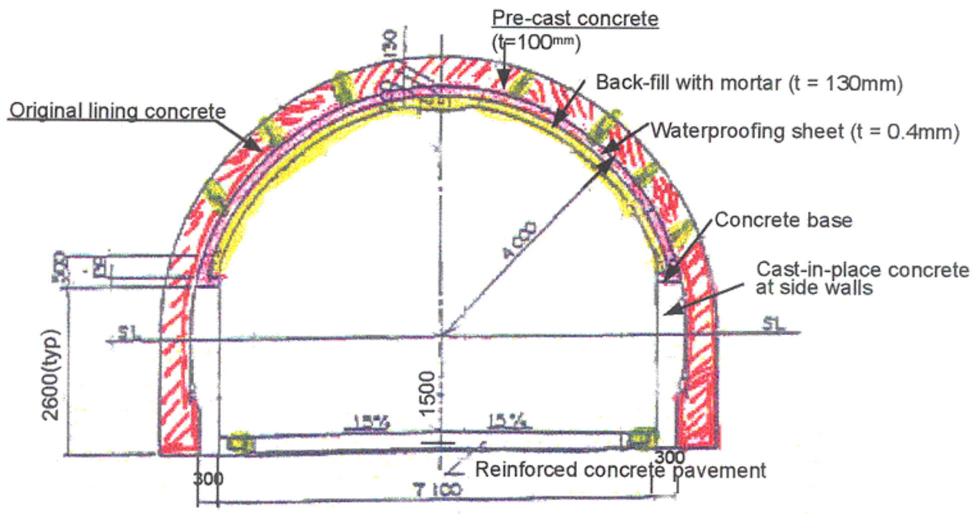
TYPE B - INNER SHELL



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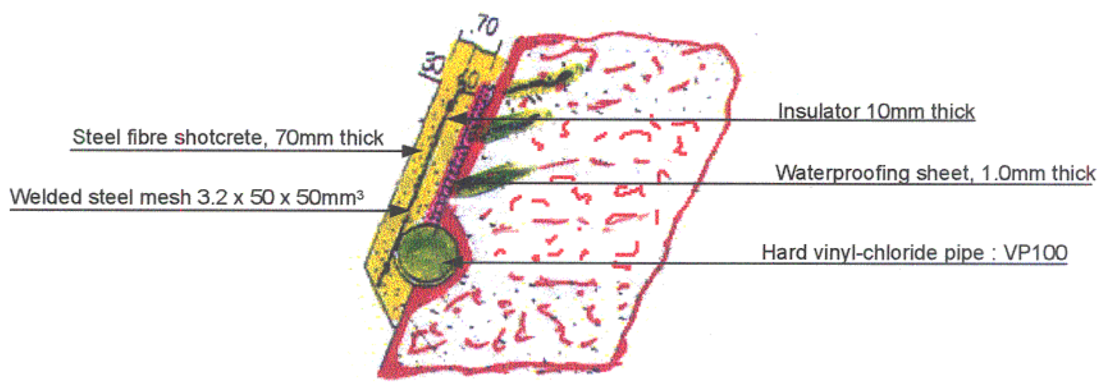
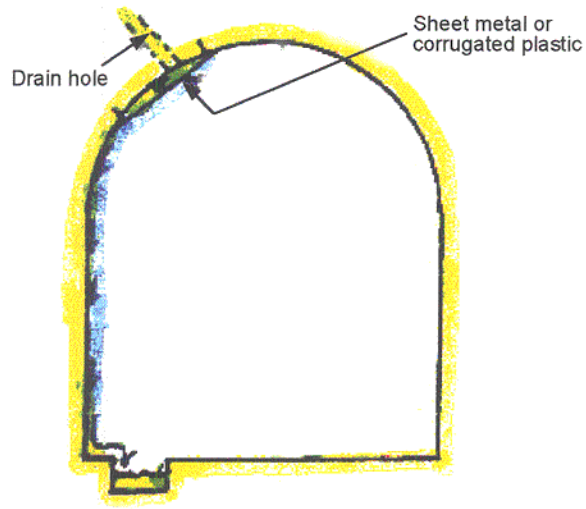


Detail of part (a) of the cross-section

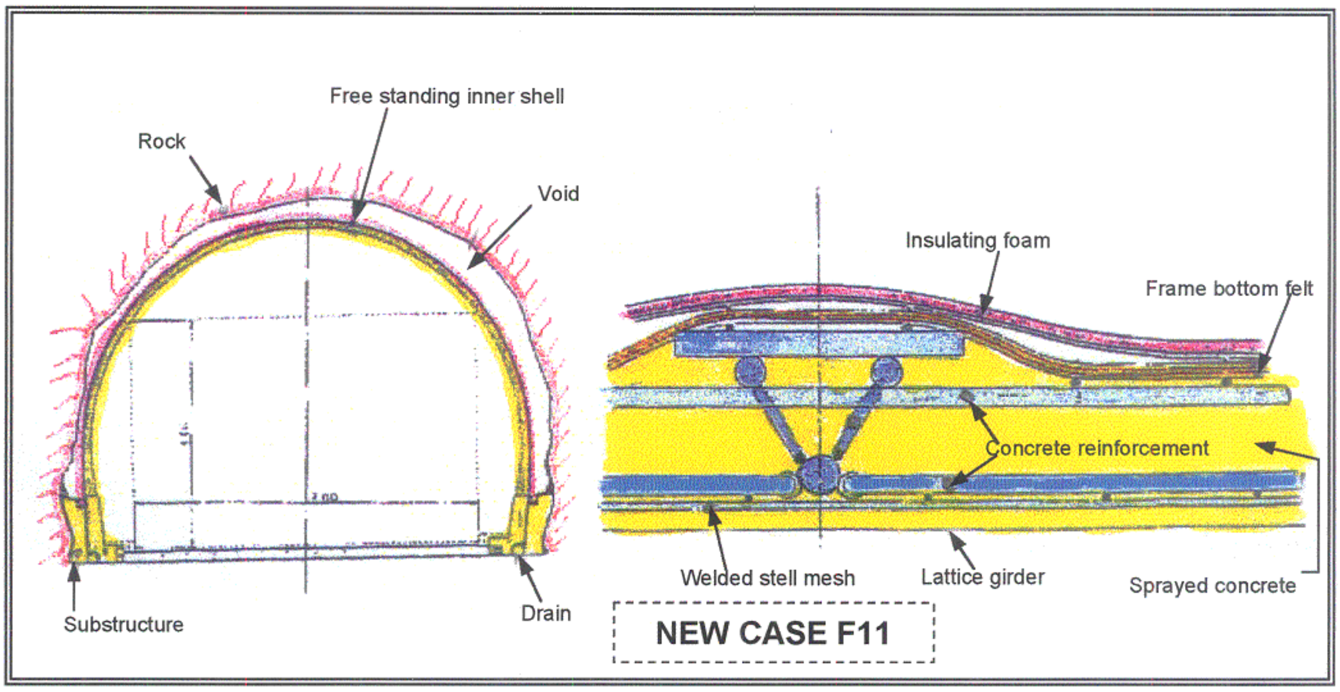
J27

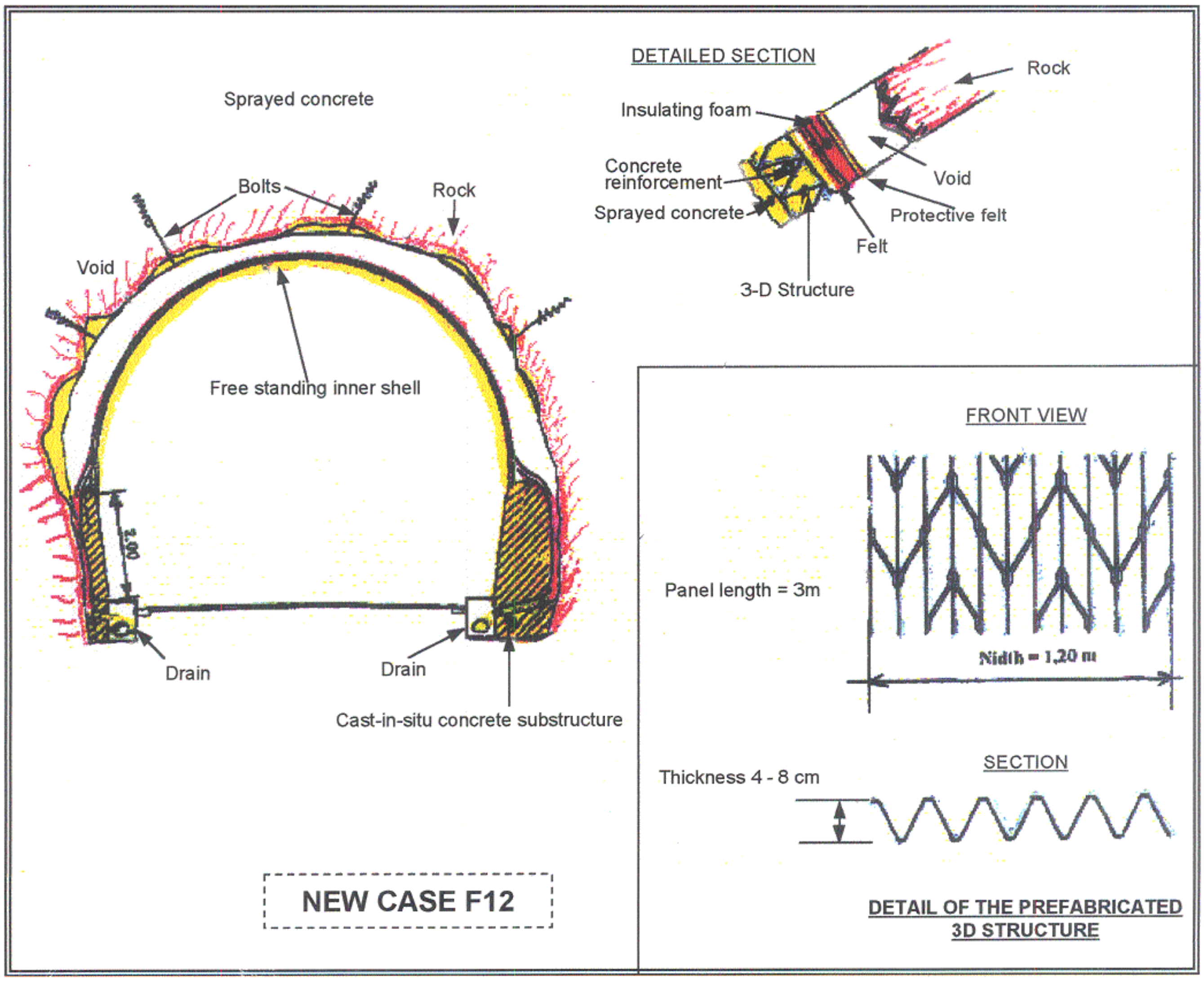


(graphic illustration)

US12

TYPE B - INNER SHELL (FREE STANDING)





4.4 Type C : Sprayed Membrane or Inner Protective Lining

4.4.1 *General Characteristics*

These techniques comprise the spraying of special mortars, reinforced by fibres or welded mesh fixed to the existing liner. The degree of waterproofing results from the properties of the mortar itself. This is achieved by the use of polymers and crystalline compounds that react with the free lime in the mortar to produce a reduced pore size in the shotcrete or sprayed concrete, which inhibits the passage of water. The reinforcement and the mortar itself are designed to limit cracking during curing and to provide some flexibility to accommodate active crack movements. Sealing capability of the liner is often supplemented by injections of particle and chemical grouts into the interface between the existing liner and the shotcrete; the shotcrete surface can also be coated with a mineralizer to reduce porosity.

4.4.2 *Construction*

The application of these methods is not particularly difficult .It can be undertaken with minimal diversion of traffic and without closing the tunnel. The major difficulty lies in the formulation of the mortar mixture, which must be sufficiently dense to reduce the migration of water and to control shrinkage cracking. Leaking cracks or joints are sealed, as a separate operation, by the injection of particle or chemical grouts into the liner at controlled injection pressures to prevent spalling or damage to the existing liner (refer to Chapter 6 for further information on grouting procedures). In all instances the application of the mortar must be performed on dry surfaces, after the sealing-off of all water inflow from the leaking cracks or joints has been completed. Failure to control the leakage prior to the spraying of the mortar will result in loss of bond and extreme difficulty in achieving adhesion and build-up of an adequate thickness of the mortar. In cases of significant local water inflows, which cannot be sealed by injection, the inflows must be diverted away from the work to prevent the washing out or dilution of the mortar.

Any supplementary sealing work involving injections of grouts into the interface between the mortar and the existing tunnel lining must be carefully controlled in terms of injection pressure to prevent loss of adherence of the membrane.

4.4.3 *Effectiveness*

These systems are efficient only on structures where the water inflow is either very low (seep or standing drop) and, in the case of active leaks, where these can be sealed by injection of grouts. In the latter circumstances, the proper application of the grouting programme in conjunction with the application of the special mortars can provide a long term satisfactory repair of the structure. A complete sealing of the structure is difficult to achieve, particularly where localised water inflows can occur. If leakage cannot be tolerated in any form, an alternative method of repair would be recommended.

4.4.4 *Durability*

The inner lining must be shrinkage controlled during application to reduce micro-cracking. Failure to limit the micro-cracking due to shrinkage will result in damage to the liner over the long term in areas where the tunnel is exposed to frost-thaw cycles. Such cracking can lead to the deterioration and loss of the waterproofing function in the medium to long term. Furthermore, these inner linings can be sensitive to external water pressure arising outside the liner during periods of exceptional flow due to seasonal changes. As stated above, it is critical to eliminate water inflow through the liner.

4.4.5 *Inspection and Maintenance*

Periodic inspections can be made to detect damaged areas, and repairs are possible. Repairs are easily performed using similar materials and equipment to that used for the original work.

4.4.6 *Aesthetics*

The untreated shotcrete provides an acceptable rough gun finish for standard tunnel line sections. In public areas such as stations and in some highway tunnels a steel trowel or wood float may be applied to give a more desirable finish. The coating minimally protrudes into the interior space of the tunnel and can follow the contour of the original tunnel profile. If the waterproofing function is compromised and leakage reoccurs, water staining and deposits will appear.

4.4.7 *Cost*

The cost can vary considerably according to the formulation of mortar, which can incorporate expensive components or additives to improve the membrane performances. The cost per square metre ranges from US$ 200 to US$ 400, according to the mortar formula and application conditions.

4.4.8 *Conclusions*

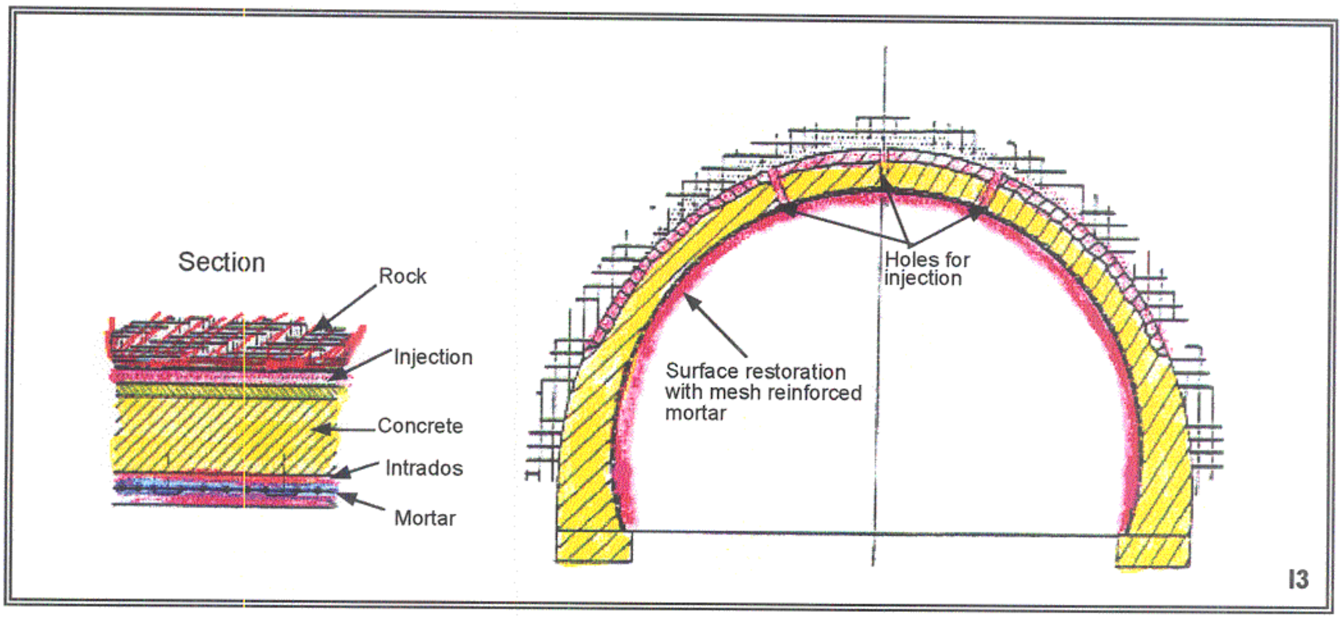
This technique requires detailed inspection of the existing conditions, the selection of a suitable mortar, and the use of qualified specialist applicators to achieve acceptable results. In order to be effective, all leaks must be sealed prior to the application of the shotcrete with a suitable chemical or particle grout. Proper selection and application of the materials will provide a suitable medium to long-term repair.

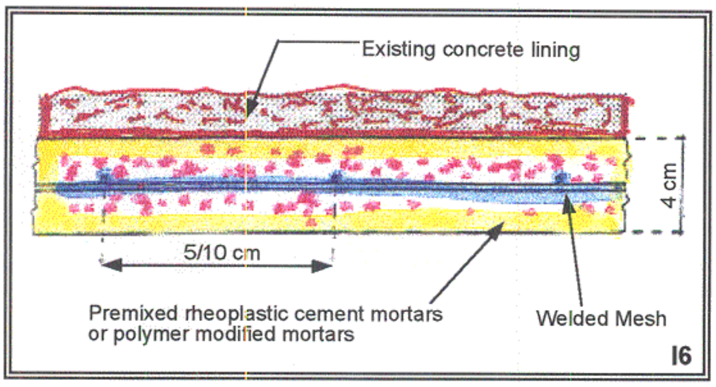
For further information on this method of water proofing, please refer to the following diagrams showing typical examples for Type C-Sprayed Membrane or Inner Lining.

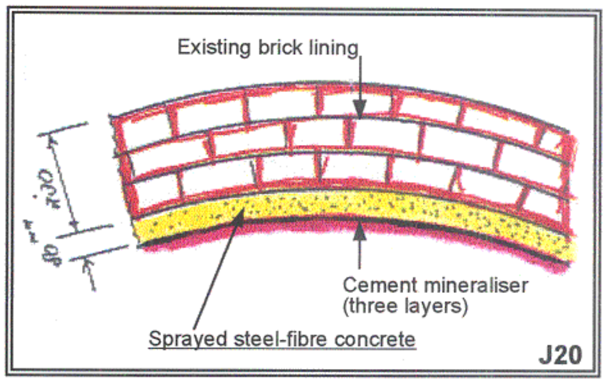
References:

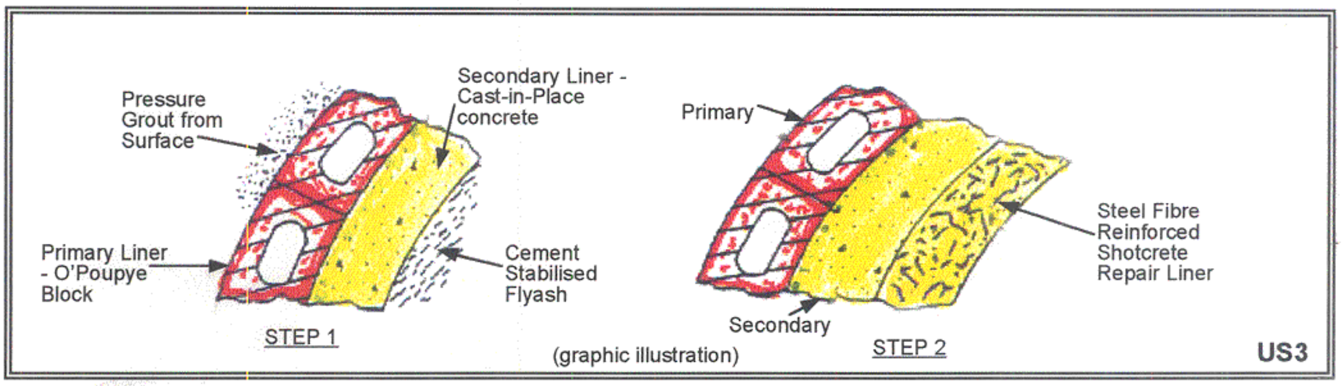
[1] DS 853, 1993. Eisenbahntunnel planen, bauen und instandhalten [Planning, building, and maintenance of Railway Tunnels], Anhang 16 [supplement 16], Paragraph 10 [paragraph 10], Karlsruhe: Deutsche Bahn AG.

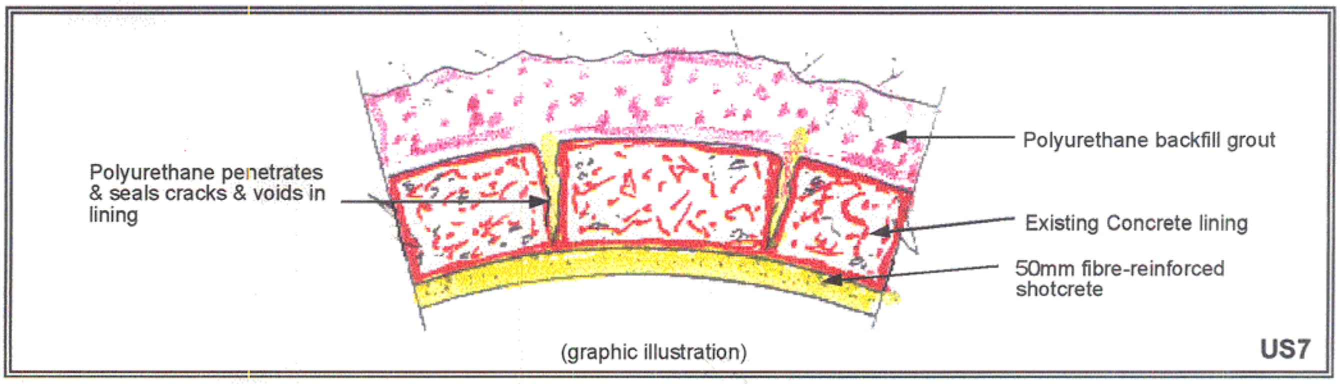
TYPE C - SPRAYED MEMBRANE OR INNER LINING











CHAPTER 5

TUNNEL LINER REINSTATEMENT (EXCLUDING THE TREATMENT OF LEAKAGE)

5.1 Introduction

The reinstatement of tunnel liners, as considered in this chapter, is the undertaking of repairs to restore the structural integrity of a liner, which has deteriorated as a result of factors such as environmental effects, operational condition, poor construction techniques and ageing. The reinstatement of tunnel liners affected by water leakage is described in Chapter 6. However, it is recognised that liner reinstatement often involves the sealing of water leakage before proceeding with the repair in accordance with the guidelines described in this chapter. The two types of tunnel liners reinstatement (one excluding dealing with water leakage and the other including leakage) cannot therefore be considered totally exclusive of each other. There is therefore some inevitable overlap between Chapters 5 and 6, although this has been purposefully kept to a minimum.

The deterioration of the lining often manifests itself in the form of concrete spalling, delamination, loss of strength, and in the case of steel liners loss of cross section, enbrittlement, and corrosion. These defects in the liner can affect the service or use of the tunnel, and if left unchecked, can result in total loss of use of the tunnel and severe economic consequences for the area served by the tunnel system. The inspection of the tunnel liner must be comprehensive, fully identifying the nature of the defects, determining the causes and recommending a suitable method of repair. Ideally, the repair should be durable, easy to perform and be rapidly implemented during non-revenue or low usage periods. In addition, it must not pose a safety hazard to the users of the tunnel.

The Study addresses typical repairs for the most common types of tunnel liners and describes repair procedures for concrete restoration, repair to structural steel elements, segmental liners, brick liners and stone and ashlar masonry liners. The repairs are typical of those commonly implemented in most highway and rail tunnels, and which are generally appropriate to other types of service tunnels. However, it is important to note that no two sites are exactly the same and specific site requirements and conditions may render a repair technique unsuitable.

The smaller more cosmetic type surface repairs, which do not affect the structural integrity of the tunnel liner, are not covered in this study. The recommended repair methods take into account the case histories collected from ITA Member Countries and summarised in Appendix B by category.

The procedures for controlling and sealing of ground water infiltration into tunnels, which may form part of the repair process, are described in Chapters 6 and 7.

5.2 Concrete Repair

Concrete deterioration is often the result of poor workmanship, groundwater infiltration through cracks and construction joints, insufficient concrete cover over the reinforcement, electrolytic corrosion, or chemical reaction in the concrete.

Concrete repairs to existing tunnels are dependent on the type of construction, tunnel operations, and the severity of the defects. The elements which most directly affect the selection of the repair technique are:

- The required strength of the repair material;
- The required durability of the repair material;
- The environmental setting of the repair location including type of useage of the tunnel; and
- The time frame for the construction of the repair.

The strength of the type of repair is generally dictated by the strength of the original construction material. The durability of the repair is a function of the strength and the long-term suitability of the repair, taking into account the environment setting and tunnel usage.

The environmental setting is of prime importance due to the varied environments that exist within the tunnel setting. The presence of water; the occurrence of atmospheric and temperature changes (freeze and thaw cycles) within the tunnel; locations of ventilation ducts, ventilation shafts and portals; exposure to exhaust fumes from road vehicles or rail locomotives; and the chemical composition of the groundwater and the soil or rock that surround the tunnel have a strong influence on the selection of the proper repair product.

The allowable time frame for the implementation of the repair is probably the most unique element in the repair selection process. This time frame is dependent on the owner's operations, which include the hours of shutdown for repair construction and the maintenance of clearance envelopes for rail or vehicular traffic during the construction period.

5.2.1 *Concrete Restoration Methods*

Based on the aforementioned elements and recent relevant experience in tunnel projects, concrete repair methods may be divided into the following categories:

- Concrete restoration by patching;
- Concrete restoration by the application of cast-in-place concrete with or without reinforcement;
- Concrete restoration by the application of shotcrete; and
- Sealing of concrete cracks by grouting.

This section deals with the first three categories of concrete restoration, while grouting of cracks is considered in Section 5.3 of this chapter.

Concrete restoration is a process of replacing loose, spalled, or crumbling concrete with new material. Appropriate restoration will restore the structural integrity, be compatible with the surrounding concrete, and last as long as the original structure. Suitable materials for the restoration of concrete by the aforementioned processes are:

- Portland Cement mortar/concrete (PCC)
- Polymer modified PCC;
- Epoxy modified PCC;
- Polymer mortar;
- Epoxy mortar; and
- Special cements.

The selection of the product and method used for restoration depends on such criteria as breathability, shrinkage, thermal coefficient of expansion of the product and the tunnel liner, thickness of the repairs, chemical resistance, application and cost. Limited site access within the tunnel creates additional problems in delivery and installation of the repair.

Concrete restoration of tunnels, regardless of which product or method is used, requires good surface preparation and, in linings with steel bar reinforcement, requires treatment of and/or repairs to the reinforcing steel.

5.2.2 *Surface Preparation*

Common to the application of any of the repair products and methods is the surface preparation prior to the application of the appropriate material. Surface preparation consists of the following:

- Removal of all loose, unsound concrete;
- Cleaning of all corrosion from reinforcing steel (as applicable); and
- If required, replacement of reinforcing steel.

The removal of all loose unsound concrete is best performed by the use of air powered chipping hammers. These hammers should be sized so as to not remove excessive quantities of sound concrete. The best method for sizing chipping hammers is to specify the total weight of the hammer. The acceptable size for concrete removal in tunnels is a hammer of a weight not exceeding 13.6kg including the bit. A steel hammer is preferred, since a hammer made of aluminum will be too large and will tend to over-excavate the concrete by providing excess energy.

The unsound concrete must be removed by a chipping process starting at the middle of the identified defect and moving horizontally to the edges of the defect. The hammers will seek their own depth of penetration and be refused when the hammer's force is repelled by sound concrete. The edges of the area to be patched must not have featheredges, but rather a shoulder. In the case of repairs using cast-in-place concrete or shotcrete a shoulder of 20mm depth or 1,5 times the size of the largest aggregate of the repair material is appropriate. (Refer Fig 5.2.2).

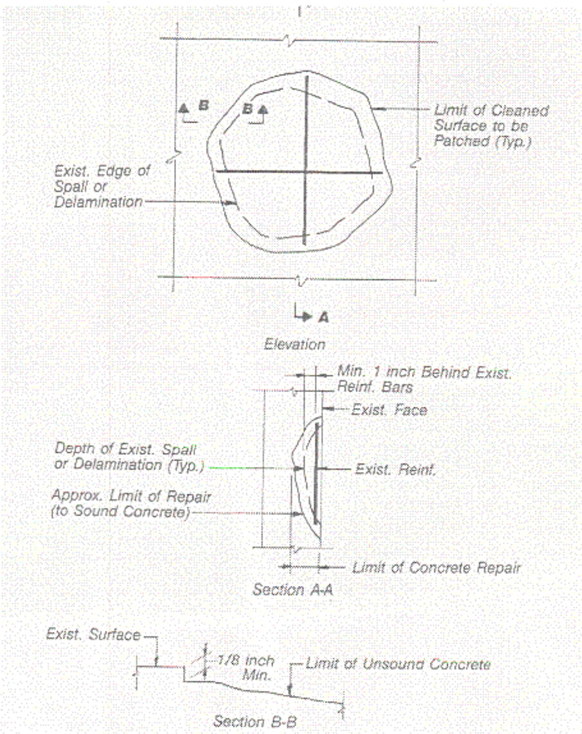


Figure 5.2.2 Typical Concrete Spall Repair – showing surface preparation

If milling machine and robots are used to remove sizeable sections from the liner, careful analysis must be performed to evaluate the effect on the overall structural integrity of the tunnel liner before proceeding.

5.2.3 *Cleaning of Reinforcing Steel*

After the removal of all loose and unsound concrete, and prior to the placement of any cementitious product, the reinforcing steel must be cleaned of all surface corrosion. Cleaning of large repairs is sometimes best performed by sandblasting with sharp sand or synthetic grit; the most common material used being a synthetic carbide grit. The grit size is dependent on the type of equipment used in the application. In other cases, the steel is cleaned by the use of wire brushes, chipping hammers and/or pneumatic scalers.

The steel must be cleaned to a "white metal" condition. Once cleaned, the reinforcing steel should be coated with a zinc or epoxy coating material (of these, a zinc rich coating is the most commonly used) to prevent the potential for corrosion due to electrolysis.

After the steel within the repair area is cleaned, the entire patch area must be cleaned of all dust, rust scale and other debris. Note: if the repair area is to be left for long periods of time prior to the completion of the repair, the area must be cleaned again with compressed air or high pressure water immediately prior to the placement of the repair product.

However, high-pressure waterblasting for cleaning is not recommended for rail transit tunnels due to the presence of numerous electrical cables and contact wires or rails. Although high-pressure waterblasting is generally acceptable for use in highway tunnels, a thorough check of the equipment and fittings in the vicinity of the work area should be made to ensure that these are not affected.

5.2.4 *Reinforcing Steel Repairs*

Treatment of reinforcing steel is generally limited to cleaning as described above. Reinforcing steel that is out of plane, bent, or buckled is restored to its original configuration by cold bending. However, reinforcing steel that has had a loss of section greater than 25 % must be analysed and replaced, if necessary. The replacement of reinforcing steel must be performed in accordance with the applicable current codes and standards (refer Fig 5.2.4). In some cases, if only an occasional bar requires replacement and the structural analysis indicates that the bar is not critical to the structural design, the bar need not be replaced. The new bars should be treated with zinc rich coatings in a similar manner to that described above.

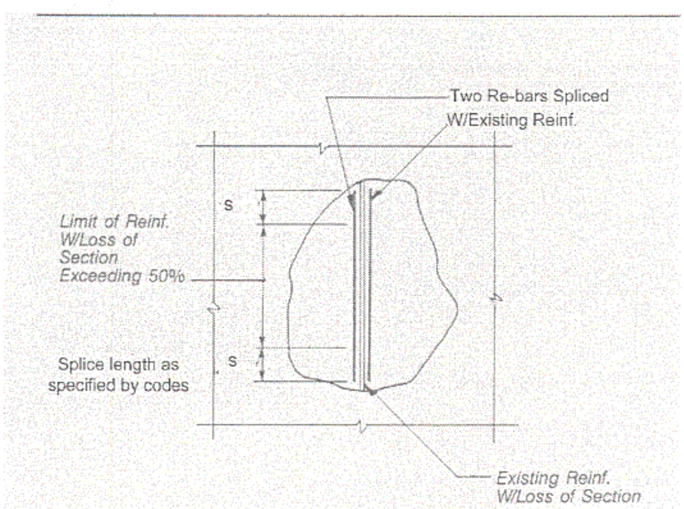


Figure 5.2.4 Typical Reinforcing Steel Repair

5.2.5 *Cast-In-Place Concrete*

The use of cast-in-place concrete for the repair of the tunnel structure in rail and highway tunnels is restricted to locations where good site access is available in terms of time and clearances for construction. Cast-in-place concrete requires formwork, which can only be constructed in areas where sufficient space prevents encroachment into the operating envelope of the tunnel. The use of formwork for cast-in-place concrete poses additional problems in the actual placing of the concrete to achieve a complete filling of the repair area at both wall and roof locations, requiring special forms and construction procedures.

The installation of cast-in-place concrete requires the use of a bonding agent to provide a strong bond between the existing sound concrete and the new concrete. The bonding agent is usually a latex or epoxy compound, which is applied to the existing concrete surface strictly as directed by the manufacturer. In certain circumstances, the use of dowel bars inserted in the existing sound concrete in predrilled holes and fixed in position with cement or polymer grouts, can be recommended to enhance the bond with new concrete. Once the bonding agent has been placed, the forms are sealed up and the concrete is cast within the forms.

In actuality the proper application of the bonding agent and the timely placement of the concrete is seldom done properly and the integrity of the concrete bond is questionable. In response to this problem, special polymer modified Portland Cement concrete mixes were developed which incorporate the bonding agent in the concrete mix as a substitution for 30-50% of the water in the mix. This mix has provided a positive method of ensuring a good bond to the existing concrete surface, while increasing the compressive strength of the design mix. Cast-in-place polymer modified Portland Cement concrete is particularly advantageous in areas where a smooth or a special architectural finish is required.

Concrete for this type of application is generally transported into the tunnel by either rail mounted or truck mounted equipment. In some instance the use of a “slick line” to pump the concrete into the work area is feasible. It is important that the concrete supply is continuous and is able to accommodate limited construction windows applicable in certain cases.

After curing the forms are removed. The removal of the forms is generally between one and seven days, depending on the design criteria in terms of the compressive or tension bending strength of the new concrete and the actual corresponding strength of the site test samples.

Cast-in-place concrete has been widely and successfully used for the strengthening or rehabilitation of tunnel structures to new clearance envelopes. In general, cast-in-place concrete has been most successfully used in rehabilitation projects where the tunnel has been totally closed to traffic for a period of weeks or months for the construction of the repairs.

5.2.6 *Polymer Modified Cementitious Mortars*

Portland cementitious mortars with the addition of polymers create a high strength two-component, rapid curing material for the restoration of structural concrete. Polymers are used in concrete to fulfil the following requirements:

- Improvement of water resistance;
- Improvement of freeze/thaw resistance;
- Improvement of bond/adhesion;
- Reduction /elimination of shrinkage; and/or
- Improvement of setting time

The polymers that best fulfill the aforementioned criteria are the acrylic copolymers. These acrylic copolymers are incorporated in numerous premixed products, and are best suited for concrete restoration due to their "breathability". This unique characteristic, which allows the passage of water vapor through the repair, prevents the build up of moisture at the interface between the repair and the existing concrete surface; thereby eliminating freeze/thaw problems and corrosion to the reinforcing steel within the repair area. These products are supplied in both wet and dry polymer configurations. They can be applied by hand in layers similar to the European practice of "plastering" or by low pressure wet shotcrete application.

In three road tunnels in Italy, Polymer Modified Cementitious Mortars were successfully used for the repair of the concrete surface which had deteriorated because of carbonation. In one case microfissures were observed in the mortar, but it was unclear as to the cause of this; this can be avoided because of the low shrinkage potential of the product.

5.2.7 *Shotcrete*

Shotcrete is a pneumatically placed Portland Cement concrete mixture. This mixture is projected by compressed air against the area to be repaired using a dry or wet process.

In the dry process, the dry concrete mixture of sand and cement is pumped through hoses and the water is added at the nozzle. With respect to additives: if these are dry compounds, they are added to the dry mixture of sand and cement; if the additive is a liquid, this is added at the nozzle with the water.

In the wet process, the sand and cement are premixed and pumped wet to the nozzle and applied by the use of compressed air, which is added at the nozzle.

The use of polymers in the shotcrete is well suited for the repair of tunnel structures. The repair is monolithic and bonds well to the existing concrete. The pneumatic application "wets" the surface of the concrete and provides a strong bond.

The selection of which process to use is dependent on the limitation of the area to be repaired and availability of equipment and expertise. Wet process is a lower pressure application and is well suited for work in areas where rebound of the material and the creation of dust are unacceptable. However, for extensive repairs the use of dry process higher pressure shotcrete may be more appropriate due to the fact that the storage of the dry mixture is easier and can be for extended periods, and more rapid placement of large quantities of material is achievable.

The surface preparation for the application of shotcrete is identical to that described earlier in this chapter in Sections 5.2.2 and 5.2.3. However, in addition to cleaning the reinforcement bars, wire is added over the surface of the reinforcement and is attached to the reinforcement. This wire mesh enhances the strength of the repair and assists in rapid buildup of material in the area to be repaired. Wet process shotcrete requires a large open weave mesh of not less than 8 cm by 8 cm. Dry process shotcrete requires a smaller open weave of not less than 4 cm by 4 cm. The different size wire mesh is due to the tendency of the wet process to build up the repair product at the surface of the wire mesh and cause voids behind the mesh. This build up is not such a problem with dry process shotcreteing.

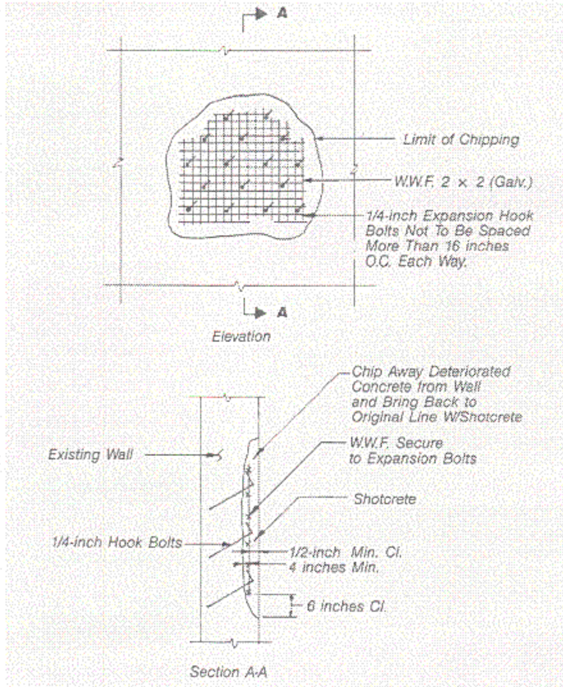


Figure 5.2.7 Typical Shotcrete Repair

The typical finish of shotcrete as placed by the equipment in the tunnel is a "gun" finish, which is a reasonably smooth finish. However, if a specifically smooth finish is required, it may be appropriate to apply a steel trowel or wood float to the shotcrete surface. The trowelling of the repair should be performed after the initial set to prevent "tearing" of the surface.

It is noted from the case histories that, in a road runnel where shotcrete repairs were carried out, the shotcrete repair deteriorated due to carbonation because of exhaust fumes. In another road tunnel, the uneven surface of the shotcrete gave an unsatisfactory appearance. The effects of carbonation can be reduced to acceptable limits by the use of a dense shotcrete mix and the use of trowelling to provide a more dense and resistant surface. Alternatively the surface of the shotcrete may be coated with a mineraliser to reduce porosity. The trowelling will also overcome the problems of a rough uneven surface, where a good aesthetic appearance is important.

5.3 Structural Crack Repair with Epoxy Resins

The sealing/bonding of structural cracks in tunnels is performed to restore the monolithic condition of the structure. Cracking is the result of concrete shrinkage and movements of the structure caused by settlement or other external forces acting on the tunnel system. Cracks are often the cause of water inflow into the structure and the subsequent corrosion of the reinforcing steel and the deterioration of the concrete structure. It is desirable to restore the bond of the sides of these cracks and thereby restore the structural integrity of the tunnel system as originally designed. Rigid epoxy injection systems have been developed to successfully repair these defects.

However, it should be noted that epoxy grouts are generally moisture sensitive and can only be used in cracks, which are dry or just damp. The injection of leaking cracks and construction joints are described in Chapter 6.

The repair of structural cracks in concrete tunnel liners, which are not actively leaking, is performed in a number of steps:

- The surface of the crack to be injected is sealed with a paste gel;
- Injection ports are installed in the crack, where the space between injection ports is equal to the thickness of the concrete liner to be injected up to a maximum spacing of 600 mm (refer Fig. 5.3);
- After the initial set of the gel surface coating a two component, moisture insensitive, epoxy resin is injected into the crack; and
- The injection of the resin into the joint is performed using a special high-pressure rotary mixing pump. The injection starts at the lowest point on the vertical surfaces. When the resin is observed flowing from the next port up the crack, the injection nozzle is moved up to the next port, and the lower port is plugged. This process is continued until all of the ports have been injected and filled with resin. Injection pressures must not exceed 0.70 Mpa and a working pressure of 275Kpa. Polyester resin and Amine resin epoxies are the best suited for this application. Vinyl ester resins should be avoided, since they do not bond to saturated concrete surfaces.

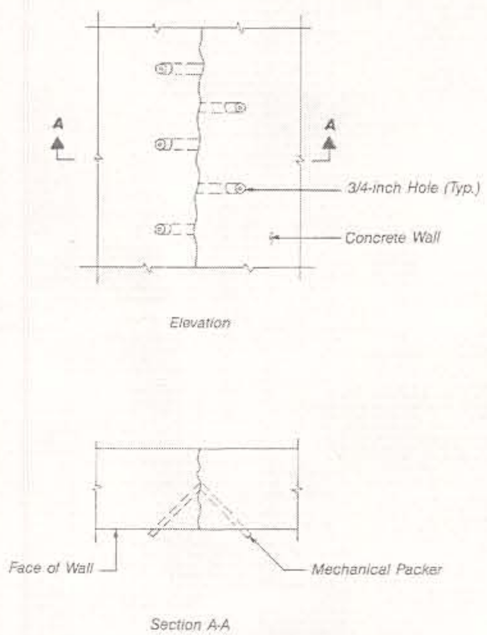


Figure 5.3 Typical Injection Ports for Epoxy Resin

5.4 Metal repairs

The restoration of structural metal elements in tunnels other than segmental liners includes the repair of cast iron elements in the case of older tunnels. These mental elements are generally incorporated into the tunnel system as framing steel, structural columns or construction items such as arches or ribs. The use of cast iron for structural elements is generally confined to tunnels where the segmental liner is of cast iron and the repairs will be as described for cast iron liners in Section 5.7.3.

The repair of structural steel is performed in the same manner as steel repairs for bridges and other above ground structures. Steel elements which have a loss of section in excess of 20% must be analysed and, if required, repaired by accepted practices and local codes.

The steel unit to be repaired is either built up by the addition of steel plates, which are either bolted or welded to sound existing steel, or the unit is completely replaced by a new structural element. The bolting of replacement steel elements is to be performed with the use of high strength bolts in accordance with ASTM Standard A325 or other applicable codes.

The painting of steel elements is the best protection against future corrosion caused by moisture. An effective painting program requires the thorough cleaning (sandblasting) of the steel element. Epoxy paints can be particularly effective but as with all types of paints, the surface preparation and application should be strictly in accordance with the manufacturer's instructions or specifications.

5.5 Brick Masonry Repair

The restoration of masonry structures comprised of clay brick, generally consists of repointing of mortar joints and replacement of defective brickwork. The repointing of masonry joints requires cleaning of the joints to be repaired to a minimum depth of approximately 3 cms and where appropriate, wedges are installed. Once the joints have been raked clean of old mortar they are repointed by cementitious mortar fortified with polymer bonding agents.

Construction of brick lined tunnels involved the erection of a timber framework to provide initial support, inside of which the brickwork was placed. At times, the voids between the ground and the lining were filled with tunnel muck. Subsequent decay of the supports and inadequate backfilling with tunnel muck has led in some cases to the creation of voids, causing uneven ground pressure and water leakage, which in turn has led to the deterioration and cracking of the lining. Other causes of damage are exhaust fumes from rail locomotives and or ageing.

The repair or filling of voids is described in more detail in Section 5.6 for Stone and Ashlar Masonry linings.

Replacement of broken, slaked, or crushed brick requires detailed analysis to determine the cause and extent of the problem. Once the cause and extent of the defective masonry is identified, repairs may be performed. The removal of more than the occasional brick in the structure requires detailed procedures. The design of repairs must be performed by specialists who are familiar with brick masonry construction.

In severe cases, repairs may include the partial or total removal of the brickwork and replacement with a reinforced concrete or shotcrete lining. Alternatively the lining may be reinforced and strengthened with shotcrete, steel plates and/or bolting.

Brickwork linings are most commonly encountered in rail and canal tunnels. The case histories would indicate that the most popular method of repair incorporates the application of reinforced shotcrete, which reduces the construction periods and the obstruction of the tunnel, as well as providing for the maintenance of the clearance envelope for the traffic.

5.6 Stone and Ashlar Masonry Repair

Linings made from stone and ashlars are found in tunnels built before 1940. These tunnels often are lined with a composite lining to suit the site conditions: the abutments are made from stone, and the crown is lined with bricks. All of these tunnels were built in ground with unstable conditions. The traffic technology prevailing in that era did not require a tunnel lining for safe operation of steam powered locomotives and trains, both cruising with only moderate velocity. An inner lining was only constructed, if rock falls occurred, or circumferential stresses – not compensated by the behaviour of the ground surrounding the tunnel under construction – were expected.

Commonly found types of damage of the masonry are:

- Decay of the mortar filling of joints;
- Displacement of stones or ashlars as a consequence of the failure of the mortar; and sometimes jointly caused by impacts from outside the tunnel; and
- Chipping of the surfaces of the ashlars on the intrados.

As in the case of brick lined tunnels, voids and cavities are often found behind the lining, giving rise to ground settlement, uneven ground pressures water leakage and/or damage to the lining. The situation and the dimensions of these voids must be included in the investigation and planning of the repair. Other causes of damage are exhaust fume and ageing. The engineer in charge must be familiar with the use of natural stone, the old technology of stone masonry, and the construction of vaults and arches, even those of large spans.

Principal objectives of the investigation are the safety of the crew working near damaged parts of the lining and the safety of the operation of the tunnel. Without an expert's guidance, disturbance to parts of the lining can result in the collapse of parts of the vault or the entire lining of the tunnel. Commonly, no warning precedes the collapse. Adequate shoring and bracing must be installed prior to carrying out any repair work on the liner. Especially in the case of rail tunnels, there are generally set procedures and arrangements for the repair of damaged masonry tunnels while operating the tunnel. Depending on the operating clearance, different arrangements are defined by the railway companies to provide for the operation of at least one track and diversion of the trains. The same considerations are equally appropriate for road tunnels lined by masonry.

Shoring and bracing must be installed prior to carrying out any repair. Once the vault and the abutment are in stable condition, all loose stones and ashlars must be fixed by driving wedges into the joints.

There are two basic philosophies regarding the rehabilitation of masonry, taking into account the place where the defective parts are situated. The heritage of the tunnel portals built in the nineteenth century require the reconstruction of the masonry according to the methods used in the era of their construction. In most other situations, tunnels are restored using modern technology to obtain a more inexpensive repair. As the vast quantity of repair work is done using modern technologies, the study confines itself to a consideration of these modern procedures.

In cases of loose mortar in the masonry, the mortar is removed up to a minimum depth of 80mm. All debris should be removed by flushing and the repointing work is done by the application of one layer of shotcrete. Where there is low water ingress, a waterproofing agent could be added to the shotcrete mortar. Larger quantities of water should be conducted and drained to the catwalk using drainage systems similar to those described in Chapter 4 as Type A. The dewatering system may be placed inside the body of masonry by cutting chases.

The rehabilitation of partially displaced linings can only be performed after a detailed study to establish the reasons for the displacement. If the analysis determines that the original liner is not able to counteract the stresses and strains from the surrounding ground, the liner must be strengthened with additional support.

In cases of displaced linings occurring over small sections of the tunnel, the strengthening can be done by guarded removal of the ashlars followed by an excavation of a laminar of the ground outside the lining to allow the application of an adequately dimensioned layer of shotcrete. This layer is fixed to the rock by rock bolts. Afterwards, the ashlars are reset in the desired position. Preferably the shotcrete layer should be applied around the entire intrados enhancing the support.

Rehabilitation of larger sections of masonry lining failure usually involves complete modification of the lining by shotcrete shells or by applying the well-known rib-cutting method. The latter method comprises the cutting of slots in the masonry lining and the installation of steel ribs or reinforcement bent to shape. The slots are then filled with either concrete or shotcrete. The ribs are installed in a careful sequence to preserve as much as possible the strength of the lining. Rockbolts may also be used to secure the ribs to provide additional strength. When the ribs have been completed, the damaged parts of the lining are removed and replaced by shotcrete, incorporating a waterproofing membrane and drainage as necessary.

If the thickness of the original masonry lining is 0,5m (20 ins) or more, it is preferable to replace only a certain part of the liner cross-section. This avoids total loss of strength and support incumbent in the existing lining. The new inner shell enhancing the vault and the abutment can be made from stone, ashlar, or sprayed concrete. The choice depends on conditions found at the site and project requirements. The contact joint between the existing masonry and the repair can be closed by grouting of a suspension of plain cement or Portland cement mortar.

In cases of surface damage to the masonry lining, the faces of the chipped ashlars are removed by milling or chiseling. After flushing of the debris from the surface and the joints, a protective layer of sprayed concrete is applied to restore the entire thickness of the lining.

A commonly found problem of older built rail tunnels are the voids and cavities behind the masonry. If the lining is found to be stable, access to the voids may be gained by small drives, starting from niches in the tunnel, at the level of the invert or the crown. The extrados of the liner is cleaned of debris and smoothed by the application of sprayed concrete or lean concrete. Since most cavities are caused by the presence of water, a sealing layer or water proof membrane is spread on the outside of the masonry. At the springline or at the invert level, a drainage system is built with conducting pipes to the main drainage of the tunnel. The voids are backpacked using stone or concrete for proper filling. Sometimes, the space is permeated with mortar grout, preceded by an appropriate protection of the draining system.

A complete renewal or replacement of a masonry lining is appropriate, if there is also a need to modify the tunnel, regarding height, and width, and may also be necessary, if the operating system is changed from steam powered to electrical traction.

5.7 Segmental Liners

The repairs to segmental liners are a combination of the processes discussed in earlier sections of this chapter. These repair processes are adaptable to the repair of segmental liners, but using repair materials which exhibit the same construction composition as the segments to restore the structural integrity of the liners. Segmental tunnel liners consist of three basic types:

- Precast concrete segmental liners;
- Steel segmental liners; and
- Cast iron segmental liners

Common defects in segmental liners are:

- Cracking of segmental liner plates or precast elements;
- Leakage through joints and bolt holes at the interface between the segments;
- Corrosion caused by leakage or electrical currents; and
- Distortion of liner segments due to impact or changes in stress.

5.7.1 *Precast Concrete Segmental Liners*

The structural bonding of cracks in precast liners is performed by the injection of epoxy resins as described in Section 5.3. The control of water seepage through precast liners is controlled by the following:

- Injection of chemical grout in the segmental joints (see Chapter 6 for further information);
- Restoration of the original seal or gasket in the segmental joint; and
- Sealing of the bolt hole leakage by installation of new gaskets or chemical grouting.

Impact damage to precast segmental liners typically cause the liner segments to crack or spall. Repairs can be carried out by injection of resins or by one of the concrete restoration methods previously described in this chapter.

5.7.2 *Steel Segmental Liners*

Damage to liners is invariably related to corrosion of the liner plate and subsequent loss of section. This is repaired by the addition of steel plates to the affected area. These plates are attached to the liner by either bolting or welding. Electrolytic corrosion in segmental steel liners is primarily in areas of dissimilar metals such as bolt connections. The preferred method for the control of this type of corrosion is to isolate the bolts from the liner section by the use of an insulating sleeve or jacket. The treating of the water infiltration, which gives cause to corrosion, is dealt with in Chapter 6.

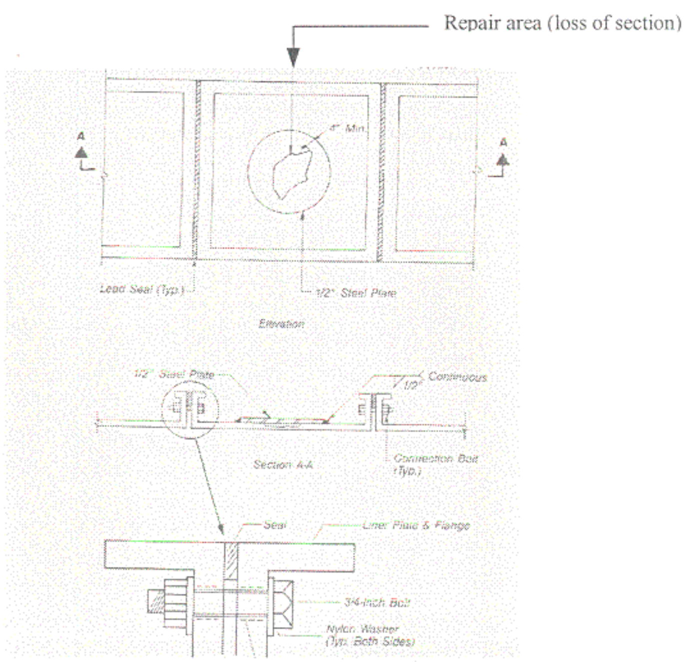


Figure 5.7.1 Typical Repair to Segmental Steel Liner

5.7.3 *Cast Iron Segmental Liners*

Similar to the steel segments, damage to cast iron liners is generally due to corrosion. However, the loss of section and/or replacement of a defective structural element is more difficult than steel since cast iron liners cannot be welded. Therefore the replacement/ repair of defective cast iron panels requires extensive site specific information and analysis which must be tailored to the repair. These segmental liners are often repaired by infilling of the panel with cast-in-place concrete. Electrolytic corrosion, as in steel liners, attacks the connection bolts and this corrosion can be eliminated by the use of insulating sleeves or jackets

5.8 Conclusions

The repair of tunnel liner systems must be a long lasting repair, designed to restore the structural integrity of the tunnel liner. All repair methods require detailed investigation and a thorough understanding of the original design. The use of new repair products will allow for older tunnel systems to be repaired effectively, ensuring many years of continued service. The new technologies should also be cost effective, allowing repairs to be performed in a short work window and be sufficiently durable to allow the tunnel to be placed back in service at the end of the work shift. It is important to note that the most optimum repair method is site specific and no two sites are alike. Therefore careful consideration to the selection of the repair product and method is crucial to a successful project.

References:

[1] white metal condition: Reinheitsgrad SA 2½ [Degree of cleanliness SA 2½] nach DIN 55928 Teil 4 [according to DIN Standard 55928 Section 4].

CHAPTER 6

REINSTATEMENT OF TUNNEL LINER DAMAGED BY WATER LEAKAGE

6.1 Introduction

The reinstatement of liners damaged by causes other than water leakage was considered in Chapter 5. The state of the art of reinstating linings of the tunnels affected by water ingress is now considered. Infiltration of water into tunnels is the primary cause of damage to tunnel liners and therefore, the effective treatment and elimination of this problem is of primary importance in prolonging the useful life of a tunnel.

Damage, which requires the cutting out and replacement of part or whole of the tunnel liner, can only be properly effected when the water infiltration has been controlled or eliminated. After sealing, the repairs can be undertaken in the same manner as described in Chapter 5.

This chapter accordingly deals only with the sealing of cracks and joints in the tunnel liner, through which infiltration is occurring, as well as the sealing of permeable linings.

The selection of the proper equipment and materials, as well as the use of construction crews experienced in this type of work is critical to the successful sealing of the tunnel. These aspects are accordingly considered in some detail. Recommendations and precautions are noted and references are made to the case histories of repair work provided by various ITA member countries and summarized in Appendix A.

6.2 Selection of Equipment

The selection of the equipment must be included in planning of injection or grouting work. This equipment includes pumps, drills and batching plants. For small quantities a hand-operated pump is best suited, while for dealing with major quantities a pump actuated by compressed air or electric power is required. Suitable ranges of working pressure of the pumps are from 0.5 bar (8 psi) to 20 bar (300 psi) for grouting of cementitious materials and minerals. Injection of other media requires high-pressure systems up to 150 bar (2200 psi). Sometimes a secondary injection requires working pressures up to 250 bar (3600 psi). A high-pressure water pump is also necessary for flushing out and cleaning the cracks and areas to be grouted. The holes for the insertion of the fittings may be drilled by an electric powered drill with high torque. The selection of batching and mixing plants depends on the materials to be used.

6.3 Selection of Materials

Repair materials should be selected based on the material components and dimensions of the lining to be repaired, the structural design of the lining, and the physical characteristics of the cracks, joints, and wet areas. Other considerations are the volume of the repair, the availability of the materials, and the cost. Numerous products for repairing and sealing of leakages and repairs to the tunnel lining are available. Detailed specifications of these products (mostly proprietary) cannot feasibly be addressed in these recommendations concerning all the tunnels in the member nations of AITES/ITA. Table 6-1 shows the use of the typical and commonly used materials for the repair of leakages.

Procedure to apply	Types of Repair Materials for specific rates of leakage			
	Moisture Leakage at Apex/Faces of Cracks			
	dry	damp	Steady Flow	
			Free Flow	Pressure Flow
close	EP-perm.	EP-perm [1]		
	EP-inj	EP-inj [1]		
	PUR-inj	PUR-inj	PUR-inj	PUR-inj [2]
	CP-inj	CP-inj	CP-inj	CP-inj [3]
	CS-inj	CS-inj	CS-inj	CS- inj [3]
seal	EP-inj	EP-inj [1]		
	PUR-inj	PUR-inj	PUR-inj	PUR-inj [2]
	CP-inj	CP-inj	CP-inj	CP-inj [3]
	CS-inj	CS-inj	CS-inj	CS- inj [3]
rigid bond	EP-inj	EP-inj [1]		
	CP-inj	CP-inj	CP-inj	CP-inj [3]
	CS-inj	CS-inj	CS-inj	CS- inj [3]
elastic bond	PUR-inj	PUR-inj	PUR-inj	PUR-inj [2]

Table 6-1 : Application of materials, according to ZTV-Riss 88 [2]

Legend:
- EP-perm — Permeation with epoxy resin
- EP-inj — Injection with epoxy resin
- PUR-inj — Injection with polyurethane
- CP-inj — Injection with cement paste
- CS-inj — Injection with microfine cement suspension

Superscripts:
- 1 — only water tolerant materials
- 2 — previously inject rapid acting foam
- 3 — previously reduce water flow

All materials used to stop water leakage into a tunnel will naturally come into contact with the groundwater and grouting/injecting may cause unacceptable contamination. They should be tested and approved by the appropriate authorities, e.g. Authorities of Water and/or Public Health, and/or Environmental Protection Agencies. It is noted that the use of all noxious and toxic injection materials and agents containing such materials are prohibited within the borders of the European Union and other jurisdictions and should be avoided.

High-alumina cement used for the temporary sealing of tunnel leaks should not be used as a permanent repair for tunnel liners. These high alumina cements degrade over time and do not provide a suitable long-term repair.

It is essential that the grouting materials are compatible with the material of the lining of the tunnel and all of its ancillary components such as waterstops, waterproofing membranes and joint fillers. In summary, the following considerations of compatibility and suitability of grouting materials are important:

(i) The environmental compatibility of the ground materials.
(ii) The width of the cracks or joints and/or the volume of the repair.
(iii) The compatibility of the material properties of the grouting or injection material with the properties of the tunnel lining;
(iv) Resistance to washout by infiltrating ground water and resistance to mechanical and chemical attack;
(v) Injectability of the selected material into the area of leakage;
(vi) Setting and rheological characteristics of the mix;
(vii) The particle size distribution (cementitious materials only);
(viii) The volume stability of the grout at various temperatures humidities, and pressures;
(ix) The long-terms durability and strength; and
(x) The viscosity of the grout at given conditions at the site e.g. the temperature, the humidity of the air.
(xi) The availability and cost of the grout materials.

The dynamic and the kinematic viscosity of the materials must be tested in advance in the laboratory and routinely at the site in accordance with appropriate standards. A very simple test can be made in accordance with to DIN 53211[1] or similar.

6.4 Selection of Construction Crews

In order to ensure good results, it is essential that the rehabilitation work is undertaken by a crew of appropriately skilled workers, under the overall supervision of an experienced engineer and his field staff.

6.5 Grouting of Cracks

6.5.1 General

For best results, the injection or grouting should fill the full depth of the crack as completely as possible, thereby providing the best seal to water infiltration, as well as restoring the structural integrity of the liner.

Investigations are carried out to measure the depth of the cracks in relation to the intrinsic thickness of the lining before grouting the cracks. This information will enable the grout injection ports (nipples) to be placed correctly and at the proper angle to the surface of the lining, and will assist in the selection of the appropriate type of fitting or packer. If the crack extends the full thickness of the lining (totally cracked structure), further investigations of the ground around the tunnel will be necessary to establish the optimum grouting method.

The surfaces of the crack are cleaned, generally by high-pressure water before installing the packers. The types of fittings or packers used are dependent on the method and the equipment used for injection. In certain types of cracks (mostly wide open cracks), glueing of grouting ports just to the surface of the lining may be possible; a test will be helpful to assess the suitability of this system. The spacing of the grouting ports is determined by the viscosity of the grout used, the porosity of the lining, and the dimensions of the lining to be injected. If there are reinforcement bars intersecting the area of the crack, the location of the drill holes or ports for grout injection should be checked to ensure that they do not intersect with the reinforcement.

The diameter of the drill holes is sized to accommodate the injection ports to be inserted. Sealing of the ports in the drilled holes is done with rapid hardening cement. One port more than the number of the ports to inject the crack is needed; the last or highest one is for venting. The surface of the crack is sealed with patch mortar or a special sealing material mix. Before grouting, the crack is flushed with water to clean and wet the surfaces to be grouted, removing any excess water by compressed air.

Grouting of vertical cracks is commenced from the bottom port, working sequentially upwards to the top. When grouting horizontal cracks, grouting is started at one end of the crack and proceeds progressively to the other end. As soon as grout emerges from the next port, injection is stopped and the injection port sealed. The injection point is then moved to the next port and recommenced. The grout pressure is maintained for a period at the last port to ensure complete filling before injection is stopped and the port sealed.

At the completion of grouting and after the grout has set, the ports are removed by breaking them out and sealing the drill holes using rapid hardening Portland Cement mortar. If necessary, the sealing mortar on the surface of the lining can be removed using a grinding machine and a specific patch mortar may be applied to improve the appearance of the concrete surface.

Special information relating to the use of different types of materials is described in the following sections.

In the UK, a small gauge railway tunnel suffered from dripping in various locations above the axis level. The leakages were stopped by injection of special grouts between the lining segments and into the cracks of the concrete.

6.5.2 *Repair of cracks using a cement paste (mortar) grout*

Cracks ranging from 0,5 mm (2/100 in.) up to 3mm (1/8 in.) in width, which can be typical of shrinkage cracks, can be grouted using a Portland cement suspension or paste. Plain Portland cement paste or paste with stabilisers can be used, the stabilisers comprising bentonite, Pozzolanic filler or pulverised fuel ash. Special admixtures may also be added to swell the grout and/or to improve the workability of the grout. A series of tests are normally carried out to optimise the grout mixture. Fine grained sand is only added to stabilise the grout when injecting into large voids.

The paste is mixed by a turbo or high-speed colloidal mixer, which serves to break up the grains of the cement. Injection of the paste is commenced using a medium water/cement ratio (W/C ratio) and low pressure. When this has been completed and has been checked, it may be necessary to do a further round of grouting. In the second round, a reduced W/C ratio and higher grouting pressure may be recommended. The spacing of the injection holes for Portland cement paste or suspension grouts at temperatures of about 20^0C (70^0F) are typically 0,1m (4ins.) in concrete with a high porosity, 0,15m (6 ins.) in shotcrete and concrete of medium porosity, and 0,3m (12 ins.) in top quality concrete of low porosity.

6.5.3 *Repair of cracks using micro fine cement grouts*

Microfine ground Portland cements were developed in the early 80's, with a controlled particle size distribution (maximum grain size $d_{95} < 16$ µm), which can be used to grout narrow cracks or fissures smaller than 0,25 mm (1/100 in.). The grouts themselves are also less permeable than normal cement pastes or suspensions, have improved durability and a strength similar to chemical grouts, have zero toxicity and can be applied using standard cement grouting equipment and technology. The hardened grout is however rigid and brittle and cannot tolerate any movement.

Narrow cracks of less than 0,5mm (2/100 in.) are typical of structural cracks caused by overstressing of the tunnel liner by static or dynamic overloading. The investigation of the failure should therefore include an analysis of the loads on the liner and the case history. Movements, displacements, impacts, ground settlement, thermal loading, etc., can be the cause of the cracking, which needs to be established and dealt with before grouting commences. Otherwise further cracking of the liner should be expected.

Apart from sealing seepage through the cracks, the injection of the grout serves to restore the structural integrity of the lining by bonding the sides of the crack. Different types of microfine cements are available; in cases where the concrete aggregates are susceptible to alkali reaction, low alkali cements should be used.

The preparation of the crack surfaces and the setting out of the injection ports would be the same as described in Section 6.5.1. The stabilisation of the suspension, the equipment to be used, and the general procedures for grouting are as described in Section 6.5.2. Grouting should not take place at temperatures lower that 10°C (50°F) and the W/C ratio should be kept as low as feasibly possible to reduce shrinkage and to provide for a high strength grout.

In cases of very high water inflow, pretreatment of the crack is necessary to prevent washing out of the grout. In Japan, a lined tunnel with varying degrees of leakage was successfully treated by a pre-injection of a sealant material to reduce the water flow and installing drainage plugs along the cracks before grouting.

6.5.4 *Repair of Cracks using Epoxy Grouts*

Epoxy grouts are generally moisture sensitive and cannot be used in cracks, which are actively leaking (ranging from seeping to continuous leaks) and cannot be substantially dried out. Water or contamination such as silt or dust in the bottom of a crack will significantly reduce the effectiveness of the grout.

The use of epoxy grouts can only be recommended for filling of dry or damp cracks. Further information on the use of epoxy grouts for repair of cracks is given in Section 5.3.

6.5.5 *Repair of Cracks using Chemical Grouts*

Chemical grouts are normally composed of two or more components (urethane, sodium silicates and acrylomides) which combine to form a gel, a solid precipitate or a foam. Chemical grouts are particularly appropriate for sealing of cracks as narrow as 0,05 mm (0,002 in.) and are suitable for use in wet conditions.

Polyurethane grouts incorporating special catalyst elements can be used as one component systems, which react rapidly with water, forming a foam which increases in volume four times over. These are particularly useful for the initial sealing off of a steady flow of water through a crack. For best results, a wide range of trials are necessary to optimise the grouting procedures, including the selection of injection pressures, temperatures, and setting times. The foam grout is not totally rigid and can accommodate small movements during subsequent grout injections to fill the crack completely.

Mixing of chemical grouts can be done with use of a paddle or paint mixer for small applications. The injection pump should have a capacity of up to 300 bars (4350 psi) and be capable of maintaining the pressure in narrow ranges, in compliance with the trial tests carried out before commencement of grouting. A specially adapted stainless steel pump with simultaneous feeding of the two components is useful for large repairs.

The preparation of the cracks, the insertion of injection ports and sealing of the cracked surface prior to commencing the grouting operation is largely as described in Section 6.5.1. The spacing of the ports typically varies from 0.1 m (4 in.) for injecting in good dense concrete up to 0.30 m (12 in.) for masonry. In cases of steady water flow through cracks, the grouting procedure would typically follow the following steps:

- Inject the crack with a one component urethane grout to form an instant foam, which will reduce the velocity and quantity of seeping water; and
- Inject a second round of grout comprising a urethane consisting of two or more components to form a soft elastic resin, which fills the crack. The foam placed in the first round of grouting will be compressed. The new grout will bind both faces of the crack and form a seal.

In some cases it may be necessary to inject a third round of grout. This may happen when water confined in the pores of the concrete reacts with the resin injected in the second stage to form a foam which causes a loss of binding between the resin and the lining material. This reduction of the bond may allow water to start seeping through the crack again. The third round of grouting, involving a Polyurethane grout of two or more components will generally require increased injection pressures of up to 250 bars (3600 psi). While these pressures are not harmful to good concrete, care must be taken to ensure that the lining is not damaged, particularly in the case of old stone masonry or brick linings.

The advantage of Polyurethane grouts is the wide range of applications, which can be catered for. In the case of polyester materials, the chemistry of the resin system can be designed by varying the ratio of the proportions of resin to catalyst to provide a material with a particularly easy and reliable mixing and cure performance. Viscosity of the urethane resins can be varied, dependent on the speed of pumping and the injection pressure: low speed lowers the viscosity and vice versa. On the other hand, high pumping speed combined with larger quantities of material being injected, reduces the penetration of the resin as it comes into contact with the seeping water.

The disadvantage of using urethane grout is the necessity to carry out a comprehensive testing programme at the laboratory and at the site to optimise the mix of materials and the procedures for grouting. Furthermore it is necessary to use a skilled and experienced team to complete the sealing successfully. It should also be noted that some of the grouting components currently used are toxic, caustic or combustible (see Chapter 7). It is therefore important to ensure that the environmental conditions of the tunnel are not negatively impacted by the use of chemical grouts. It is also not possible to define the compressive and tensile strengths of hardened grout, which may be important in the confirmation of the structural integrity of the repaired liner.

There have been several examples of successful application of chemical grouts:

- Australia has reported successfully stopping leakages in a tunnel using a combined injection of Polyurethane and epoxy resin.
- Two subway tunnels in Belgium were sealed by the use of a one-component water reactive Polyurethane.

- The construction joint between the slab and walls in a German motorway tunnel was sealed using injection pipes to insert a one-component water reactive Polyurethane in grout. The material was modified to provide for a low viscosity, deep penetration and high strength properties.
- Japan has used two-stage injection of Polyurethane and epoxy resins to seal tunnel linings.
- Many tunnels in the USA were successfully treated by drilling 5/8-in. holes, equipped with rubber packers and one-way valves and injecting water reactive Polyurethane foam, applied two or three times until clear Polyurethane came out of the cracks.

6.6 Repair of Leaking Joints

6.6.1 *Construction Joints*

Construction joints in cast-in-situ concrete linings vary in design from a simple unkeyed joint through a key unbonded joint to a keyed, bonded and sealed joint. The sealed joint may incorporate one or more waterstops. Repairs to construction joints should therefore be preceded by a study of the construction drawings of the lining to confirm the joint configuration and location of waterstops and reinforcement, if any.

In cases of leaking construction joints, which incorporate a water stop, the problem is mostly associated with poor compaction of the concrete around the water stop. The location of the specific point of water ingress is difficult because the water tends to run along the water stop. In most cases the whole length of the joint has to be treated.

Repair of rigid bonded and unbonded construction joints can be carried out by grouting with Portland cement paste or microfine cement suspension (refer to Section 6.5.2 and 6.5.3 respectively), or in the case of damp joints, by cutting a groove extending either side of the joint and for the full length of the joint, which is then filled and sealed using the materials and repair methods as described in Section 5.2 of Chapter 5.

Water proofing of all other types of construction joints, particularly those with waterstops, is preferably done using chemical grouts as described Section 6.5.5. Injection of the grout is through drilled holes spaced at about 0.1m (4 in.) along the length of the joint, adjusting the hole locations locally to avoid any steel reinforcement. In a joint with an internal water stop, the depth of the holes should be alternated, so each second hole ends above the water stop, while the other hole penetrates the water stop. In this way the grout is enabled to seal around both sides of the water stop completely. In some cases construction joints are fitted with waterstops on the outside surface of the tunnel lining. In this situation the injection holes are drilled to within 0.1 m (4 in.) of the water stop, noting any variations in the thickness of the lining, to avoid penetration of the water stop. In all cases the adopted spacing of the injection ports, the viscosity of the grout and the grouting pressures should be confirmed by tests and field trials to ensure complete filling and sealing of the joint.

6.6.2 *Compensation or Expansion Joints*

Compensation joints allow for movements in the tunnel lining, caused by shrinkage or temperature changes. The design of the joints is similar to that of the construction joints, however they often incorporate a joint filler, which acts as a bond breaker, which is then covered by a sealing material placed along the surface of the joint. The method of sealing as described in this section is not appropriate for construction joints in linings having a thickness greater than 0,30m (1ft). Such joints are more effectively sealed using permeation grouting techniques as described in Section 6.8.

In order to seal leaking compensation joints, it will be necessary to remove the filler and the sealing material. Before commencement of grouting, a special adhesive sealing is applied around the surface of the joint to contain the grout. The spacing of the grout injection holes, the inclination of the holes to the lining surface, the type and viscosity of grout, and the injection pressures are all best determined by a comprehensive series of tests.

It is generally good practice to grout the whole of the joint, although the extent of the grouting can be varied dependent on the pressure and extent of the water inflow, the presence of voids and pores in the concrete, etc. The procedures for grouting are as described in Section 6.5.

In situations where the accommodation of movement in the joints is of particular importance, the excess grout should be cleaned out of the joint after completion of grouting, and the filler together with a bond breaker and the surface sealing should be replaced.

There are two reports from Germany referring to the application of Polyurethane foam and epoxy grouts in two tunnels. In the first, a rail transit tunnel with seepages of water through the joints, a major proportion of the joints were successfully sealed. Some points of water inflow could not be sealed to the standards set by the owner, Deutsche Bahn AG, which were tightness Class 1 (completely dry – refer Table 2-2, Chapter 2). In the second tunnel system comprising two motorway tunnels, the construction and expansion joints could not be satisfactorily sealed, even after three treatments: some of the joints are still seeping. In the latter case, the water head above the tunnel crown is up to 30 meters and this, together with squeezing ground conditions around the tunnel, is probably the principal reason for failing to seal the tunnel satisfactorily.

6.7 Sealing of Fissures in Rock Tunnels by Grouting

The procedure used to seal seeping fissures in rock tunnels, which have been excavated and left untreated, is similar to that used to seal cracks by grout injection in concrete lined tunnels. There are two principal types of materials currently in use: Polyurethane-based gels and resins; and Portland and microfine cements and materials. Before the development of microfine suspensions, only Portland cement suspensions including additives for workability, such as Bentonite, were used. Some aspects of particular note in comparing the injection in concrete and in rock are considered.

For successful sealing of rock fissures, the bond of the injected materials and the surface of the fissures of the rock is important. Each site is unique and a thorough testing program must be considered. These tests should take into account the water inflow pressures within the fissures. The width of the fissures dictates the material properties of the constituent parts of the grout. To insure a successful grout application and avoid early blockage of the fissure before it is complete, the maximum particle size of the grout should be no more than one third to one fifth of the width of the fissure.

In order to accomplish the desired distribution of the particle grout or the resin within the rock fissure and to determine the required injection pressure, special tests should be performed to analyze the rheological properties of the suspension of micro fine cements, or the properties of resin. In extremely tight fissures, the selection of grouts is limited to microfine cement suspensions or chemical grouts.

Testing the permeability of the rock would be useful to obtain an appropriate standard of waterproofing. The arrangement of the packers and the sealing of the apex of the fissure during the injection is dependent on the aforementioned tests and investigations. Once the results of the investigations are accepted, the procedure for injection should follow that described in Section 6.5.3 for the injection of microfine cement suspension, or in Section 6.5.5 for the injection of chemical grouts, as applicable.

6.8 Rehabilitation of moist areas in concrete linings by permeation grouting

Moist areas in concrete linings of tunnels generally arise from adverse properties of the lining such as lack of compaction, poor selection of aggregates, or cold joints inside the lining, all of which increase the porosity of the lining. Depending on the hydrostatic pressure in the granular skeleton of the concrete, there are different methods of treatment. At low ranges of pressure, the sealing of the surface may be done by patching with mortar. If the hydrostatic pressure is medium to high, a permeating injection of grout may successfully seal the leakage. Two types of grout materials are available for this purpose, comprising either water tolerant epoxy resins or urethane-based materials.

The first step of the grouting process is the confinement of the moist areas within the surrounding impermeable sound concrete. The design of the confining waterproof barrier is dependent on the thickness of the lining and the viscosity of the grout. The barrier is constructed by the injection of grout through two rows of ports installed around the moist areas. The spacing between each port and each row of ports encircling the moist area is approximately the same. Within these rows, a simple arrangement of equally spaced grouting ports throughout the moist area would be installed. The depth of the drilled holes for grouting, which form the barrier, would typically alternate between 40% and 80% of the intrinsic thickness of the lining. The permeation grout injection holes, within the confines of the barrier, may be drilled at depths alternating between 60% and 75% of the intrinsic thickness of the lining. When reinforced linings are being treated, it is obviously important to adjust the pattern of drillholes to avoid intersection of the rebars. Following the insertion of the injection ports, the surface area of the lining including an overlap of 0.50 m (20in.) outside the barrier is sealed using a special water tolerant adhesive and sealing mixture. The grouting is started at one port of the outer row of the barrier proceeding progressively around the outer row of ports, followed by the inner row of ports forming the barrier. If there is seeping or running water in the moist area, injection should be undertaken in the wet area itself, probably using a water reactive one-component Urethane grout to reduce the water inflow. Following this, the progressive grouting of the moist area is carried out to complete the sealing. With the exception of the case of sealing active water seepage or inflows, the appropriate chemical grout comprises a multi-component Urethane based material. The procedures for injection of the grouts are as described in Section 6.5.5.

On completion of the grouting, the surface seal treatment can be removed by grinding and the surface restored by the application of a suitable patching mortar, if surface appearances are important.

6.9 Conclusions

The treatment of water leakages through tunnel linings by the use of different types of grout and grouting techniques has been considered. There are a number of factors relating to the selection of grouting procedures and materials, which must be taken into account to achieve success and avoid abortive work. There is a wide range of materials and it is important to establish their performance criteria and appropriateness for specific applications.

With regard to the performance of repairs by grouting, the rate of success of the case histories considered varies between 40% and 60%. Some of these failures can be attributed to difficult working conditions. Temperature changes, varying quantities of leakage water and water vapour are some of the influences, which can determine the degree of success.

Notwithstanding this, the correct selection of equipment and materials, the employment of experienced construction crews, and the implementation of correct procedures with respect to preparation and grouting will play a major role in guaranteeing a high degree of success.

References:

[1] DIN 53211, issue 04.1974, test of paint materials, determination of the time of effusion with DIN-cup No. 4

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CHAPTER 7

ELIMINATION OF LEAKAGE AT SOURCE

7.1 Introduction

Leakage in tunnels may result either from infiltration of groundwater or the exfiltration of any fluid transported in the tunnel. The most common type of leakage encountered is groundwater infiltration, occurring in rail, highway or pedestrian tunnels. Exfiltration leaks typically occur in high pressure penstocks in hydroelectric schemes, water supply aqueducts and sewer systems. In general and particularly with regard to exfiltration, the leakage is controlled by the use of liner repair techniques as described in Chapter 6.

However, in extreme cases or in cases where the water leakage has created an avenue for the transport of the soil or rock surrounding the tunnel, the use of ground modification systems is required either to restore the structural integrity of the soil and rock mass or to create an impermeable zone around the tunnel. This is a specialist and extensive subject, which is generally very site specific.

This chapter considers only infiltration of water into the tunnel and the most common methods for the modification of the soil or rock around the tunnels, identifying the typical grouting procedures for the elimination of the groundwater inflow at the source.

7.2 Soil Grouting

The method of grouting soils is dependent on the type and permeability of the soils. Prior to the selection of the grouting method and the type of grout to be used, an extensive exploration programme must be undertaken to determine the soil properties. This exploration programme is similar to that used for the design of tunnels, with the exception that more attention is given to the determination of the grain size distribution and the permeability of the soils.

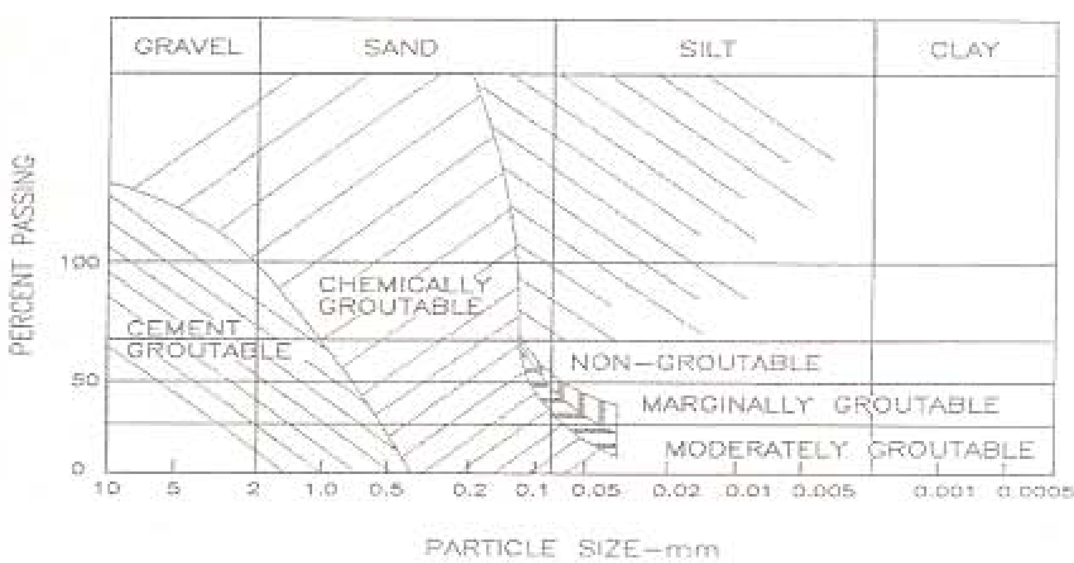

Figure 7-1: Grain-size ranges for groutable soils[1].

The influence of grain size distribution on the groutability of the soil mass is illustrated by Baker (1992)[1] and shown in Figure 7-1. This programme should include the use of trace dyes to determine the connectivity of the area to be grouted and that of the structure which is to be protected. Once the grain size distribution and permeability data is known, the appropriate site specific method and grout material for the reduction of permeability of the ground mass can be selected.

7.2.1 *Grouting Methods*

The methods for grouting soil for groundwater control fall into three basic categories:

- Permeation grouting;
- Displacement grouting; and
- Replacement grouting.

Permeation grouting is the most common method used today. This is a system where grout is pumped under pressure and is used to fill the voids and interstices in the existing soil.

Displacement grouting (compaction grouting) is a process in which the grout is injected under great pressure to displace the existing soil and thereby "tighten up" the soil mass and fill the area created by the injection with a cementitious grout.

Replacement grouting (jet grouting) is a process that uses high pressure jets to remove the soil in a specific locale and replace the soil with a cementitious grout.

The selection of which process to be used must be made in conjunction with the selection of the grout type. In general the groutability of soils is determined by the percentage of fines (percent passing a 200 sieve). Gularte (1989)[2] has applied the aforementioned methods in relation to the grain size distribution of the soils to determine which method is generally used for the reduction of groundwater transmissibility. Figure 7-2 illustrates the relationship between injection method and grain size distribution. The horizontal lines (arrows) illustrate the range of successful grouting in relation to grain size.

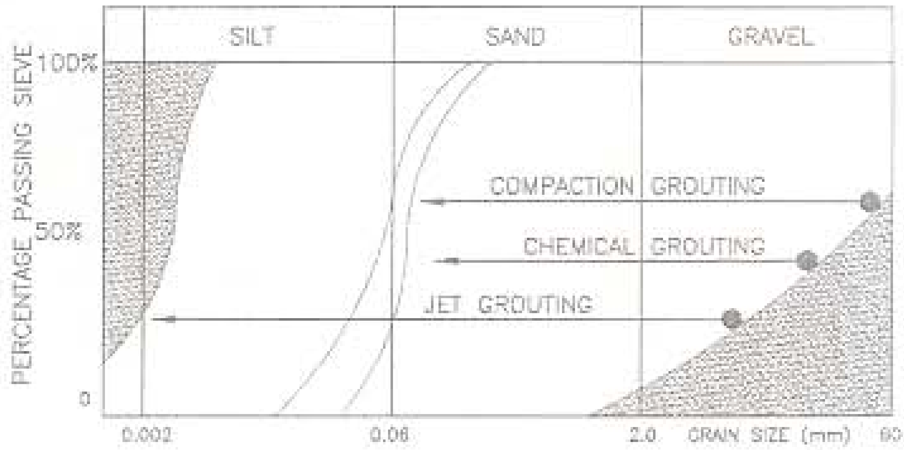

Figure 7-2: Grouting Method and Soil Type[2].

7.3 Rock Grouting

The grouting of rock lined tunnels to seal all types of fissures and voids in rock masses has been common practice in the United States and Europe for over a century. The process during this time has changed little, however the use of new chemical and particle grouts has advanced the practice of rock grouting and made the sealing of the voids in rock masses more effective and efficient.

7.3.1 *Grouting Methods*

The injection of grout into rock masses requires more sophisticated drilling methods than that for grouting concrete lined tunnels. The equipment used for the drilling of the injection holes (ports) is divided into three basic types:

- Low Speed Rotary/High Torque Rotary: a rotary drilling rig with very high torque, which uses the thrust of the bit to advance the hole. This system uses a variety of drag, roller, and finger bits suited to the rock type to drill to the desired depth for grout injection. This system is used for boreholes of large diameter, usually greater than 100 mm.
- High Speed/Low Torque Rotary: small drill rigs using small diameter diamond rock-coring bits. This system is often used to recover rock samples for inspection and is used for holes up to 100 mm.
- Rotary Percussion: the advancement of a borehole by the use of a percussion hammer. This system uses either a top drive with the hammer mounted at the drill rig or a down-the-hole hammer, which is mounted at the bottom of the drill string and is operated by the use of compressed air. Button or cross bits are used and the hole is advanced by the impact of the bit against the rock.

The selection of the proper method of advancing the borehole to the zone to be injected is dependent on the geology of the bedrock, the severity of the leak accessibility, availability of equipment and the cost of the drilling operation. There are three basic methods (Bruce, 1999)[3], which are the most commonly used:

- Downstage (descending stage) with top hole packer
- Downstage with downhole packer
- Upstage(ascending Stage)

Descending stage grouting is used where the rock is weak or highly fractured and needs to be consolidated at the surface, before grouting the deeper zones at high pressures. This entails drilling the grout hole to a specified limited depth, placing a packer at the top of the hole and grouting, prior to drilling the hole to a greater depth and repeating the process. The grout is usually washed out of the hole after initial set to minimise re-drilling for the lower stages. Some practitioners grout all successive stages with the packer at the top of the hole. However, it is considered preferable that the packer for each successive stage is set at the bottom of the preceding stage.

With ascending stage grouting, the hole is drilled continuously to the full planned depth, prior to commencement of grouting. Grouting is then carried out in a number of stages, commencing with the packer placed at the top of the lowest grouting stage. When that stage has been grouted to refusal and the backpressure has dissipated, the packer is raised to the top of the next stage up and the process is repeated.

7.4 Grout Selection

The grouts available for injection to stop water infiltration and seal concrete, masonry and rock lined tunnels are of two basic types:

- Particle grouts
- Chemical grouts

7.4.1 *Particle Grouts*

Particle grouts consist of cementitious materials, often modified with flyash and other chemical additives. All particle grouts have low toxicity and are non-flexible after curing. The lack of flexibility creates the potential for reinjection, if any movement of the structure occurs. The properties of the common types of particle grouts are presented in Table 7-1. Particle grouts are used for displacement grouting and replacement grouting of the surrounding soil and rock mass. They are also used to seal off open fissures in bedrock and to stabilise the rock mass.

Particle grouts are typically injected with a piston or worm type pump. The grout mix depends on the permeability of the rock mass, water flow, desired cure time and the environmental conditions of the rock to be injected. The spacing of the injection tubes must be designed to ensure a full permeation of the grout zone. The injection is often performed in numerous passes in order to allow for an initial set of the grout, while controlling the quantity of grout used. Injection pressures depend on the depth below the watertable for the injection and the permeability of the rock to be injected. However, caution must be exercised in the injection of grout to prevent hydro-fracturing of the tunnel liner by the injection process.

Description	Viscosity	Toxicity	Strength	Remarks
Particle Grout				
Flyash Type F;C	High (50 cps- 2:1)	Low	High	Nonflexible
Type I Cement	High (50 cps-2:1)	Low	High	Nonflexible
Type III Cement	Med (15 cps-2:1)	Low	High	Nonflexible
Microfine Cement	Low (8 cps-2:1)	Low	High	Nonflexible
Microfine Cement/silicate	Low (10 cps-2:1)	Low	High	Nonflexible
Bentonite	High (50 cps-2:1)	Low	Low	Semi-flexible
Chemical Grout				
Acrylamides	Low (2:1)	High	Low	Flexible
Acrylates	Low	Low	High	Flexible, poor success record
Silicates	Low (6 cps)	Low	High	Nonflexible, high shrinkage
Lignosulfates	Med (8 cps)	High	Low	Flexible, high cost
Polyurethane (MDI)	High (100 cps)	Med	Low	Flexible, low shrinkage, water reactive
Polyurethane(TDI)	High (300 cps)	Med	Low	Flexible

Table 7-1 Comparison of Properties of Grout Materials

7.4.2 *Chemical Grouts*

Chemical grouts are the most successful grouts in the sealing of groundwater infiltration in the sealing of leaks in the tunnel liners. These grouts have various degrees of flexibility after curing. The viscosities of the grouts range from 1 cps to over 300 cps. The use of a particular grout is site and application specific. In general the use of a specific chemical grout is based on its ability to suitably penetrate the specific soil/rock that is to be injected. Table 7-1 compares the various common chemical grout types and their ability to penetrate soils and bedrock in terms of viscosity, as well as presenting other characteristics such as toxicity, strength, and flexibility.

The use of toxic grout materials cannot be recommended because of the danger of seriously contaminating the groundwater with which they come into contact.

Chemical grouts are commonly injected by the use of a piston pump and, in the case of multi components grouts, the two stage mixing piston or worm type pump is used. The type of pump is dependent on the grout manufacturer's requirements and the depths to which the grout is to be placed. Chemical grouts must be easily mixable, have a controlled "gel" or set time, be nontoxic, non-corrosive, nonexplosive, catalysed with common chemicals and be insensitive to compounds normally found in groundwater.

Chemical grouts are used for soil and for inrock grouting at locations where the use of particle grouts is not effective due to the low permeability of the material to be injected. They are most commonly used in fine sands, silts and clayey soils, and in some instances for fractured rock. In general the cost of chemical grouts is greater than that of particle grouts and therefore is not commonly used except in instances where the particle grouts are not effective. Chemical (polyurethane) grouts have been used extensively for the application of permeation grouting repairs in rail tunnels in the United States and Europe, at locations with seismic activity, and a flexible repair is required.

7.5 Conclusions

The control of groundwater infiltration in tunnels and underground structures is a complex process. Many elements come into play to successfully control the leakage from the surrounding soil and rock. The intention of the Study is to create awareness that there is not one universal solution to the control of the leakage. The selection of the appropriate method to control the infiltration is site and operationally specific.

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CHAPTER 8

CONCLUSIONS

8.1 General

As tunnels internationally and particularly in Europe become older, the matter of maintenance and repair adopts an every increasing degree of importance. Furthermore as population densities and mobility grow, as industry develops, requiring increased and faster movement of goods and raw materials, and as modes of transport increase in efficiency in terms of size, frequency and speed, the older tunnels are being called upon to perform a service for which they were not originally designed. This leads to increased wear and rate of deterioration of the tunnel structure.

Tunnels and underground structures are constructed at high cost and provide a high value service to the regional or national economy, as either a transport link (rail or vehicular) or carrier of essential services.

Taking all of these factors into account, the effective repair of tunnels as part of a structured maintenance programme to ensure that they perform safely and efficiently is critically important.

This report provides guidelines on the aspects to be considered, the investigations and tests to be undertaken, the selection of materials to be made, and the procedures to be adopted to successfully repair a tunnel using the most appropriate techniques. The guidelines are based on an analysis of case history data provided by the member nations of ITA and the experience and expertise of the contributing members of ITA Working Group No 6.

As such, the report provides a useful tool in the hands of tunnel owners, consulting engineers and construction companies to extend the useful life of their valuable tunnel asset for as long as possible.

8.2 Analysis of Case History Data

The data forming the basis of this report was split into two components, one considering damage resulting from leakage and the repair thereof, and the other considering all other types of damage, with the exception of fire. A summary of the data collected is presented in Appendices A and B respectively.

The number of case histories of repairs dealing with leakage was 106, while those related to repair of damage excluding leakage numbered 51. Of the latter 51 cases, leakage into the tunnel had some affect on the extent of the damage in 17 cases. Therefore only 34 cases out of a total of 157 (20%) considered in the study were not related to water leakage in anyway.

From this it is clear that water leakage is the principal cause of damage to and degradation of tunnel linings. It has accordingly received more attention in the report; Chapters 4, 6 and 7 consider the repair of leakage exclusively, while Chapter 5 deals with the other causes of damage and their treatment.

8.2.1 *Case Histories of Treatment of Water Leakage*

A summary of the case history data is given in Appendix A of the report. From these data, Figure 1 analyses the types of leakage treated (the terminology used to describe the leakage is defined in Table 2-3 in Chapter 2).

The more significant leaks in terms of flow, comprising continuous leaks and drips, formed the major percentage of leaks reported in the case histories; 33% and 30% respectively. However, it would be unwise to draw the conclusion that this is the major form of leakage, because it can be expected that the more severe cases of damage involving major repair works would be recorded in more detail than the less critical cases.

However, more importantly, Figure 2 shows that only 57% of the repairs were successful. Taking into account the 7% of cases where the effectiveness of the repairs was not reported on, this percentage could grow to 64%. This indicates that in at least 36% and up to 43% of the cases, successful and permanent repairs were not accomplished. A further 28% of the repairs were only reasonably successful.

Figure 3 shows the effectiveness of the repairs related to the type of leakage encountered. Table 8-1 gives an analysis of these data. For reasons given before, no firm conclusion can be made with regard to the cases of low leakage (seep and damp patch), and the reported 100% success of all repairs in these categories can be regarded as misleading. The percentage of successful repairs for the larger leaks (standing drop to continuous) varied from 47% to 60%

Type of leak	No. of Cases	% Degree of Success		
		Successful %	Reasonably Successful %	Poor Success %
Continuous	35	60	23	9
Drip	32	53	31	3
Standing drop	15	47	33	7
Seep	4	100	-	-
Damp patch	2	100	-	-
Others	18	50	4	6

Table 8-1: Degree of Success in Treating Different Types of leaks

Although it is recognised that in a number of these cases of unsuccessful treatment, the tunnel continues to operate efficiently and that an effective repair was not achieved because of limitations on access imposed by the tunnel operations, the number of unsuccessful repairs still represents an alarmingly high percentage of the number of cases considered.

Figure 4 shows the degree of success of the different overall types of repair methods. Of the two which are considered in the report, "Conduction of Water Leakage on the Surface and Disposal" and "Sealing of Leakage" referred to in the figure as Conduction and Stoppage respectively, there were similar degrees of success : 54% and 59% successful; 5% and 4% poor success; and 32% and 29% reasonably successful respectively.

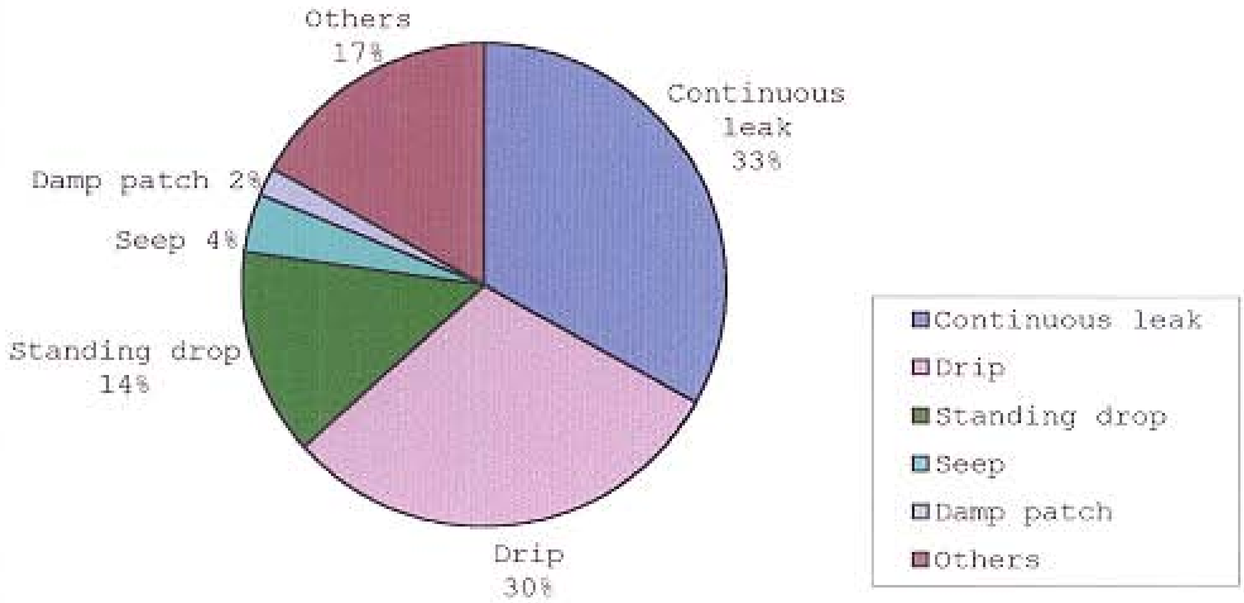

Fig.1 Type of Leakage as Reported
(Total no. of Cases: 106)

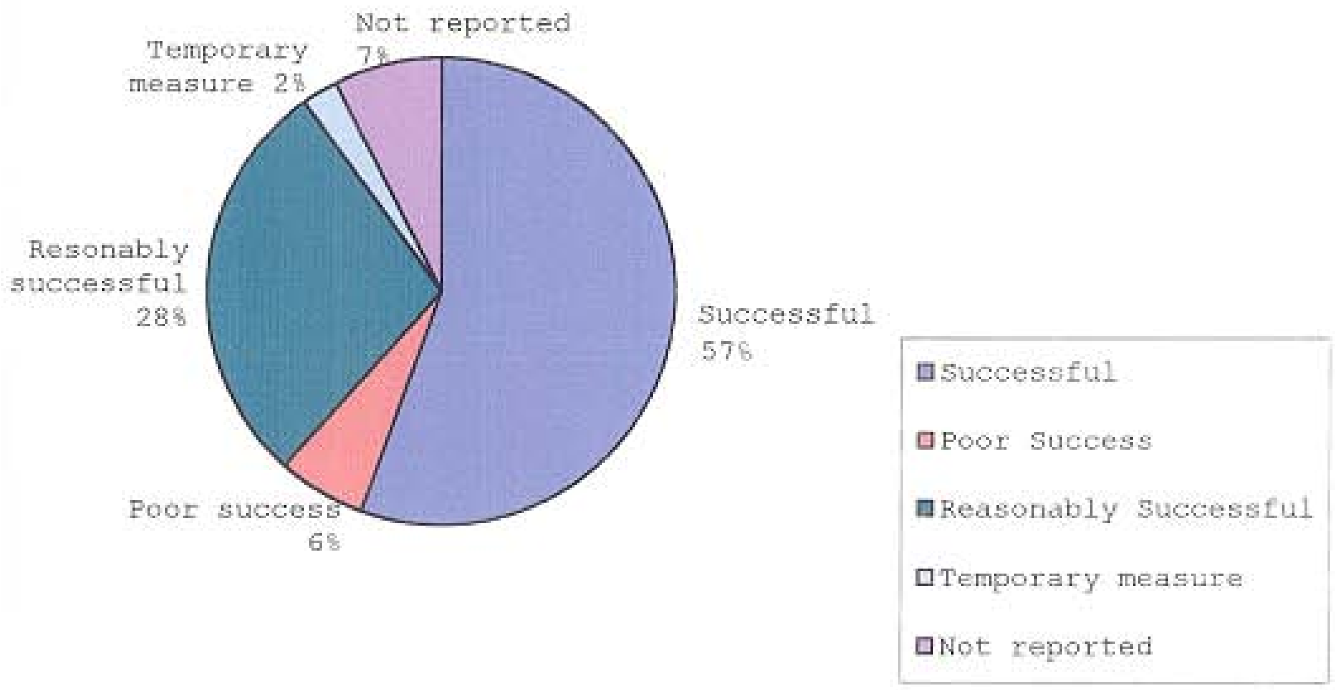

Fig.2 Leakage Repair Effectiveness
(Total no. of Cases: 81)

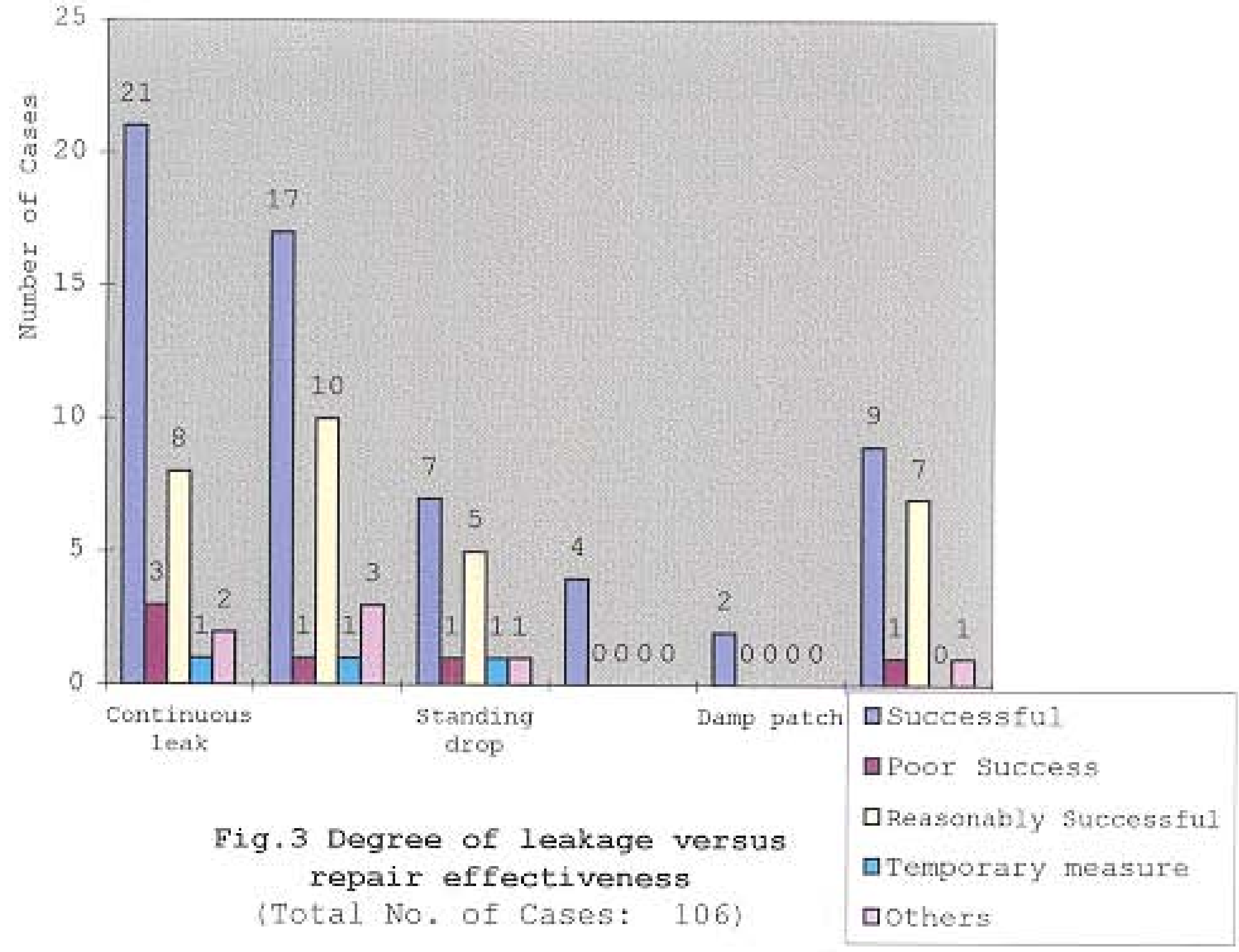

Fig.3 Degree of leakage versus repair effectiveness
(Total No. of Cases: 106)

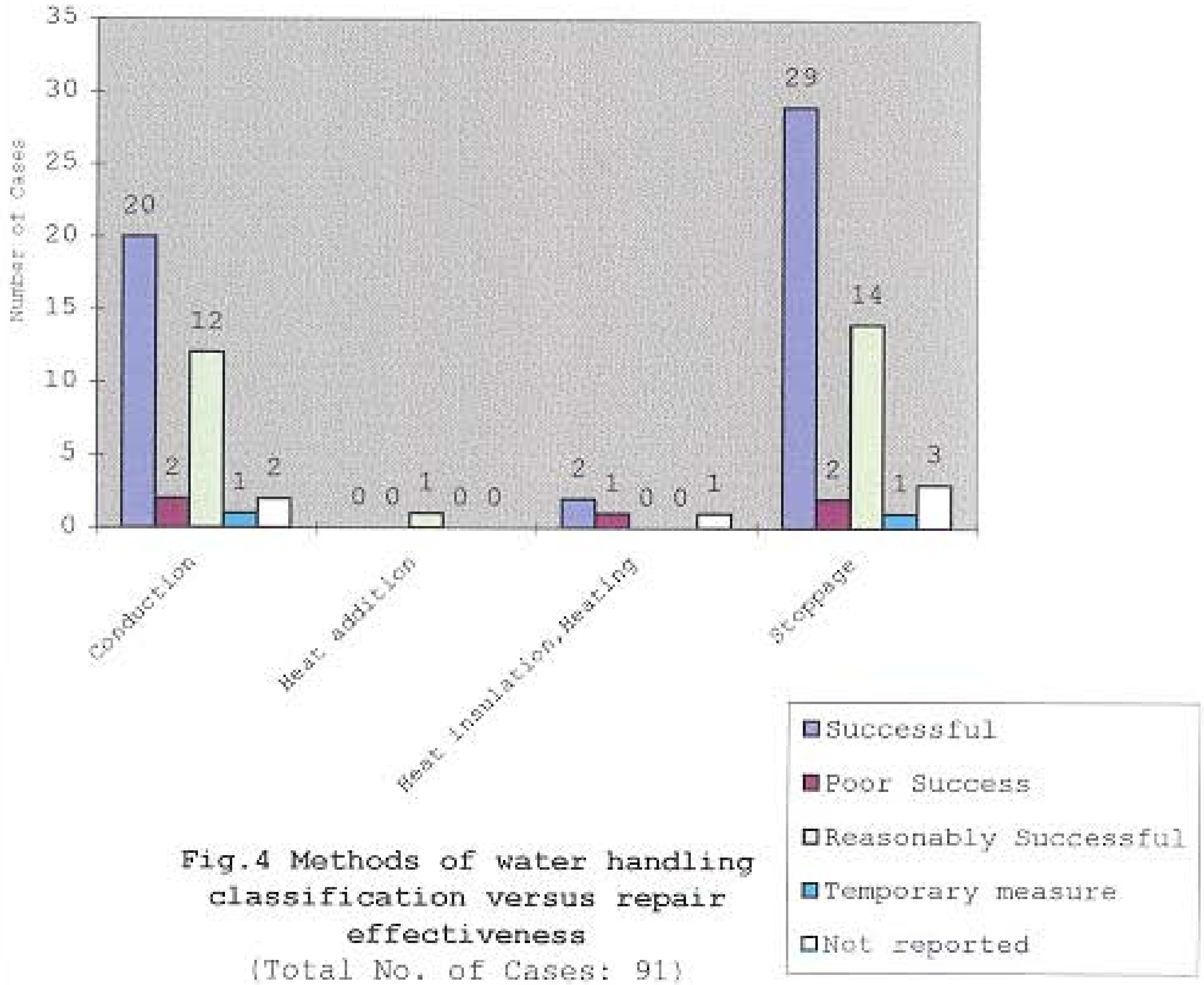

Fig.4 Methods of water handling classification versus repair effectiveness
(Total No. of Cases: 91)

In all of the above, the importance of using appropriate repair methods and materials is clear. Tunnels represent a high capital investment and make an often vital contribution to the region's economy. It is important to maintain them properly by undertaking appropriate and effective repairs, as and when required. The case histories would indicate the need for considerable improvement in this regard.

Figures 5, 6 and 7 indicate the broad range of tunnels and types of excavation and lining which were covered by the case histories, thereby confirming the integrity of the report findings.

8.2.2 *Case Histories of Repairs Excluding Water Leakage*

A summary of the data collected from the case histories reported is presented in Appendix B. Although the study covered all types of tunnels in terms of their usage, the large majority of case histories related to road and rail tunnels, with the greatest number being rail tunnels. This is understandable for a number of reasons: the majority of existing tunnels comprise transport tunnels; many of the railway tunnels in particular are old and require more maintenance; access for repair and maintenance is generally easier; and the operators place a natural emphasis on the safety of the members of the public using the tunnels. Table 8-2 gives a breakdown of the numbers of case histories in terms of type of usage and types of liner.

Tunnel Usage	**No. of Case Histories for Different Linings**					
	Total No.	**Precast Concrete Segments**	**Cast-in-Situ Concrete**	**Steel Segments[1]**	**Cast Iron Segments**	**Brick / Masonry**
Road	14	2	12			
Rail	19	2	2		1	14
Water	6		5			1
Sewer	2		1	(1)		1
Pedestrian	1	1				
Power Substation	1		1	(1)		
Telecommunication	2		2	(1)		
TOTAL NO.	45	5	23	(3)	1	16

Table 8-2: Analysis of Case Histories – Tunnel Usage and Types of Liner
(Note 1: Steel segments were always used in conjunction with a cast-in-place concrete lining.)

The case histories indicate commonality in the type of damage related to the operational uses of the tunnel. This can be expected for two principal reasons:

- Common operating environment, e.g. exhaust gases and frost damage in road and rail tunnels;
- Common types of lining material because common sizes and configurations of tunnel are determined by the use and operating conditions of the tunnel.

Of the 52 cases of repair (45 tunnels), 14 cases of repairs (i.e. 27%) could be attributed to damage caused during construction: poor workmanship and/or the use of inferior construction materials. Other common causes of damage requiring repair were ageing (8 cases) and operating environment (8 cases).

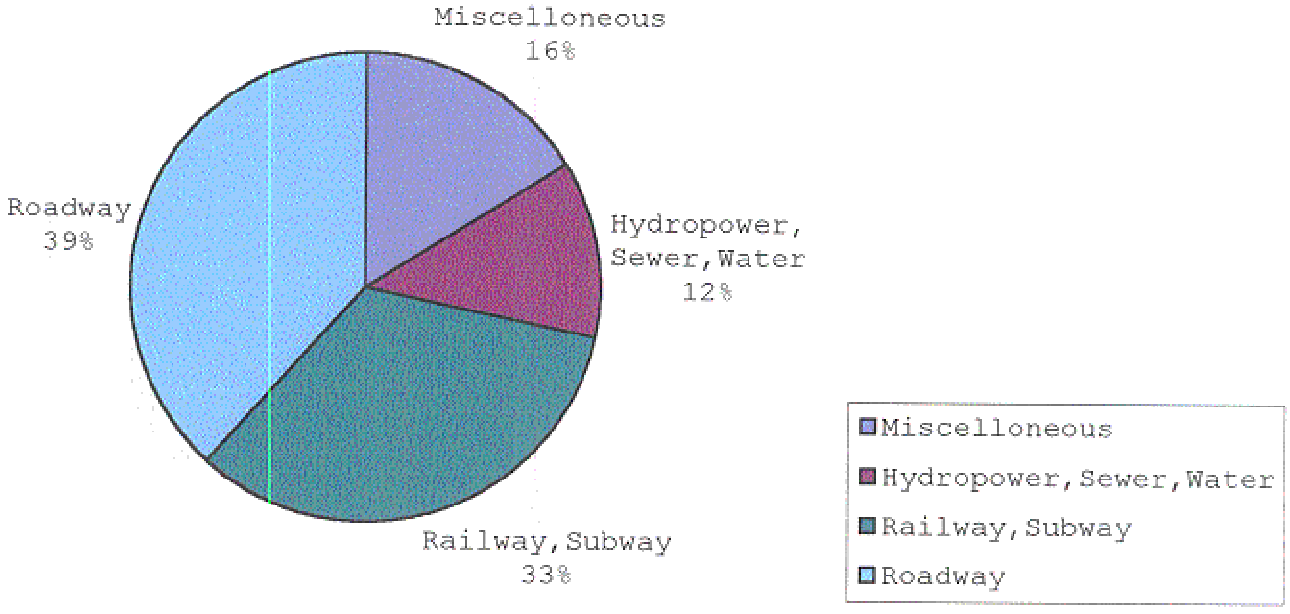

Fig.5 Types of tunnel considered in the leakage study
(Total No. of Cases: 81)

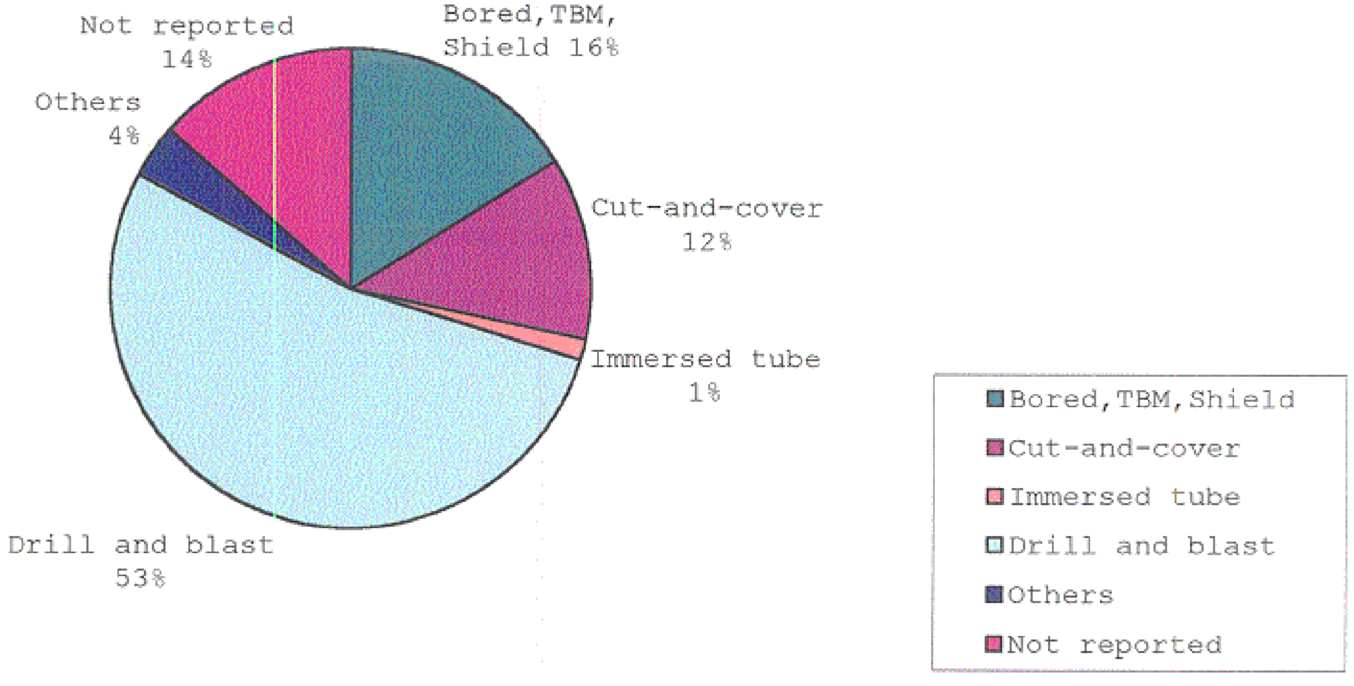

Fig.6 Types of excavation method considered in the leakage study
(Total No. of Cases: 91)

This highlights the importance of using good construction techniques and materials. This applies to the avoidance of damage caused not only by factors other than leakage, but also by leakage.

8.3 Methods of Repair

From the case histories, the more common causes of damage have been identified and the most appropriate measures of repair have been selected, based on the experience shown in these case histories and the latest technology in terms of materials and techniques. These are described in Chapters 5 to 7 of this report.

The six common rules for success for each of these methods are the giving of adequate attention by experts to the following;

- Comprehensive investigation of the damage;
- Analysis of the impact of the damage on the tunnel structure taking into account the external and internal environments, the lining materials, and the structural integrity of the lining;
- Selection of appropriate and cost effective repair procedures and materials taking into account the results of the above investigations and analysis, as well as the available skills and access conditions for carrying out the repair;
- Carrying out of tests and field trials to confirm the above selection and to refine and optimise the procedures and materials;
- Utilisation of experienced repair crews and well maintained equipment; and
- Good standards of workmanship and quality control.

The above rules may appear obvious, but the relatively high rate of failure or incomplete effectiveness of repair works, as indicated by the case histories studied, would indicate that these rules are not sufficiently adhered to. It is important to note that all repairs are site specific and must be performed utilizing the aforementioned rules to ensure success. This report provides guidelines and recommendations to assist in achieving that success in a wide range of rehabilitation and repair works.

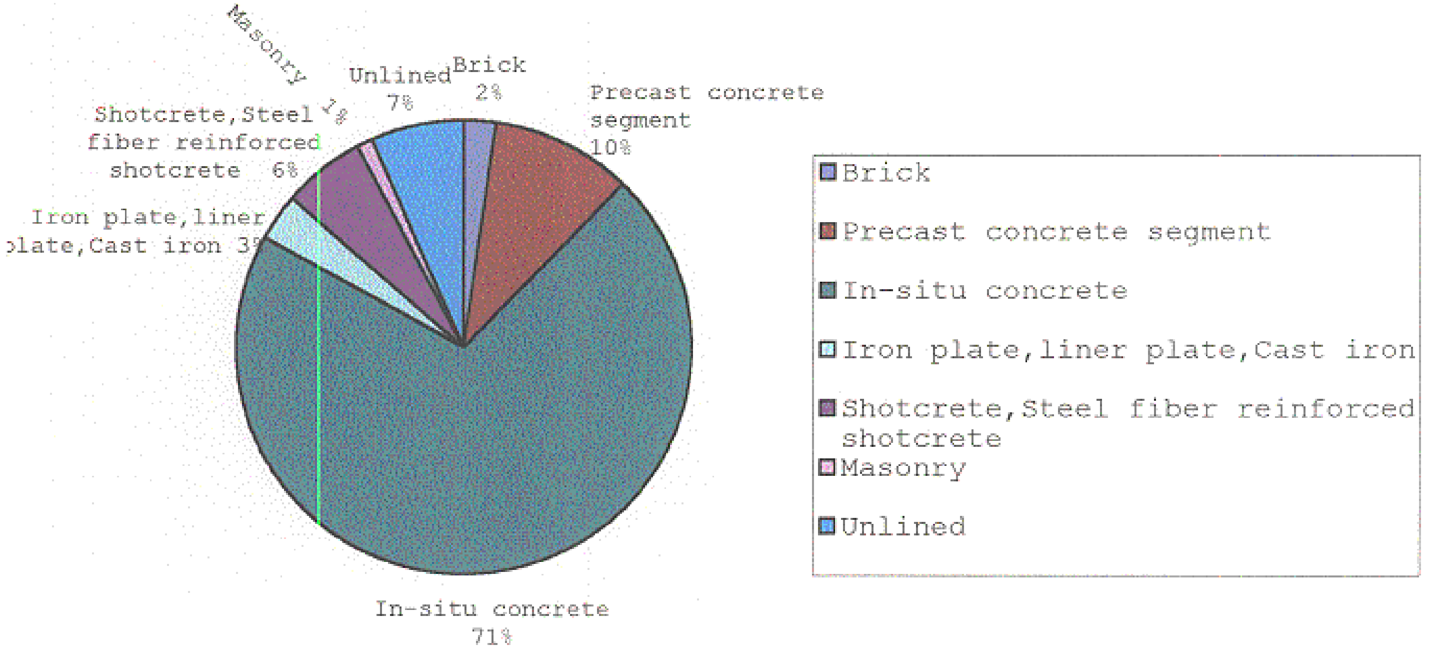

Fig.7 Types of lining considered in the leakage study
(Total No. of Cases: 95)

APPENDIX A

CASE HISTORIES OF WATER LEAKAGE

SUMMARY OF LEAK SEALING CASE HISTORIES COLLECTED

COUNTRY	USE	EXC_ METHOD	LINING1	LINING2	GEOLOGY	LEAKAGE	CLASSIFY	METHOD_REP	EFFECTIVE	YEARS
Australia	Roadway	Mined	In-situ-concrete		Massive sandstone	Drip	Conduction	Crack injection/water conduit	Effective	#N/A
Austria	Roadway	Mined	In-situ-concrete	In-situ-concrete		Drip	Conduction	Waterproof sheet	in commision	NA
Austria	Roadway	Mined	Unlined	In-situ-concrete		Drip/continuous leak	Conduction	Waterproof sheet	Effective	NA
Austria	Roadway	Mined	Shotcrete/partly	In-situ-concrete		Drip	Conduction	Waterproof sheet	Effective	NA
Belgium	Subway	Shield	Precast concrete		Sand and clay	Drip/continuous leak	Stoppage	Crack injection/channel cut + fill	Effective	4
Belgium	Subway	Cut-and-cover	Slurry walls		Sand	Drip/continuous leak	Stoppage	Crack injection	Effective	#N/A
Canada	Subway	TBM	Ribs w/ wooden laggings	cast-in place-concrete	Glacial till	Drip	Stoppage	Crack injection	Limited effectivness	10
Canada	Rail Tunnel	Cut-and-cover	Shotcrete	cast-in place-concrete		Drip	Conduction	Water conduit / Heat tracing	NA	
Canada	Rail Tunnel	Bored excavation	Shotcrete	cast-in place-concrete		Varies	Conduction	Water conduit	Somewhat effective	
Canada	Railway-LRT	NATM	Ribs w/shotcrete	concrete	Wet sand	Continuous Leak	Stoppage	Channel cut & Filling	Limited effectivness	
Canada	Railway-LRT	NATM	Ribs w/shotcrete	concrete	Wet sand	Continuous Leak	Heating	Heat tracing	in construction	
China	Railway	Mined	In-situ-concrete		#N/A	Drip	Stoppage	Back fill grout	in construction	
Cuba	Roadway	Immersed tube	Prestressed concrete		Backfill	Drip/continuous leak	Stoppage/conduction	Crack injection/water conduit	Limited effectivness	
France	Roadway	#N/A	In-situ-concrete		#N/A	#N/A	nduction	sheet/drainage/shotcre	Effective	#N/A
France	Roadway	#N/A	In-situ-concrete		#N/A	#N/A	nduction	Channel cut + fill	Effective	#N/A
France	Roadway	#N/A	In-situ-concrete		#N/A	#N/A	nduction	Channel cut + fill	Effective	#N/A
France	Roadway	#N/A	Shotcrete		#N/A	#N/A	nduction	sheet/drainage/shotcre	Effective	#N/A
France	Roadway	#N/A	In-situ-concrete		#N/A	#N/A	Conduction	sheet/drainage	Somewhat effective	#N/A
France	Roadway	#N/A	Unlined		Rock	#N/A	Stoppage/conduction	Waterproof sheet/drainage/shotcrete	Effective	#N/A
France	Roadway	#N/A	Unlined		Rock	#N/A	Conduction	Waterproof plate	Somewhat effective	#N/A
France	Roadway	#N/A	In-situ-concrete		#N/A	#N/A	nduction	sheet	Somewhat effective	#N/A
France	Roadway	#N/A	In-situ-concrete		#N/A	#N/A	nduction	sheet	Somewhat effective	#N/A
France	Roadway	#N/A	In-situ-concrete		#N/A	#N/A	nduction	Channel cut/drain hole	Somewhat effective	#N/A

Germany	Roadway	Cut-and-cover	Secant pile walls		Sandy gravel	Continuous Leak	Stoppage	Crack injection/penetration grouting soil	Temporary measure	
Germany	Roadway	Roadheader	Shotcrete	In-situ-concrete	Glacial deposites	Seep	Stoppage	Joint injection	Somewhat effective	12
Germany	Subway	Mined	Shotcrete	In-situ-concrete	Anhydrite/sand stone	Seep	Stoppage	Joint injection/fissure injection	Somewhat effective	10
Italy	Roadway	Mined	In-situ-concrete		#N/A	leak	Stoppage	Channel cut + fill	Effective	2
Italy	Roadway	Mined	Shotcrete	In-situ-concrete	#N/A	Continuous Leak	Stoppage	Lining replacement/back fill grouting	Effective	3
Italy	Roadway	Mined	Shotcrete	In-situ-concrete	Rock	Continuous Leak	Stoppage	Surface rest. w/ sprayed concrete/backfill grouting	Effective	5
Italy	Roadway	Mined	In-situ-concrete		Rock	Seep	Conduction	Drain hole	Effective	2
Italy	Railway	Various	Puddled concrete		#N/A	Drip/continuous leak	Conduction	Channel cut	Effective	#N/A
Italy	Roadway	Mined	In-situ-concrete		#N/A	Damp Patch	Stoppage	Spraying	Effective	#N/A
Italy	Roadway	Mined	In-situ-concrete		#N/A	Seep	Stoppage	sheet/structural lining	Effective	#N/A
Italy	Roadway	Mined	In-situ-concrete		#N/A	Drop/seep	Conduction	hole	Effective	4
Italy	Roadway	Mined	In-situ-concrete		#N/A	Drip	insulation/he	etc./waterproof	Effective	#N/A
Japan	Roadway	Mined	In-situ-concrete		Granite	Standing Drop/drip	Conduction	Water conduit	Effective	#N/A
Japan	Roadway	Cut-and-cover	In-situ-concrete		backfill	Standing Drop/drip	Conduction	Water conduit	Somewhat effective	#N/A
Japan	Railway	Mined	In-situ-concrete		Tuff	Standing Drop/drip	Conduction	Water conduit	Somewhat effective	#N/A
Japan	Subway	Cut-and-cover	In-situ-concrete		Sand	Standing Drop/drip	Conduction	Water conduit	Temporary measure	#N/A
Japan	Roadway	#N/A	In-situ-concrete		#N/A	Drop/drip/contin	Conduction	Channel cut	Limited effectivness	
Japan	Roadway	Mined	Shotcrete	In-situ-concrete	Granite	Damp Patch/seep	Conduction	Channel cut	Effective	#N/A
Japan	Railway	Mined	In-situ-concrete		Tuff	Standing Drop/drip	Conduction	Channel cut	Somewhat effective	#N/A
Japan	Water	Mined	In-situ-concrete		Sandstone	Standing Drop/drip/continuous leak	Conduction	Channel cut	Effective	3
Japan	Roadway	Bored	In-situ-concrete		#N/A	Drop/drip	Stoppage	Channel cut + fill	Somewhat effective	5

Japan	Subway	Cut-and-cover	In-situ-concrete		Loam/sandy clay/clay	Standing Drop/drip	Stoppage	Crack injection/channel cut + fill	Effective	4
Japan	Hydropower	Mined	In-situ-concrete		Tuff	Standing Drop/drip, damp patch/seep	Stoppage	Fissure sealing	Effective	2
Japan	Cable	Cut-and-cover	In-situ-concrete		Sand	Standing Drop/drip	Stoppage	Crack injection/channel cut + fill	Effective	8
Japan	Roadway	Mined	In-situ-concrete		Slate/sandstone	Damp Patch/seep, standing drop/drip	Stoppage	Crack injection	Effective	2
Japan	Subway	Shield	Precast concrete		Sand	Standing Drop/drip	Stoppage	Crack injection/channel cut + fill	Effective	7
Japan	Subway	Cut-and-cover	In-situ-concrete		Loam/sandy clay/clay	Standing Drop/drip	Stoppage	Crack injection/channel cut + fill	Effective	4
Japan	Cable	Cut-and-cover	In-situ-concrete		#N/A	Continuous Leak	Stoppage	Crack injection	Effective	6
Japan	Railway	Mined	In-situ-concrete		Sandstone/shale	Continuous Leak	Conduction	Waterproof plate	Effective	#N/A
Japan	Roadway	Mined	In-situ-concrete		Rhyolite/tuff	Continuous Leak	Conduction	Waterproof sheet/precast concrete	Effective	#N/A
Japan	Railway	Mined	Bricks		Tuff	Standing Drop/drip	Stoppage	Spraying	Limited effectivness	
Japan	Railway	Mined	Bricks		Tuff	Standing Drop/drip	Stoppage	Coating	Somewhat effective	#N/A
Japan	Railway	Mined	Concrete blocks		Sandstone	Standing Drop/drip	Stoppage	Back fill grout	Effective	#N/A
Japan	Roadway	Mined	Shotcrete	stonework	Slate	Continuous Leak	Ground water lowering	Drain hole	Somewhat effective	#N/A
Japan	Railway	Mined	In-situ-concrete	In-situ-concrete	Sandy tuff, dacite/tuff	Continuous Leak (gushing)	Ground water lowering	Drain gutter lowering/back fill grout	Somewhat effective	#N/A
Japan	Roadway	Mined	In-situ-concrete		Granite, diolite	Continuous Leak	Ground water lowering	Drain boring	Effective	#N/A

Japan	Railway	Mined	In-situ-concrete		Fine sand	Continuous Leak	Ground water lowering	Well-point	Limited effectivness	
Japan	Roadway	Mined	In-situ-concrete		#N/A	#N/A	insulation	surface	Effective	#N/A
Japan	Railway	Mined	Concrete blocks	In-situ-concrete	Tuff	Standing Drop/drip	Heat insulation	Thermal insulation of surface/waterproof sheet	#N/A	#N/A
Japan	Railway	Mined	In-situ-concrete		Mudstone	Continuous Leak	Heating	Electric heater etc.	Somewhat effective	#N/A
RSA	Machine sha	Mined	Shotcrete	In-situ-concrete		Continuous Leak	Conduction / stoppage	Membrane / conducts / grouting	Effective	#N/A
RSA	Railway	Mined	Shotcrete	In-situ-concrete		leak	Conduction	Water conduit	Limited effectivness	#N/A
RSA	Mining tunne	Mined	none	none		Leak	Stoppage	Rock grouting	Effective	#N/A
RSA	Valve chamb	Mined	In-situ-concrete		Granite	Drip	Stoppage	Back fill grout	#N/A	#N/A
RSA	Access shaft	Caisson	Precast concrete		Granite	Drip	Stoppage	Back fill grout	#N/A	#N/A
Sweden	Research	Mined	In-situ-concrete	ironplate	Rock	Continuous Leak	Conduction	Water conduit	Effective	#N/A
Switzerland	Roadway	Mined	Masonry	ironplate		Standing Drop	stoppage	sheet	Works in progress	NA
Switzerland	Railway	Mined	In-situ-concrete,50%			Drip	Conduction	Waterproof plate	Effective	NA
Switzerland	Cableway	Mined	Masonry	corrugated ironat invert	Chalk	Drip	Conduction	Waterproof sheet	NA	NA
Switzerland	Motorway	Shield	Precast concrete	In-situ-concrete	sandstone/mud stone	Drip	Ground water lowering	Drain boring	Scheduled in 2001	NA
Switzerland	Motorway	TBM	Precast concrete	In-situ-concrete		Continuous Leak	Conduction	Channel cut + fill	Effective	1
UK	Railway	Shield	Cast iron		Clay	Drip	Stoppage	Crack injection	in construction	
UK	Cable adit	Manual w/ spades	Precast concrete		sand and clay	Continuous Leak	Stoppage	Back fill grout	Somewhat effective	0.5
UK	Rail Transpo	TBM	Segmental concrete		Chalk marl	Drip, full range	Conduction / stoppage	Joint filling / caulking / grouting	#N/A	#N/A
USA	Water	Mined	In-situ-concrete		Cambridge argillite	Continuous Leak	Stoppage	Crack injection_rock	Effective	#N/A
USA	Sewer	Shield	Liner plate	In-situ-concrete	Soil	Continuous Leak	Stoppage	Back fill grout/structural lining	Effective	#N/A

USA	Water	Shield	Concrete blocks	In-situ-concrete	Silty clay/fine sand & silt	Continuous Leak	Stoppage	Back fill grout	Somewhat effective	0.5
USA	Sewer	Shield	Steel ribs w/ lagging	In-situ-concrete	Silt	Continuous Leak	Stoppage	Back fill grout	Effective	1.5
USA	Subway	Cut-and-cover	In-situ-concrete		Soil and rock	Drip/continuous leak	Stoppage	Crack injection	Effective	1
USA	Water	Mined	Timber sets w/ lagging	In-situ-concrete	Rock	Drip/continuous leak	Conduction	Waterproof sheet	Effective	#N/A
USA	Hydropower	Mined	Timber sets w/ lagging	In-situ-concrete	Granite	Drip/continuous leak	Stoppage	Back fill grout/shotcrete	Somewhat effective	#N/A
USA	Access	Mined	Unlined		Rock	Continuous Leak	Stoppage	Back fill grout	Effective	#N/A
USA	Exploratory	Bored	Unlined		Rock	Continuous Leak	Stoppage	Back fill grout	Effective	#N/A
USA	Hydropower	Bored	Unlined		Quartzitic gneiss	Continuous Leak	Stoppage	Joint filling	Somewhat effective	#N/A
USA	Hydropower	Mined	In-situ-concrete		Siltstone and shale	Continuous Leak	Stoppage	Back fill grout_rock/channel cut + fill	Somewhat effective	#N/A
USA	Access	Mined	In-situ-concrete		Rock	Continuous Leak	Conduction	Drain hole/waterproof plate	#N/A	#N/A
USA	Shaft	Bored	In-situ-concrete		Rock	None	Stoppage	Waterproof sheet/in-situ-concrete	#N/A	#N/A
USA	Adit	Mined	In-situ-concrete		Rock	Seep/drip	Stoppage	Crack injection	Somewhat effective	#N/A

TERMS OF U	TERMS OF EXCAVATION	TERMS OF LINING1	TERMS OF LINING2
Roadway	Mined	In-situ-concrete	cast-in place-concrete
Subway	Shield	Precast concrete	concrete
Rail Tunnel	Cut-and-cover	Slurry walls	In-situ-concrete

TERMS OF LEAKAGE	CLASSIFICATION	METHOD OF REPAIR	GRADE OF EFFECTIVNESS
Damp Patch	Conduction	Water conduit	Effective
Seep	Stoppage	Channel cut	Somewhat effective
Standing Drop	Ground water lowering	Channel cut + fill	Limited effectivness

Railway-LRT	TBM	Ribs w/ wooden laggings	stonework	Drip	Heat insulation	Crack injection	in construction
Railway	Bored excavation	Shotcrete	ironplate	Continuous Leak	Heating	Waterproof plate	Temporary measure
Cable adit	NATM	Prestressed concrete	corrugated iron			Waterproof sheet	Works in progress
Water	Immersed tube	Cast iron				Fissure injection	

APPENDIX B

SUMMARY OF CASE HISTORIES OF REPAIRS OF DAMAGE IN TUNNELS EXCLUDING LEAKAGE

APPENDIX 'B'

Tunnel name	Location	Date of completion	Type of lining	Damage	Cause	Repair materials	Date of repair	Rate of success	Remarks
ROAD TUNNELS									
Dartford	Southern England	1980	precast concrete segments	Concrete spalling, Corrosion of reinforcement	Eccentric TBM jacking forces	unknown		0-1	New repair will be with polymer modified cementitious producct
					corrosion of reinforcement	unknown		0-1	
Ahmed Hamdi	Egypt, Suez canal		precast concrete segments	Extensive concrete spalling		concrete			Tunnel relined
Fornaci	Italy, Savona	1969	cast-in-place-concrete	Voids in crown, concrete surface degradation in crown	Inadequate filling, high truck traffic and marine atmosphere	shotcrete	1991	4	Steel reinforcement, rock bolts etc. used to promote bonding to rock and concrete
Costarainera	Italy, Imperia	1969	cast-in-place-concrete	Voids in crown	Inadequate filling	grout	1988	4	
Rocca Capanca	Italy, Savona	1969	cast-in-place-concrete	Concrete surface degradation	High truck traffic, humidity, marine atmosphere	polymer cement	1988	4	Anchor bolts, steel mesh used to promote bonding. Cement applied by shotcrete equipment
Unknown	Italy	Unknown, > 20 years old	cast-in-place-concrete	High traffic (VTGM = 20000)		polymer cement	1984, ongoing	3	Some microfissures in repair observed. Application by spray
Unknown	Italy	Unknown, > 20 years old	cast-in-place-concrete	High traffic (VTGM = 20000)		polymer cement	1984, ongoing	4	Application using metal framework
Seki	Japan, Mie	1965	cast-in-place-concrete	Cracking of arch lining, Cracking and deformation in pavement and gutters	Cavities in arch lining, freezing and frost damage	concrete	1976	4	
Mizukoshi	Japan, Wakayama	1965	cast-in-place-concrete	Cracking and spalling	Uneven and sqeezing ground pressure	shotcrete, grout	1981	1-4	Repairs included ground improvement - successful. Shotcrete reinforced with steel fibre repair deteriorated - due to carbonation
				Shotcrete repair deteriorated	Carbonation	concrete	1988	4	High strength precast lining installed on internal surface

APPENDIX 'B'

Tunnel name	Location	Date of completion	Type of lining	Damage	Cause	Repair materials	Date of repair	Rate of success	Remarks
Tunnel Laaerberg	Austria, Vienna	1972	cast-in-place-concrete		Chloride contaminated concrete		1998-1999	unknown	Object of repair will be to minimize corrosion activity
Rokujuri	Japan, Nigata	1966	cast-in-place-concrete	Cracking and spalling	Cavaties behind lining and frost damage	shotcrete, grout		3	Uneven surface of shotcrete gives unsatisfactory appearance
Watatake (Up line)	Japan, Hokkaido	1970	cast-in-place-concrete	Cracking in crown	Cavities and consequent reduced lining strength	grout	1989	4	Steel plate attached to surface
Enasan Tunnel (down track), Chuo Expressway	Japan, Nagano and Gifu prefectures	1975	cast-in-place-concrete	Cracking with delamination in some parts in concrete lining	Very large earth pressure from the Nagahirasawa fault	grout	1993 - 1995		Backfilled cavity behind lining and installed eight sub-horizontal ground anchors
Nikkureyama (Down line)	Japan, Gunma	1993	cast-in-place-concrete	Cracking and exfoliation	Squeezing (mudstones) ground pressure	Epoxy resin injected in cracks. Sheet fixed to surface for appearance and 15 % exfoliation			
RAIL TUNNELS									
Channel	England / France	1993	precast concrete segments	Spalling at circumferential / radial joints	Erection damage	concrete, proprietary	1992 - 1994	4	SBD 5 Star concrete used with bonding agent
London Underground	England		precast concrete segments	Spalling at joints	Erection damage	polymer cement	1987 - 1993		
Brachbacher Tunnel	Germany, near Siegen	1861	brick/masonry	Weakening of lining	Ageing	shotcrete	1989		Brick replaced by shotcrete with mesh reinforcement
Buedenholzer Tunnel	Germany, Rheinland - Pfalz	1861	brick/masonry	Deterioration of brick lining	Water infiltration and locomotive exhaust	shotcrete	1992 - 1993	3	Water mixing with sulphates and sulphides attacks brick and mortar. Cost 213 DM/m²

APPENDIX 'B'

Tunnel name	Location	Date of completion	Type of lining	Damage	Cause	Repair materials	Date of repair	Rate of success	Remarks
Elsterberg Tunnel	Germany, Freistaat Sachsen	1874	brick/masonry	Spalling of lining	Water infiltration, engine exhaust and ice damage	shotcrete	1986 - 1991		Cost 4 DM/m². Drains installed to carry water away
Gemmenicher Tunnel	Germany	1872	brick/masonry	Delamination of liner	Water intrusion and engine exhaust	concrete / shotcrete	1988 - 1991	3	Cost 21 DM/m²
Joehlinger Tunnel	Germany, Joehlingen	1879	brick/masonry	Swelling joints and delaminated masonry	Water infiltration and engine exhaust	shotcrete	1990	4	
Tunnel ViB Ulbersdor	Germany, Freistaat Sachsen	-	brick/masonry				1969 - 1980		
Metttericher Tunnel	Germany, Rheinland - Pfalz	1871	brick/masonry	Eroded masonry joints	Exhaust of diesel locos and steam locomotives	shotcrete	1983 - 1984	4	Cost 60 DM/m² at 2 cm thickness
Tunnel Bruchsal	Germany, Baden Wuerttemberg	1903	brick/masonry	Spalling of liner and swelling joints	Water leakage	shotcrete	1992	4	
Tunnel no 6	Germany, Freistaat Sachsen	1878	brick/masonry	Spalling of liner and swelling joints	Water leakage	grout	1969 - 1980	3	
Kutsubami (JR East)	Japan, Yamagata	1914	brick, with concrete in low sidewalls	Deterioration of joint filler to masonry. Deterioration of cut rock and concrete	Frost and inferior materials	Mesh and steel straps	1990 - 1992	4	Mesh and steel straps fastened by stainless steel anchor bolts
Okihaga (JR East)	Japan, Yamanashi	1903	brick/masonry	Deterioration of bricks and joint filling	Frost and engine exhaust ageing	"steel arches and waterproof membrane"	1980 - 1983		
Schimizu_Yado (down line, JR East)	Japan, Kanawaga	1898	Bricks, concrete side walls	Deterioration of bricks and joint filling	Ageing	RHC and epoxy resin	1989	4	Rapid hardening cement RHC, inject resin in joints and seal with RHC
Kamuriki Tunnel	Japan, Nagano prefecture	1890	brick/masonry	Brick bond failure, brick separation and peeling off	Engine exhaust, water leakage and freezing	Liner plates	1987 - 1995	4	

APPENDIX 'B'

Tunnel name	Location	Date of completion	Type of lining	Damage	Cause	Repair materials	Date of repair	Rate of success	Remarks
Sobu Tunnel (Sobu Express Line, JR East)	Japan, Tokyo	1972	precast concrete segments	Segment cracking, corrosion of bolts joining segments	Leakage of water containing much salt and iron through segment joints and bolt holes	concrete	1993 ongoing	4	Install waterproof membrane and steel support with concrete panels
Kiba Station Tunnel Subway line no 5	Japan, Tokyo	1967	cast iron segments	Segment corrosion	Leakage from segment joints	Anti-corrosion water paint of cement type	1991 - 1996	4	
Delf pu. Kelenföld	Hungary, Budapest	1861	Bricks, limestone	Dolomite flour from around the tunnel lining washed into the tunnel	Broken water main	grout	1989	4	
Metro Line 2, Station Deli pu	Hungary, Budapest	1967	cast-in-place-concretesteel segments	Corrosion of steel plate	Inferior concreting during construction leftzs voids between concrete and steelplate	grout	1993	4	Corrosion was probaly speeded up by creeping currents
WATER TUNNELS									
Ikido P. ST. No 1 Tunnel	Japan, Shizuoka	1930	cast-in-place-concrete	Cavities in crown, scouring at invert, honeycomb	Inferior construction and ageing	concrete / grout PIC plate	1993	4	Invert concrete was replaced. Polymer impregnated concrete plates (PIC) fastened to arch surface with adhesive
Iwamoto P Stn Honsen Tunnel	Japan, Gunma	1949	cast-in-place-concrete	Reduction in thickness of arch, honeycomb, scour of invert	Voids in crown, inferior construction and ageing	shotcrete	1987	4	Shotcrete applied in two layers, inner layer with mesh, surface trowelled smoothly.
Takasegwa P Stn no 5 Tunnel	Japan, Nagano	1925		Corrosion of concrete and material deterioration	Ageing	concrete	1992	3	Swelling of coating due to water inflow, repair completed

APPENDIX 'B'

Tunnel name	Location	Date of completion	Type of lining	Damage	Cause	Repair materials	Date of repair	Rate of success	Remarks
Takenosawa P Stn no 6 Tunnel	Japan, Tochigi	1922	cast-in-place-concrete	Deterioration of lining	Ageing and inferior construction works	steel plate	1992	4	Steel plate welded in place, backfill grouted and coated
Takenouchi P Stn Water raceway	Japan, Fukushima	1919	bricks (invert concrete)	Deterioration of lining	Ageing	concrete	1992	4	Steel plate with supporting steel arch (H beam) to brick work, concrete layer to invert
Iwamuro P Stn headrace tunnel	Japan, Gunma prefecture	?	cast-in-place-concrete	Deterioration of lining surface, cracking	Reduction in strength, honeycombing, and cavity behind the lining	concrete	1994 - 1995	4	Deteriorated surface layer removed with chipping robots while a new concrete lining was constructed
SEWER TUNNELS									
Senkawa Main Sewer	Japan, Tokyo	1930		Cracking and spalling	Ageing	shotcrete (proprietary	1989 - 1990	4	Injected grout (CCR Slag fines) in cracked sections. Arom M shotcrete applied to arch surface
Utility Tunnel in the section from Tenjin to Watanabe-Dori Street	Japan, Kukuoka prefecture	1995	cast-in-place-concrete and steel segments	Peeling off of catwalk slab concrete	Influence of SO4 -ion contained in the chemical injected for ground improvement during construction	concrete, consisting mainly of epoxy resin, polymer cement Steel	1995		Paint OVERKREET E100V and OVERKOTE in two layers
PEDESTRIAN TUNNELS									
Conwy	Wales		' pipe jacked	Cracking	Construction damage	Resin injection			Resin injected into cracks
POWER SUBSTATION									
Metro, Line 2	Budapest, Station Kossuth Tér	1968	cast-in-place-concrete and steel segments	Water infiltration	High groundwater pressure broke down the water proofing	grout, steel	1974	4	Damaged steel plate was cut out, anchor bolts were fixed and new steel plates welded. Voids between steel plates and concrete lining were grouted

APPENDIX 'B'

Tunnel name	Location	Date of completion	Type of lining	Damage	Cause	Repair materials	Date of repair	Rate of success	Remarks
TELECOMMUNICATION/UTILITY TUNNELS									
NTT Tunnel 238-20	Japan, Osaka	1988	cast-in-place-concrete	Cracking and spalling	Water leakage and chemical grout reacting with RHC	polymer cement mortar expansive urethane grout	1992	4	Sealing off water with grout, polymer cement mortar used with mesh and resin coated
Utility Tunnel in the section from Tenjin to Watanabe-Dori Street	Japan, Kukuoka prefecture	1995	cast-in-place-concrete and steel segments	Peeling off of catwalk slab concrete	Influence of SO4 -ion contained in the chemical injected for ground improvement during construction	concrete, consisting mainly of epoxy resin, polymer cement Steel	1995		Paint OVERKREET E100V and OVERKOTE in two layers

Notes:

1. Success ratings:

0 - Unsuccessful
1 - Successful for a short period, did not meet expectations
2 - Successful in view of difficult conditions, but will have to be redone in due course
3 - Generally successful with limited imperfections
4 - Completely successful