# DEVELOPMENT OF GUIDELINES FOR REHABILITATION OF EXISTING HIGHWAY AND RAIL TRANSIT TUNNELS

*Prepared for:*

AASHTO Technical Committee for Tunnels (T-20)

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Disclaimer



Instructions to Panel Members

This project is being conducted for the *AASHTO Subcommittee on Bridges and Structures* as part of NCHRP Project 20-07/Task 276, *Development of Guidelines for Rehabilitation of Existing Highway and Rail Transit Tunnels.* The report has not gone through the usual rigorous review process established and monitored by the Transportation Research Board Executive Committee or the Governing Board of the National Research Council, and should not be described as a “TRB Report”. It should be described as a contractor’s report conducted for the *AASHTO Technical Committee for Tunnels (T-20)* with funding provided through National Cooperative Highway Research Program Project 20-07/Task 276.

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# NCHRP HR 20-07/TASK 276
# TASK 6 – Final Report
# Development of Guidelines for Rehabilitation of Existing Highway and Rail Transit Tunnels

## Introduction/Background Research

Existing highway and rail transit tunnels are gradually becoming functionally obsolete and structurally deficient. Older tunnels need frequent inspections, higher levels of maintenance, and rehabilitation. The nation's tunnels are aging and the increasing traffic volumes and environmental deterioration they experience result in a reduction in their service lives. Structural deterioration also causes safety concerns. There is limited experience in the State Departments of Transportation and other tunnel authorities with respect to rehabilitation of existing tunnels. For these issues, most agencies rely on assistance from bridge engineers or consultants specializing in tunnels. Rock bolting, grouting, shotcrete, and other techniques have often been used in tunnel rehabilitation. Other techniques have been used to improve tunnel safety by increasing vertical and horizontal clearances, drainage, extending tunnel portals for rock fall mitigation, tunnel illumination, and ventilation.

Section 12 of the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications addresses buried structures, but very little guidance is provided for tunnel rehabilitation. Additional guidance must be developed in a separate stand-alone document on rehabilitation of existing tunnels. Guidance should be provided to the engineer to provide cost-effective preventive rehabilitation strategies to preserve existing tunnel structures. Advancements in the knowledge of materials, details, components, structures, and an increased array of construction materials and methods, make it an opportune time to develop solutions to extend the service life and preventing premature deterioration of existing tunnel structures. This project supports "Extending Service Life" and "Optimizing Structural Systems", as noted in the 2005 version of the AASHTO Grand Challenges for strategic planning.

The impetus for this research project was initially based on the deficient existing rock tunnels built in the 1930s in state of Washington. These tunnels have experienced signs of deterioration due to rock falls inside and at the portals causing safety hazards. In the 1950s, a series of tunnel rehabilitation projects were initiated to install timber bents to protect the travelling public from potential rock falls. Shattered rocks and debris continued to accumulate behind the timber bents causing excessive deformation, partial collapse, and safety hazards. In the late 1980s, Washington Department of Transportation (WSDOT) began the rehabilitation of these tunnels using techniques such as rock bolting, sequential grouting, and shotcreting for new linings. Maintaining the structural integrity of the tunnels while improving vertical clearances and drainage was among the challenges in these projects.

The funding available for this Task 276 project includes research for the following six tasks:

- Task 1 – Review Relevant Domestic and International Data Related to Tunnel Field Conditions

- Task 2 – Identify Rehabilitation and Construction Issues for Structural and Drainage Items Critical to Existing Highway and Rail Transit Tunnels
- Task 3 – Develop an Outline of Proposed Guidelines for Rehabilitation
- Task 4 – Develop Recommendations for Best Practices in Rehabilitation of Existing Tunnels
- Task 5 – Submit Draft Task 4 Report
- Task 6 – Submit Final Report

As part of the research for this project, telephone calls were made to domestic tunnel owners, and a web search of tunnel problems related to structural and drainage issues was instituted as part of Task 1. A summary of this research is provided in Appendix A; a general description of typical problems existing in tunnels from the research is also provided below:

- Falling rock in unlined rock tunnels outside of rock bolted areas.
- Shotcrete liner repairs in rock tunnels with timber liners not performing as originally expected (Appendix B, Photos 1-3).
- Deteriorating reinforcing steel (due to insufficient cover or deleterious chemicals).
- Spalled and delaminated concrete in walls, ceiling slabs, structural roadway slabs, and construction joints.
- Stalactites forming from leakage through cracks or between precast liners where seepage self seals over the cracks.
- Missing bolts at isolated locations between concrete and steel liners.
- Slight corrosion on steel liner panels.
- Spalled and delaminated tiles on tunnel walls and on underside of ceiling slabs and ceiling panels.
- Active leakage through cracks and joints varying from dampness to running water in many tunnels, formation of stalactites and stalagmites, icicles prevalent in certain tunnels during winter months (Appendix B, Photo 4), and severe leakage causing power interruptions in at least one transit tunnel.
- Prior replacement of deteriorated roadway ceiling slabs and isolated hanger replacements.
- Additional structural supports for ceiling slabs that have lost some of their structural load carrying capacity due to freeze-thaw actions.
- Major slides from overburden rock and soil causing serious structural damage to tunnel and portal structures.
- Significant water infiltration causing water to overflow roadway drainage system.
- Over height vehicle impacts and damage to the tunnel roof structure.
- Leakage at fire standpipes requiring replacement of the standpipes.

Upon completion of Task 2, further research was conducted on the types of repairs that have been used to correct the typical problems identified above. These were initially presented in the Task 3 Report, but were more fully refined with the submission of the Task 4 Report. The best practices presented were for suggested/actual repairs based upon information provided in Chapter 4 of the 2005 FHWA *Highway and Rail Transit Tunnel Maintenance and Rehabilitation Manual* (FHWA, 2005) and in the International Tunnelling Association's (ITA's) *Study of Methods for Repair of Tunnel Linings,* June 2001 by Working Group No. 6 Maintenance and Repair (ITA, 2001). For this Final Report (Task 6), the intent is to provide guidance on best

practices for designing repairs by discussing the characteristics of construction methods and materials for general types of structural problems typically occurring in tunnels.

The ultimate end result from this research project is the development of AASHTO specifications to provide tunnel owners guidance in completing repairs that may be needed in their tunnels. This will be accomplished as a separate project from AASHTO's Subcommittee on Bridges and Structures (SCOBS) at a later date.

## Proposed Guidelines for Designing Repairs for Structural and Drainage Problems in Tunnels

It is clear from the research that aging domestic and international highway and rail transit tunnels are experiencing significant structural and drainage issues that require repair and rehabilitation for them to continue to function as originally designed and constructed. The research revealed that the majority of the problems have been from water leakage through the tunnel lining or through the rock surfaces in unlined tunnels. Various repair methods have been applied to conduct or arrest the water infiltration. Many repairs have achieved the desired results, but some have been less than satisfactory. As tunnel owners are faced with repairing their tunnels based upon deficiencies encountered, it is important that a thorough understanding of the problem, and the effects it causes, be evaluated before a repair process is implemented. Tunnel owners may need to seek geologic, geotechnical, and structural expertise beyond the capabilities of their own staffs to devise such repair procedures and processes.

Guidance on best practices will be provided for many typical structural and drainage problems that exist in tunnels. It should be noted that there is no particular best practice priority as to which method of repair should be used by the tunnel owner. The tunnel owner is most familiar with the magnitude of the deficiencies in his tunnels and may elect to follow a certain best practice at that point in time based upon constraints such as funding available for the repairs, overall schedule to complete the repairs, time of the year for making the repairs, operational constraints, recommendations from geologists and geotechnical/structural engineers, the severity of the problem, etc. The best practices presented below are various alternatives in the toolbox for the tunnel owner to consider when selecting a repair method for a particular deficiency; therefore, they are not in any priority order.

### A. Elimination of Groundwater From Penetrating the Tunnel Liner

Both domestic and international research indicates that water leakage through the liner is the primary cause of deterioration within an existing tunnel. It is a best practice to eliminate this ground water from penetrating through the tunnel liner if at all possible. However, not all tunnel owners consider this as a first resort due to the unknown cost, the applicability of accomplishing grouting from deep tunnels where through-the-liner techniques must be employed, and uncertainty that a complete sealing can be accomplished. Before this method is selected, the owner should have a geologist or geotechnical engineer conduct a study of the types of soil/rock present; determine if any voids exist between the tunnel liner and the soil/rock interface; determine if it is practical to dewater the region adjacent to the tunnel prior to performing repairs; and offer recommendations as to the design of the particle/cementitious or chemical

grouts to be used. It is considerably more cost effective if cementitious grouts can achieve the desired results as they are less costly than chemical grouts. (NOTE: Further discussion will be presented later in this report on particle and chemical grouts under sealing of cracks with active leakage.)

Grouting methods for tunnel rehabilitation typically include permeation grouting, compaction grouting, and jet grouting (ITA, 2001). These methods typically focus on cementitious grouting of fissures in the soil and rock around the tunnel exterior as a deterrent to the groundwater reaching the tunnel's exterior face. Sealing of soils adjacent to the tunnel exterior is typically achieved by permeation grouting the soil and void spaces outside the tunnel where the grout permeates the soil and consolidates it. Other methods include compaction grouting and jet grouting. The selection of the grout type is dependent upon the characteristics of the soil; hence, the need for engaging a geologist/geotechnical engineer to provide recommendations for the most appropriate repair method.

Grouting as a repair concept has been employed behind several arch bridges in New York City. For these bridges, several injection port holes were drilled through the liner from the interior abutment face; then, an acrylate ester resin (chemical grout) was injected from the lowest set of injection ports to those higher up on the walls and arch ceiling. This process continued until the grout filled the soil area behind the abutment. Other similar exterior face sealings have been accomplished with polyacrylic gels (also a chemical group). A potential disadvantage of this repair method is the numerous new paths that will exist through the tunnel liner in case the membrane fails over time. From others knowledgeable of the particular repair to the arch bridges in New York City, they have been performing well to date.

B. <u>Sealing of Cracks and Joints With Active Leakage</u>

When it is deemed necessary by the tunnel owner to seal off the infiltrating water by injection of materials in cracks and joints, three methods are considered best practices due to their worldwide use by tunnel owners (FHWA, 2005) (ITA, 2001):

- Conduction of water leakage through the liner and unlined rock tunnels, and disposal by channeling to the roadway or track bed's outlet drainage system.

- Repairs to tunnel liners caused by water leakage by sealing of cracks, adding a waterproof sheet membrane, using a sprayed membrane, cleaning of reinforcement steel where corroded, replacing delaminated areas in regions of leakage, and using a protective coating (often shotcrete) over the membrane sheets on the tunnel interior.

- Repairs to tunnel elements where leakage is not the cause of damage, but where deterioration, such as spalling and delaminations, occurs from poor workmanship during the original construction; chemical reactions in concrete from the presence of oxygen, chlorides, and low pH (acidity); stray currents (especially in transit tunnels); etc. The materials that are typically used to correct these deficiencies include mortars, special cements, epoxies, chemical grouts, and shotcrete.

*1. Conduction of Water Leakage and Disposal*

This practice has been used by both domestic and international tunnel owners as a fairly inexpensive method to channel water leakage through the tunnel liner via troughs and pipes into an existing drainage system at the roadway or track bed level for subsequent disposal outside the tunnel. By channeling the water into an existing drainage system, the owner is eliminating a build-up of water from the top of air plenum slab over the roadway, if such a slab is present, and from water potentially accumulating directly atop the roadway surface or on the third rail of the track bed. These situations cause both operational and safety problems. Some tunnel owners may use this method as a temporary, cost-effective measure to divert the flow of water without trying to eliminate such leakage by injecting cracks or other more extensive methods. Other tunnel owners may also view this as a reasonable, longer-term approach of conveying water infiltration until such time that a more robust repair is warranted. Regardless of the reason, tunnel owners are indeed employing this technique as a viable repair method for channeling water that is infiltrating through the liner.

The types and sizes of trough systems (neoprene, steel, fiberglass, flexible or rigid polyvinyl chloride (PVC)) to be installed depend upon the severity of the water infiltration, the potential for freezing in winter weather, the inclination of the cracks (typically used for transverse or radial cracks), and whether the materials are appropriate should a fire event occur in the tunnel. It is commonly known that PVC gives off toxic gases when burned and is not recommended, although these were used in two international tunnels (Appendix C, Type A Repairs, Figures F5 and I8).

Several systems in place are fairly simple, such as using neoprene troughs adhered by anchor bolts to the concrete liner (Appendix B, Photo 5) and inserting pipes on the underside of a fairly straight crack (Appendix B, Photo 6). It is readily apparent that the attachments in Appendix B, Photo 5 indicate an owner considering this to be a temporary repair. Where repairs are considered more permanent by methods used by international tunnel owners (Appendix C, Type A Repairs, Figures CU1, F5, I8, J1, J2, J3, and J4), considerably more attention is given to sealing off the edges of the troughs by mechanical compression or with caulking/adhesives to prevent seepage outside the troughs (ITA, 2001).

For severe leakage in cold climates where freezing is prevalent, heating of the troughs or covering them with insulation may be required to prevent ice build-up that could destroy the troughs and their supports, thus making the system ineffective. This is certainly a detriment to using such systems when freezing can occur.

For the special case where radial drainage holes are drilled through the liner into the soil to relieve water pressure from the exterior of the tunnel, (Appendix C, Type A Repairs, Figures I4 and J22), strainers may be provided to prevent clogging of the installed pipes. These strainers must be accessible for cleaning or replacement or the system could clog and be ineffective. This drilling through a liner to reduce exterior water pressures against the liner and conducting the water through a series of pipes into an existing drainage system should be considered a last resort alternative as compared to sealing the back face of the tunnel with a waterproofing membrane.

Although some owners may install such systems on the underside of rectangular box tunnels (Appendix C, Type A Repairs, Figure J2), a highway tunnel owner must be aware that these regions are susceptible to damage from over height vehicles, which could destroy the system. It is critical that this method only be considered where there is adequate vertical clearance.

As far as construction, these systems are fairly easy to install. The surrounding liner surface should be cleaned of any efflorescence build-up or deleterious materials prior to the troughs being installed. This can be accomplished by means of a small chipping hammer, wire brushes, or high pressure water. Installation in air plenum areas above the roadway can be accomplished without lane closures on the roadway below as long as any debris is contained within the air plenum. For repairs in tunnels with no plenum areas, closures during off-peak hours are ideal for accomplishing these repairs. None of these installations require long shut-down periods within the tunnel.

Based on the above discussion and photos/sketches of actual installations, this method for conducting water infiltration through a liner and into an existing drainage system as a best practice has advantages of being easily constructible, fairly inexpensive, interferes minimally with tunnel operations, and is best applicable to radial or transverse cracks. The disadvantages for employing this method include using materials such as neoprene and PVC that are not best suited for fire events; allows water to continue to pass through the liner and engage embedded reinforcement steel, which will eventually corrode and lead to subsequent delamination and spalling in the liner surface; requires heating or insulating the troughs in colder climates to prevent ice formations and subsequent destruction of the troughs and anchorages; and, requires that provisions be made for accessing the troughs for cleaning where silt or soil can penetrate the liner resulting in a build-up of residue that could cause clogging of the trough over time.

*2. Repairing Tunnel Liners with a Presence of Active Water Leakage*

Since this research deals with existing tunnels, it is assumed that repairs will generally be limited to the inside face of the tunnel versus exposing an exterior face and adding a waterproofing system to the tunnel exterior walls. Although an exterior waterproofing system is recommended for new construction where it is feasible to install, it is typically not an option in most existing tunnels as exposing the tunnel outside surface is only possible at a cut-and-cover section near the portal or for those tunnels with shallow depth. Furthermore, in older tunnels, there may never have been an external waterproofing system, or it has been breached and is no longer effective. Hence, the best practices of current repair methods will be limited to repairs made from within the tunnel interior.

Depending upon the location and depth of the tunnel, the owner might consider dewatering the area adjacent to the tunnel prior to making interior repairs to the liner.  A geotechnical engineer should be consulted to determine if this is feasible and cost effective.  Otherwise, the materials selected should account for a presence of water as indicated in this section.

An international study provided 106 case histories of repairs to tunnels with leakage damage (ITA, 2001). Of the 106 case histories involving water leakage, 76 cases were for highway and rail transit tunnels and 30 cases were for water, sewer, and other miscellaneous tunnels. The

repairs for leakage incorporated the severity of water present. In addition, the percentage of cases for this severity is indicated by the parentheses after the description.

- Past moisture – staining arising from former moisture (17%)
- Damp patch – discoloration of part of the surface of a lining, moist to the touch (2%)
- Seep – visible movement of a film of water across the surface (4%)
- Standing drop – a drop of water, which does not fall within a period of one minute (14%)
- Drip – drops of water which fall at a rate of at least one drop per minute (30%)
- Continuous leak – a trickle or jet of water; also includes drops exceeding 300 drops/minute (33%)

The above indicates that the majority of repairs was for drips of water or continuous leakage and equated to 63% of the repair cases. Although such a comprehensive report on leakage does not exist for domestic tunnels, it is anticipated that the results would be fairly consistent with the international findings.

Based on the above, tunnel owners have certain alternatives as best practices to select for arresting or minimizing water infiltration problems other than installing troughs as discussed in Paragraph B.1 above. These best practices alternatives are in no particular priority order and include the following:

a. <u>Installing a waterproofing membrane system over the interior surfaces of the tunnel liner</u>. This system is typically comprised of a geotextile, a High Density Polyurethane (HDPE) or PVC membrane, and a protective coating of shotcrete or other fire retardant protective material over the effected tunnel areas (Appendix B, Figure 1). This system is fairly comparable to the Type B Inner Shell methods from actual international installations (Appendix C, Type B Repairs, Figures F1, F4, F6, I9, J18, and J27) (ITA, 2001). This would also be considered a more long-term solution for controlling leakage water penetrating the liner than using troughs as described previously.

   Before installing any membrane system, the tunnel ceiling or walls should be cleaned of any excessive build-up of efflorescence on the surfaces by using a small chipping hammer, high pressure water, or wire brush, as appropriate. It is also best to inject leaking cracks or joints with appropriate sealing materials (to be discussed later under injecting leaking cracks) to minimize further water leakage passing through the tunnel liner and onto the membrane system. Once the sealing of existing leakage water is accomplished, the remainder of the membrane system – the geotextile, the HDPE/PVC membrane, insulated panel (if desired by the owner), and protective barrier – should then be installed for the effected region selected by the tunnel owner. If anchorages of the geotextile and HDPE/PVC membrane penetrate these systems, then a heat-sealed patch of membrane should be placed over the anchorage to minimize the potential of future water penetration through the anchorage location. Please note how this was accomplished for cast-in-place concrete liners (Appendix C, Type B Repairs, Figures F1, F4, I9, J18, and J27) and for unlined rock tunnels (Appendix C, Type B Repairs, Figures F6 and F7).

Similar locations of such membrane uses without a fire retardant protective barrier are shown for both a highway and a rail tunnel (Appendix B, Photos 7 – 9). Please note for the highway tunnel that none of the anchorages for attaching the membrane to the plenum arch ceiling or attaching the insulated panels to the underside of the membrane penetrated through the materials. Anchorages for the membrane were attached to the underside of the arch ceiling with mechanical anchors; the membrane was then heat sealed to these attachments. Similarly, the anchorages for the insulated panels were also heat sealed to the underside of the membrane. As can be seen in the photos, there is a tendency for isolated insulated panels to detach from the underside of the membrane requiring reattaching. But, after more than a decade in operation, the system remains effective as a viable method to keep infiltrating water out of the plenum arch area and transferring it to the tunnel's existing drainage system for disposal. Also, the insulated panels in unlined rock tunnels may be used to keep infiltrating water from freezing and falling onto the tracks (Appendix B, Photo 9).

This method is a long-term, best practices repair solution for eliminating water from penetrating onto the plenum slab, roadway slab, or tunnel track bed. It eliminates the possibility of water freezing and causing subsequent operational problems. However, it is considerably more difficult to install and will require tunnel shutdowns to accomplish, especially if no plenum area is present above the tunnel roadway.

b. <u>Installing a sprayed cementitious waterproofing membrane over the interior surfaces of the tunnel liner</u>. This best practices method has been employed along with the sealing of cracks and joints in cast-in-place concrete tunnel liners to minimize water penetration through the concrete liner (Appendix B, Photo 10). This sprayed membrane was applied in 2005 in a Pennsylvania highway tunnel. This system is made of a blend of co-polymers and Portland cement. The co-polymers in the mixture reduce the pore size within the concrete substrate to impede the passing of water molecules through the cementitious coating, but do allow water vapor to pass through. This offers the advantage of fairly rapid installation thus minimizing disruptions to tunnel operations, can be performed with similar equipment to that for shotcrete, and is less costly than the total system described in Paragraph B.2.a. However, the disadvantages of this system are that it is rigid, is not self healing, and may crack if there is movement in the tunnel structure (Appendix B, Photo 11). Although most of the system is performing well for more than five years since its installation, there are several isolated locations of water leakage through the coating at crack/joint locations.

Similar installations at international tunnels were depicted for Type C – Sprayed Membrane or Inner Lining repairs (Appendix C, Type C Repairs, Figures I3, I6, J20, US3, and US7) (ITA, 2001). The ITA Report reinforces that leakage may occur over time with sealed cracks that fail or through additional cracks formed by movements in the tunnel structure. But, the system is fairly easy to correct in that the same materials can be used to repair an isolated area of failure.

c. Injecting leaking cracks with grouts to arrest water infiltration through the tunnel liner. This best practice method is certainly applicable and has been used by numerous tunnel owners to control water infiltration through the tunnel liners. But, it is extremely important that the proper grout be used when sealing cracks to obtain the desired results. There have been numerous occasions where an owner has been disappointed because the improper grout was specified for the repair leading to a failed repair. In other occasions, the sealing of the cracks in a region was accomplished, but the water moved to another location and began to penetrate the liner through other cracks. Potential types of grouts that are used in cracks with active leakage include particle grouts and chemical grouts. Epoxy grouts are moisture sensitive and are not appropriate for cracks with active leakage. Epoxy grouts are only appropriate for sealing dry cracks.

   Particle grouts consist of Types I/II and III Portland Cement, microfine cement, and microfine silicates. These are referred to as fine cementitious grouts and can only be applied where no crack movement is anticipated, because they are rigid with no flexibility. If movement is anticipated, then these grouts should not be used. Types I/II and III Cements have a medium to high viscosity, respectively, and are used in larger cracks (.02” up to 1/8”), whereas microfine grouts have a low viscosity and are used in very narrow cracks, typically less than .02” wide.

   Chemical grouts typically used in tunnel repairs consist of acrylate esters and polyurethanes. Other chemical grouts include acrylamides and sodium silicates. Acrylamides are not typically used in tunnel repairs due to their high toxicity, and sodium silicates exhibit a high degree of shrinkage. Acrylate esters are a semi-rigid grout with low viscosity. They form a gel when reacting to water and are not as susceptible to drying out as are polyurethane grouts. They have been used in several projects throughout the U.S. over the last several years and have performed well when installed properly. Polyurethanes have a medium to high viscosity and may be either hydrophilic or hydrophobic. Hydrophilic grouts react in the presence of water without requiring a catalyst to initiate a reaction, whereas hydrophobic grouts do not react well with water and require a catalyst to initiate a reaction. Polyurethanes often form a foam that expands up to four times its width in the presence of water, and bonds well to the concrete substrate as long as there is a water presence. If a presence of water remains, this grout will remain flexible and usually continues to perform as designed. But, should the water migrate to a different location, this grout will dry out, become rigid, crack, and often debond from the concrete substrate. There have been numerous occurrences of these failures over the last several years in the U.S.

   Applications of these grouts should follow the manufacturer’s specification for cleaning out the crack, drilling and installing injection ports at 45 degree angles to the crack, and then injecting the grout (Appendix B, Figure 2).

   Crack injection is a typical best practice that owners will most probably need to use to minimize leakage water penetrating the tunnel lining. The owner should employ experienced contractors skilled in performing such repairs, to include one who has a very

good knowledge of grout behaviors versus the environmental conditions that occur at the locations to be injected.

d. Repairing Leaking Construction Joints. Undoubtedly, many tunnel owners with older tunnels will find it a necessity to repair leaking construction joints. Depending on the age of the tunnels, the continual passage of water through these construction joints may have led to severe delaminations and spalls adjacent to the joints. If the tunnels are newer, they may have waterstops within the joints; older tunnels most likely have some sort of keyed joint only with no waterstop. Prior to initiating any repairs, available drawings of the constructed tunnel should be reviewed before implementing repair methods for deteriorated construction joints.

If waterstops are present in the joint, typical problems include the improper placement of the waterstops and the inadequate vibration and placement of the concrete around the waterstop. Often, poor construction techniques for not anchoring the waterstop properly and permitting it to bend out of plane during concrete placement has led to failure of the waterstop to perform its intended function. This also can result in inadequately consolidated concrete around the waterstop, thus creating porous concrete. The final result is a joint which is easily penetrated by water present along the exterior tunnel surface.

It is recommended that injecting chemical grout into the interior of the construction joint with defective waterstops is the best practice for sealing the joint against further leakage. It is necessary to locate the injection ports at locations to miss reinforcing steel along the edge of the joint; it is also recommended that injection ports be alternately drilled on both sides of the waterstop for the injected chemical grout to reach both sides of the ineffective waterstop. Similarly, keyed joints without waterstops should be chemical grouted in a manner that fills all sides of the keyed joint for maximum protection against further water leakage.

If the joint has experienced delaminations and spalls near the surface, which is often the case, the deteriorated concrete should be removed with a chipping hammer or hydro demolition (if sufficient volume of delaminated concrete is present to use this method in the repairs) to remove the deleterious material down to sound material. The edge of the joint can then be rebuilt with a polymer modified mortar that has similar characteristics as the concrete substrate. Depending upon the severity of the water passing through a construction joint, the owner may elect to use other methods to arrest the water passing through the joint (Appendix B, Figures 3 and 4). However, the method employed in Figure 4 will need to be weighed against potential freezing temperatures for it to be fully effective.

An alternative method which has been employed by tunnel owners where the concrete on either side of a vertical construction joint is in good condition is to rout out the joint and install a flexible chemical grout, a drainage pipe, mastic, and mortar near the surface of the joint to prevent further leakage through the joint (Appendix B, Figure 5). The drain

pipe serves as a dual backup system for water penetrating through the chemical grout and into the pipe before being discharged through the existing drainage system.

The above methods are best practices from which an owner can choose to arrest water infiltrating through construction joints in the tunnel liner. The selection of the method to employ for the repair will be based on the degree of leakage penetration, the condition of the concrete on either side of the joint, the characteristics of the built joint, and the anticipated temperature ranges within the tunnel.

e. Repairing leaking joints between segmental liners and leakage around bolt holes between liner segments. If there is a breakdown in the waterproofing materials between segments in segmental liners, these joints should be repaired by replacing deteriorated gaskets between the liners with new gaskets to seal off the leakage. An alternative approach is to inject chemical grouts in the joint between liner segments to fill the void between the segments. This breakdown in sealing materials may coincide with leakage around bolt hole locations connecting the liner segments, or the bolts have deteriorated and should be replaced. If so, this area should also be sealed with new gaskets or chemical grouting, new bolts installed, and the bolts separated from the liner material by an insulating sleeve or jacket to avoid dissimilar materials in contact with each other, and corrosion occurring from a potential electrolytic process.

f. Installing a free standing inner shell where there is sufficient clearance, both vertically and horizontally, in exposed rock tunnels. This practice has been used by certain international tunnel owners (Appendix C, Type B Repairs, New Cases F11 and F12) (ITA, 2001). This method of directing infiltrating water into the existing drainage system is only possible where there are substantial clearances, both vertically and horizontally, to do so. As indicated in the figures, this was employed in existing unlined rock tunnels where there was sufficient clearance to use this repair method. The existing rock ceiling was first repaired by the installation of rock bolts into the upper regions of the tunnel to maintain the integrity of the liner. Then, the new inner tunnel shell was constructed of felt, insulating foam, concrete reinforcement, and shotcrete. This system permits water to penetrate through the existing unlined rock onto the rear face of the new inner shell where it is transferred down to the tunnel invert and into a new or existing drainage system. This method may have very little use in highway and rail transit tunnels in the U.S. as clearances are usually limited for this type of repair. But, where the potential exists for unlined rock tunnels where clearances are not an issue, the owner could consider this a viable repair method.

g. Grouting cracks in unlined rock tunnels. Grouting of rock tunnels has been common practice in the U.S. and Europe for more than a century. But, the use of new chemical and particle grouts have made the sealing of voids in the rock more effective and efficient.

There are three basic methods for effectively grouting the voids in the rock mass (ITA, 2001). These include downstage (descending stage) with a hole packer, downstage with downhole packer, and upstage (ascending stage).

> Experienced professionals recommend descending stage grouting when the rock is weak or highly fractured and needs to be consolidated at the surface, before grouting deeper zones at high pressure. The grout hole is drilled first at shallow depths near the face of the rock and grout injected through a packer at the top of the hole. When this is completed, the hole is then drilled deeper to reach the internal areas of the rock. During the second stage, either a packer at the top of the hole or one at the bottom of the hole may be used, although it is preferable that the packer is set at the bottom of the preceding stage.
>
> For ascending stage grouting, the grout hole is drilled to the full planned depth. Then grouting is carried out in stages with the packer placed at the top of the lowest grouting stage. For subsequent grouting stages, the packer is raised to the top of the next stage up and the grouting process repeated until grouting operations are completed.

For the repairs with water leakage performed in the international tunnels, the tunnel owners further rated the success of the three types of repairs in Paragraphs B.1, B.2.a, B.2.b, and B.2.f by the following scale (ITA, 2001). Please note that only 81 case histories out of the 106 total case histories were reported for leakage repair effectiveness. The results were as follows:

- Successful (57%)
- Reasonably successful (28%)
- Poor success (6%)
- Temporary measure (2%)
- Not reported (7%)

This clearly indicates that not all repairs are as successful as an owner would desire. Although no data is present for such findings from tunnel repairs in the U.S., the results may be very comparable as far as owner satisfaction is concerned.

C. Repairs to Tunnel Liners Where Deterioration has Occurred Without Active Leakage as the Primary Cause of the Deterioration.

Tunnel liners deteriorate when active leakage may not be present at the effected region. This does not preclude that moisture or active leakage may have been present at a particular location previously. But, on-going deterioration of the liners, as described below, is present and may need to be repaired based upon the owner's assessment of the damage.

The international study presented 51 case histories of repairs in 45 tunnels where there was other damage to the interior linings in highway, rail, pedestrian, sewer, water, and miscellaneous tunnels that were not specifically related to water leakage (ITA, 2001). However, leakage had some affect on the extent of the damage in 17 of these cases. Therefore, only 34 cases out of a total of 157 (20%) considered in the entire study were not related to water leakage in any way. Of the 45 tunnels included in this category of case history repairs, 33 were for highway and rail tunnels.

The 51 case histories indicated that the damage other than water leakage included environmental effects, operational condition, poor construction techniques, and aging in older railroad tunnels.

The types of deterioration included concrete spalling, delamination, loss of strength, and in the case of steel liners – loss of cross section, embrittlement, and corrosion.

Typical problems occurring in domestic tunnels are similar to those found in international tunnels and include the following:

- Concrete Liner Deterioration
  - Corrosion from embedded reinforcing steel caused by oxygen, stray currents, chemicals, chlorides, and low pH (acidity) resulting in cracks, delaminations, and subsequent spalling of the concrete surfaces.
  - Degradation of the material from certain acidic chemicals, alkaline solutions, and salt solutions leading to porous concrete surfaces. Water penetrates these porous surfaces, freezes within the concrete capillaries and pores, and causes degradation of the concrete over time due to freezing and thawing cycles.
  - Thermal effects where loads on the concrete structure cause the concrete to expand and contract putting undue stress on the concrete.
  - Loading conditions causing cracking of the concrete in tensile regions.
  - Poor workmanship affecting the long-term durability of the concrete. This may be caused by improperly placed reinforcing steel, insufficient vibration of the concrete when placing, segregation of the concrete when placing, and improper methods for finishing or curing the concrete.
  - Deterioration of the concrete matrix in structural slabs built before the 1950's when air entrainment was introduced causing a loss of structural strength after numerous freeze/thaw cycles.

- Metal Liners (Steel and Cast Iron) Deterioration – Deterioration is often in the form of loss of section in the liner plates or deterioration of the bolts between liner segments.

- Brick Liner Deterioration – Deterioration usually consists of cracks within or between bricks, loss of mortar between bricks, and missing bricks.

Once the defect has been evaluated, the cause determined, and it is judged that a repair is in order, one of the following potential best practices repairs should be implemented:

*1. Repairing Dry Cracks*

"Dry" cracks greater than 1/32" at the top of a horizontal surface can be repaired as indicated in Appendix B, Figure 6. The crack should be cleaned of all loose matter, dirt, and stains using high pressure water, compressed air, or other approved means. If the crack penetrates the full depth of the structural slab, which is accessible on the underside as in air plenums under the roadway in a highway tunnel, then an epoxy resin should be used to seal the underside of the crack. The top surface can be dammed with sand prior to pouring the epoxy resin in the crack.

Vertical and over head "dry" cracks where no further movement of the crack is anticipated can be repaired using injection ports and injecting an epoxy resin to seal the crack (Appendix B, Figure 7). Alternately, some repairs have been made by drilling ports at 45 degree angles

(Appendix B, Figure 2). The crack should be cleaned as mentioned above, injection ports installed at no more than 12” spacing, and epoxy resin injected into the cracks beginning at the lowest elevation.

*2. Repairing Delaminated Areas and Spalls*

Delaminated areas can be repaired by several methods. Depending on the depth of the delamination and the overall intent of the rehabilitation occurring in the tunnel, the delaminated area can be removed with a chipping hammer or by hydro demolition (Appendix B, Photo 12) to sound concrete. Then, depending upon the size and depth of the spalled area, whether reinforcing steel is present and/or whether the reinforcing steel has adequate area remaining, either polymer repair mortars can be used for small areas and small repair depths (Appendix B, Figures 8 and 9) or shotcrete can be used for larger areas and greater depths (Appendix B, Figures 10 and 11 and Photos 13 and 14). It is typically recommended that welded wire fabric attached by “J” bolts to sound substrate be used in greater depth shotcrete repairs as an additional anchorage for the shotcrete. Many shotcrete repairs include the addition of synthetic or steel fibers added to the mix to control shrinkage and strengthen the overall product, especially when no wire mesh is used. The repair contractor shall strictly follow manufacturer’s suggested installation procedures for the selected material to be used.

Shotcrete can either be placed using a dry or a wet process. For a dry mix, sand and cement are pumped through hoses and mixed with water at the nozzle. Additives can also be added either dry with the material or liquid with the water at the nozzle. For a wet mix, the sand and cement are premixed and pumped wet to the nozzle and applied to the concrete surface using compressed air added at the nozzle. The process used depends upon the volume of surface to be treated, if rebound of the material (considerably higher with a wet mix) is acceptable, and the amount of time that is available to place the shotcrete (more material can be deposited with a dry mix process). It is recommended that test panels be made by the shotcrete contractor to approximate the actual installation at the site. The shotcrete should be placed on these panels by the nozzle operator who will perform the actual repairs within the tunnel. These test panels provide a means of mix adjustment and for taking of cores to test for strength at various intervals.

Often, it is necessary to screed or trowel the shotcrete surface for aesthetics purposes, especially in highway tunnels where the walls and ceilings are visible to persons traversing the tunnel. Troweling, as well as the use of a dense shotcrete mix, also provides a denser surface that will offset any future detrimental effects from environmental conditions and carbonation from vehicle exhausts.

Please note that the above discussion assumes the area to be repaired is dry and without leakage through the substrate. If shotcrete is to be applied over a spalled area where the presence of water has not been arrested, the water will penetrate through the shotcrete and lead to unsatisfactory results. Although a different case where shotcrete was placed over timber cribbing in an unlined rock tunnel, it would appear that water was present behind the timber cribbing and not sealed prior to placing the shotcrete as severe leakage is occurring at the face of the shotcrete surface (Appendix B, Photos 1-3).

But, it is not absolutely necessary to remove the delaminated area if a vacuum injection process is used to rebond delaminated surfaces together. This was used on a tunnel in Washington, D.C. where there were delaminations within the mortar depth under the ceramic tiles on the tunnel wall face. Rather than remove the tile, chip away the delaminated mortar to sound mortar, replace the deteriorated area with polymer repair mortar, and then reattach the tiles, the contractor elected to use a vacuum injection process to seal the cracked region in the mortar. This was done by vacuuming a methyl methacrylate resin through injection ports located at intervals on the face of the tunnel wall into the gap between the mortar surfaces (Appendix B, Photos 15 and 16). Please note from the photos that this method becomes less viable when the surface mortar between the tiles contains micro fissures and must be covered with an epoxy gel to create the vacuum needed for the repair process. Once the methyl methacrylate cures and hardens, subsequent tapping of the wall revealed no delaminations on the surface. Also note that it was verified by the taking of cores that the mortar truly was bonded together and provided a successful solution (Appendix B, Photo 17). This method may not be cost effective for fairly shallow repairs if every mortar joint between tiles must be sealed with an epoxy resin prior to commencing the vacuum injection process.

When the reinforcement has deteriorated and needs to be replaced, the new reinforcement cage needs to be lap spliced to sound reinforcement (Appendix B, Figure 11). This requires exposing a sufficient length of sound reinforcement to make an effective splice. Although not shown in Figure 11, one domestic tunnel agency is also installing an anode in the location of the new reinforcement in case further deterioration under adverse environmental conditions could potentially occur.

*3. Repairing Metal Liners*

Metal liners consist of steel and cast iron. Typical steel liner defects include deteriorated or missing bolts between segments and corrosion of flanges of the liner. For missing or deteriorated anchor bolts, these should be replaced with new bolts. If there is any indication of stray currents causing the deterioration, then the bolts should be separated from the liner material by an insulating sleeve or jacket.

If the steel flanges have undergone significant section loss, then the loss of section can be replaced by bolting new plates at the flange location of sufficient thickness to replace the loss of section. If there is a question if steel plates should be added, then an analysis of the stress levels should be made by a structural engineer to determine if additional plates are warranted. Severe deterioration in the steel liners should be sandblasted to near white metal and a rust inhibitive primer and finish coat be applied to the liner.

Repairs to cast iron liners usually result from corrosion. However, the loss of section and/or replacement of a defective structural element is more difficult than steel since cast iron cannot be welded. These liners are often repaired by infilling of the panel with cast-in-place concrete. Deteriorated bolts between the liners are repaired similarly to those between steel liners.

*4. Repairing Brick Liners*

Brick liners are typically used in rail tunnels versus highway tunnels. They typically consist of several layers of brick and may have a steel shell on the exterior as part of retaining the soil during the original installation. Typical deficiencies in brick lined tunnels include deteriorated or missing mortar between the brick joints, missing brick, and cracks in the brick liner. Replacement of deteriorated or missing mortar can be accomplished by raking the mortar joint to sound mortar, but typically no less than 1". Then, new cementitious mortar with necessary polymer bonding agents should be placed in the joints to rebuild the brick structure. Where there are missing bricks, these should also be replaced and may need to have temporary supports to hold them in place while the mortar is curing. If there are indications that voids may exist between the brick/steel shell outer layer and the surrounding soil, then holes may need to be drilled through the brick and into the void area, injection packers installed at the hole locations, and particle grouts pumped into the grout holes and void space to provide support to the steel outer shell and brick tunnel.

The degree of success of the repairs to the highway and rail tunnels from the international repairs performed (ITA, 2001) was based on a success scale of 0 to 4 as described below:

- 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

The highway and rail tunnel owners rated these repairs as completely successful (55%), generally successful (15%), and no response (30%). No rating data is available from domestic tunnel owners as a comparison to those ratings assessed by international tunnel owners.

D. <u>Repairs to Deteriorated Concrete Structural Slabs from Freeze/Thaw or Salt Penetrations</u>

Concrete tunnels built before 1950 were constructed without air-entrainment admixtures included in the concrete mix. Although all concrete has a small amount of natural air entrainment, the percentage is very small when no admixtures are present. Hence, some of these structural slabs (between the roadway and the air plenum space above the roadway or between the vehicles and the underneath air plenum spaces at the invert) within tunnels in cold weather climates have lost their structural strengths due to decomposition of the mix design from numerous freeze/thaw cycles over the last 60 years or longer. In addition, certain roadway tunnel structural invert slabs near the tunnel portals in cold weather climates may have had numerous salt applications placed over them during winter conditions. This may have led to further deterioration of the reinforcing steel and further degradation of the concrete mix, such that the slab will require major rehabilitation or replacement.

If these or similar circumstances exist where the tunnel owner is faced with major rehabilitation of the structural slabs, a structural engineer should be engaged to conduct a study to determine the best course of action for the tunnel owner. These studies would include taking of concrete

cores 1) to determine the remaining strength when freeze/thaw problems are anticipated, 2) to perform a petrographic analysis to determine the characteristics of the in-place concrete mix, and 3) to analyze for chloride ion concentration when major deterioration occurs in the invert slabs. Further, a structural analysis may need to be conducted to determine the load-carrying capacity of the existing slab based upon its current condition. The recommendations from the study and analysis could range from performing isolated repairs to complete removal and replacement of the concrete slabs. Both of these will require major closures of the tunnel for extended periods of time until the repairs or replacement slabs are completed. In the interim until the tunnel owner has the funding to implement these long-term solutions, a temporary solution, such as installing various support mechanisms to allow the structural slabs to remain in operation may be needed. Similar major slab replacements have been performed on highway tunnels in New York City, and temporary supports for overhead structural slabs that have lost their strength from freeze/thaw cycles have been installed in a roadway tunnel in Pennsylvania.

## Summary

The research for this project, along with common knowledge of older highway and rail transit tunnel deterioration, reveals that many tunnels throughout the U.S. require repair and rehabilitation for them to function as originally designed and constructed. The majority of the deterioration problems in the tunnel structural elements or in unlined rock tunnels is from groundwater within the soil/rock substrate around the tunnel seeping/flowing through cracks, joints, and segmental panels into the constructed tunnel. However, there are other factors besides leakage water that leads to deterioration within the tunnel. These include poor construction techniques employed during the original construction such as inadequate concrete vibration, poorly placed or poorly sealed waterproofing materials, inadequate provisions for temperature conditions at time of construction, inadequate curing of the concrete, etc. Other factors such as overspray from roadway vehicles and damaging exhaust fumes also contribute to degradation of the exposed tunnel liner structural elements.

This report has identified several of the geologic and structural problems that typically occur and has presented numerous best practices used by tunnel owners worldwide to remedy the problems. The potential repair solutions have been briefly outlined and supplemented with photos and sketches (figures) for further clarification of the methods employed for the owner's reference. Please note that the intent of this research project was to outline the best practices, not to provide specifications or detailed installation procedures for each of the suggested or employed repair methods.

The tunnel owners must use their judgment, if qualified, or seek that of knowledgeable geologists, geotechnical engineers or structural engineers, as to which of the best practices presented may be most appropriate for repair of their tunnels. Certain repairs will work better in warmer climates than in colder climates where freezing of the leakage water can damage or render a repair ineffective. The tunnel owner may be constrained financially, as is often the case, and may need to perform repairs over a period of years. This would suggest a prioritization of the repairs for the most crucial elements based upon monies available. In addition, the time to complete the repairs and the schedule for performing them must be considered when deciding a course of action.

There is no one repair that is best for all tunnels as all problems are different. For some owners, successfully eliminating the water from entering the tunnel would be the best course of action. But this is just one of many solutions that an owner must consider when deciding upon a repair/rehabilitation method. There have been numerous worldwide solutions shown that provide the owner a starting point as to what others have done when faced with a particular problem. It will be up to the owner, their staff, or their consultants if any of these methods are applicable to their tunnel situation, or if new methods/materials should be derived to alleviate the problem.

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# APPENDIX A

**Research Approach to Task 276**

Since Gannett Fleming, Inc. (Gannett Fleming), had just conducted research related to NCHRP 20-07/Task 261 *Best Practices for Implementing Quality Control and Quality Assurance for Tunnel Inspections,* the firm already had the contact names for numerous highway and rail transit tunnel owners in the U.S. Due to a limited two-month period for completing *Task 1 – Review Relevant Domestic and International Data Related to Tunnel Field Problems* of this project, the firm selected a three-pronged approach as follows:

1. A web search was conducted of tunnels for both national and international tunnel owners to determine the general causes of problems in tunnels and potential rehabilitation techniques employed.

2. Gannett Fleming called several tunnel owners throughout the U.S. from the database developed during the research for the NCHRP 20-07 Task 261 Project to discuss the types of problems occurring in existing tunnels. It was envisioned their responses would corroborate some of the problems identified above in the Introduction/Background. In addition, information was sought on the types of repair/rehabilitation methods employed to correct these problems. It was felt that this method would yield more results for the research during the two-month time limit for Task 1, which included the Christmas and New Year's Holidays. Each discussion was documented for further reference.

3. Gannett Fleming called tunnel repair and rehabilitation specialists to elicit their experience with the typical types of problems encountered when repairing/rehabilitating existing tunnels and the materials/methods that were used to correct the problems.

It was felt that by using these three methods that many of problems in existing tunnels would be discovered from the research, and that the methods used for repair would indicate current technologies/materials being employed.

**Summary of Research Findings**

A. Web Search for Domestic and International Data – The web search through Google concentrated on key words such as tunnel repairs, tunnel rehabilitation, tunnel waterproofing, shotcrete, hydro demolition, polyurethane grouts, etc. A number of domestic and international articles were reviewed where the penetration of water through failed exterior waterproofing systems or through concrete with no waterproofing systems is degrading the tunnel structure. A bibliography of the information gathered is provided at the end of this Appendix. The research included tunnel problems in Norway, England, Scotland, Sweden, Germany, Egypt, Hong Kong, Singapore, the Faroe Islands (between Iceland and Norway), and in several states in the U.S. The extent of the problems included: major water leakage, corrosion of embedded reinforcing steel, delaminations and spalls in the concrete liner, corrosion of bolts between liner segments, debonding/spalling of surface tiles, etc. But, this is not the only source of deterioration in highway and rail transit tunnels. For highway tunnels, truck and auto traffic are carriers of contaminants, such as unburned carbons, deicing salts, airborne salts, and other chemicals which penetrate into the concrete substrate through hydrostatic pressure. When no effective protective waterproofing system exists, this also leads to degradation of the exposed concrete surfaces and causes delaminations, spalls,

corrosion of reinforcing steel, etc. This occurs on concrete surfaces for highway tunnels with air plenums under or above the roadway slab or where there are no air plenums, i.e. where there is natural ventilation or longitudinal jet fans.

As stated above, there are several unlined rock highway tunnels in the western and southwestern U.S. With water seepage over time, potential movements in the rock, and falling rock segments, rock bolts are used to maintain the integrity of the tunnel. In addition, some owners have added wood liners inside the rock surface to contain falling debris for safe passage of patrons through the tunnel. But, continual rock falls have led to deflections in the timber liner requiring additional measures, such as providing a shotcrete liner over the timber, to maintain the integrity of the liner and ensure safe passageway through the tunnel.

There are other problems that U.S. tunnel owners have experienced. These include slides from overburden materials that have caused structural cracking to the tunnel roof and tunnel portal of such magnitudes that closure of the tunnel was necessary before and during repairs. Secondly, settlements or squeezing movements in the soil structure can lead to increased tension on the inside concrete liner resulting in necessary repairs. Thirdly, several tunnels in the U.S. were built before concrete was air-entrained. Although there is a slight amount of intrinsic air-entrainment in any concrete, the slabs separating the roadways from the air-plenum spaces have undergone many freeze-thaw cycles in their 60 plus years such that their structural carrying capacity is greatly reduced.

Other tunnels located in seismic zones must be carefully inspected after seismic events to verify that any resulting damage does not prevent the safe passage of vehicular or pedestrians through the tunnel.

B. Calls to Highway and Rail Transit Tunnel Owners – During the course of this research, the Principal Investigator made numerous repeat calls to obtain information related to structural and drainage problems that occurred previously or are currently present in existing tunnels, the types of materials used in the repairs, and any specialized techniques used during the repair/rehabilitation. Calls were made to 22 highway tunnel owners with responses received from 18 of those owners, to 10 transit tunnel owners with 4 of those owners responding, and to 3 contractors/suppliers for their input into repairs/methods/materials currently being used to repair tunnels.

For highway and transit tunnels, calls were made to different regions of the U.S. to encompass the different types of settings – urban versus rural, mountainous versus subaqueous, warm versus cold climates; different construction methods – bored, cut-and-cover, drill and blast, sequential excavation, shield driven, and immersed tube; different types of ventilation – natural, longitudinal jet fans, semi-transverse, full transverse; and different types of liners – unlined rock to various liner systems. The 18 highway tunnel owners responding were from the states of Arizona, California, Colorado, Connecticut, Hawaii, Maryland, Nevada, New York, North Carolina, Oregon, Pennsylvania, Tennessee, Washington, Wisconsin, and Wyoming. These responses cover the northeast, mid-Atlantic, mid-south, southwest, west, upper northwest, and far west (Hawaii). Transit agencies responding included Metropolitan Atlanta Regional Transit Authority, Maryland Mass Transit Administration, New Jersey Transit, and Washington Metropolitan Area Transit Authority (WMATA) (via information received from internet search).

The general types of problems that have existed or are currently present include, but are not limited to, the following for highway and rail transit tunnels:

- Falling rock in unlined rock tunnels outside of rock bolted areas.
- Shotcrete liner repairs in rock tunnels with timber liners not performing as originally expected.
- Deteriorating reinforcing steel (due to insufficient cover or deleterious chemicals).
- Spalled and delaminated concrete in walls, ceiling slabs, structural roadway slabs, and construction joints.
- Stalactites forming from leakage through cracks or between precast liners where seepage self seals over the cracks.
- Missing bolts at isolated locations between concrete and steel liners.
- Slight corrosion on steel liner panels.
- Spalled and delaminated tiles on tunnel walls and on underside of ceiling slabs and ceiling panels.
- Active leakage through cracks and joints varying from dampness to running water in many tunnels, formation of stalactites and stalagmites, icicles prevalent in certain tunnels during winter months, and severe leakage causing power interruptions in at least one transit tunnel.
- Prior replacement of deteriorated roadway ceiling slabs and isolated hanger replacements.
- Additional structural supports for ceiling slabs that have lost some of their structural load carrying capacity due to freeze-thaw actions.
- Major slides from overburden rock and soil causing serious structural damage to tunnel and portal structures.
- Significant water infiltration causing water to overflow roadway drainage system.
- Over height vehicle impacts and damage to the tunnel roof structure.
- Leakage at fire standpipes requiring replacement.

It is interesting to note that only two tunnel owners (located in the Midwest and northwest) from all those responding stated that they have no significant structural or drainage issues currently in their tunnels. This is remarkable considering that these tunnels were constructed in the 1940s and 1960s.

C. Calls to Contractors/Material Suppliers – Calls were made to Dry Works Inc. and TecVac, Inc. as contractors who have been involved in numerous tunnel repair projects, with familiarity on projects throughout the U.S. Information was received on materials, specifications, and specialized methods to make tunnel repairs. In addition, drawings and specifications were received from tunnel owners showing repair drawings/specifications for their specific tunnels. These owners included the State of Washington, the Pennsylvania Department of Transportation (PennDOT), and the Maryland Mass Transit Administration. Since shotcrete is being used in a widespread manner to make repairs in many tunnels, the Quikrete Company was also contacted and material specifications received regarding products used in shotcrete repairs to the Liberty Tunnel in Pittsburgh.

D. General Summary of Findings – The number one problem that tunnel owners are facing are the problems caused by continual leakage through cracks, either in unlined rock tunnels or through lined tunnels. Many owners have completed repairs to leaks by sealing cracks or creating barriers to the outside surface of the tunnel at the soil interface. Some of these have been effective in accomplishing the purpose intended and some have failed. It is vital for owners to specify the correct material for the environment whether 1) the cracks are to be sealed and if the crack resulted from shrinkage (stationary) or expansion/contraction and 2) if there will be a continual presence of water behind the sealed area to specify the appropriate grout material. But, in addition to some sealing of cracks with grout, certain tunnel owners are choosing to divert the flow of water into the designed drainage system for the tunnel as the water often moves from the sealed crack to a different location for entry into the tunnel.

It is vitally important that any rehabilitation or repairs must address water infiltration before the repair/rehabilitation is completed. This includes the construction of both isolated large repair patches and a new interior tunnel liner. If not, the water will penetrate through the new repair patch or new liner and continue to cause damaging effects to the tunnel structure. A careful analysis of the situation is necessary in designing the appropriate repair to arrest the deleterious water infiltration effects.

Secondly, shotcrete has become a recognized acceptable repair method for replacing either isolated locations of damaged concrete or the installation of new liners in existing tunnels. However, for this “structural concrete” to perform as expected, it is vital that all water problems be addressed, that proper materials be specified, and that installation practices are carefully followed to obtain the desired finished product.

One tunnel owner specifically stated that he is concerned about the long term performance of shotcrete repairs with respect to placement, durability, cracking, permeability, service life, corrosion protection, mix designs, visual quality, and overall safety as compared to traditional vibrated reinforced concrete repairs. The Principal Investigator has sought guidance on these concerns from experts in the shotcrete field. Essentially, the shotcrete industry stands behind their product performing equally as well as concrete as long as it is placed properly, and offered the following in response to the mentioned concerns:

- Placement Method – It is correct that shotcrete is not vibrated, but it does not need to be. If a proper velocity of application in excess of 100 mph is achieved, this will pack the material creating a higher density than vibration could.
- Durability – There are numerous examples of shotcrete jobs that are very old and the material is still performing well.
- Cracking – Cracking depends upon installation techniques, weather factors, condition of the substrate, as well as the mix used. Also, short strand synthetic fibers are often added to help control shrinkage cracking.
- Permeability – The specification sheets for shotcrete mix show that it has good permeability resistance. However, if there was a water problem to begin with and it wasn’t addressed, it will reappear after the repairs have been made.
- Service Life – Shotcrete testing typically exceeds traditional concrete in testing across the board and will not have a reduced service life.

- Corrosion Protection – Again, the assumption that shotcrete is more porous than concrete is invalid. However, an integral corrosion inhibitor can easily be added to the mix at the time of manufacture or installation to reduce even further potential corrosion protection.
- Mix Designs – Shotcrete should perform properly if recommended mix designs are followed and proper placement techniques are used.
- Performance Characteristics – The common misconception is that shotcrete is a product. Shotcrete is actually a method of placement; shotcrete is concrete with some minor differences. The formulas are not very far apart and the differences, such as micro silica, make shotcrete mixes as good as, if not superior to, traditional concrete mixes.
- Safety – Shotcrete does not deteriorate faster than concrete. If such instances have occurred, it may be due to loosely and/or incorrectly specified mix designs and application techniques.
- Visual Quality – Shotcrete can be successfully finished to any appearance that traditional concrete can to provide an aesthetically pleasing finish.

It is clear that appropriate specifications be prepared and appropriate application techniques be applied to give the best possible shotcrete repair that the owner is expecting. In addition, in preparation of the substrate for subsequent shotcrete applications, many tunnel owners are choosing hydro demolition as an effective technique to remove the thickness of damaged concrete to an acceptable substrate.

It is crucial that the specifications being developed in subsequent research address these and other issues in a sufficient manner to provide tunnel owners with suggested guidance on repairing or rehabilitating their tunnels.

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# APPENDIX B

**Photo 1 –** New shotcrete lining over timber supports in rock tunnel.
Note timber lining in background.

**Photo 2 –** Interface between timber supports and new shotcrete.

**Photo 3 –** Leakage through shotcrete liner.

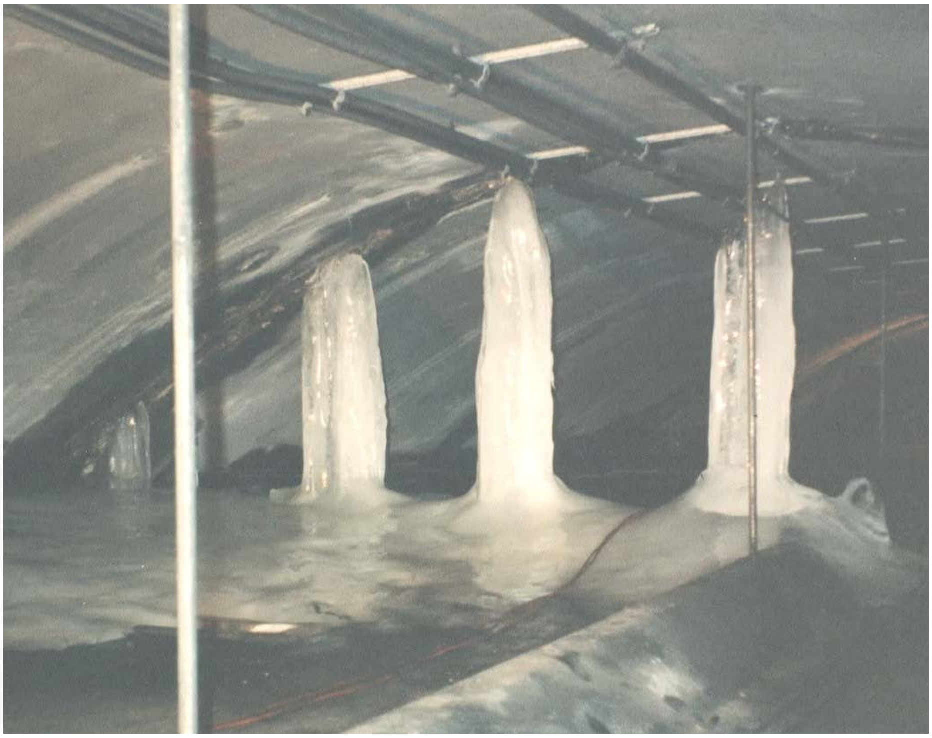


**Photo 4 –** Ice formation through liner in plenum area above roadway ceiling slab. (FHWA, 2005)

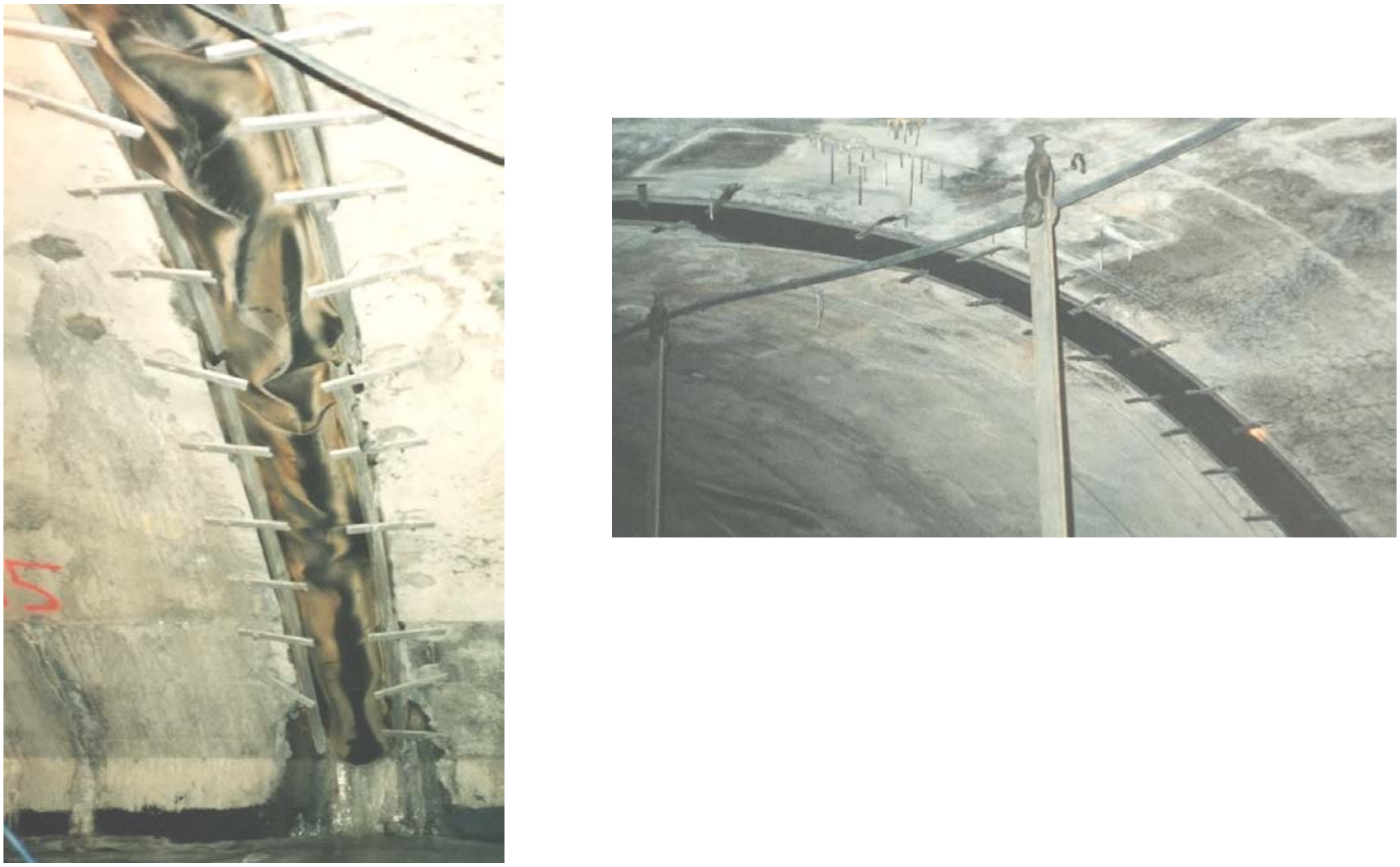


**Photo 5 –** Temporary drainage systems comprised of neoprene rubber troughs and 25 mm (1”) aluminum channels. (FHWA, 2005)

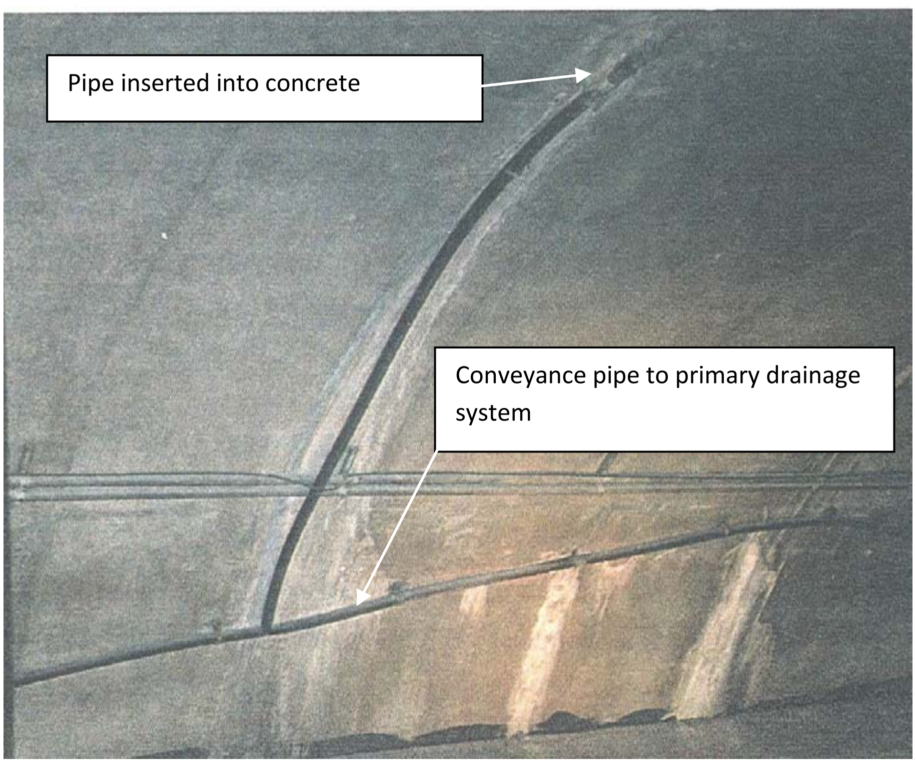



**Photo 6 –** Temporary drainage system comprised of 50 mm (2”) plastic pipe. (FHWA, 2005)

**Photo 7 –** Insulated panels under waterproofing membrane in air plenum region above roadway have dislodged in an isolated location.

**Photo 8 –** Underside of waterproofing membrane in air plenum slab. Note that heat welded attachments on the underside of the white membrane receive the insulation panels' anchors without penetrating the membrane.

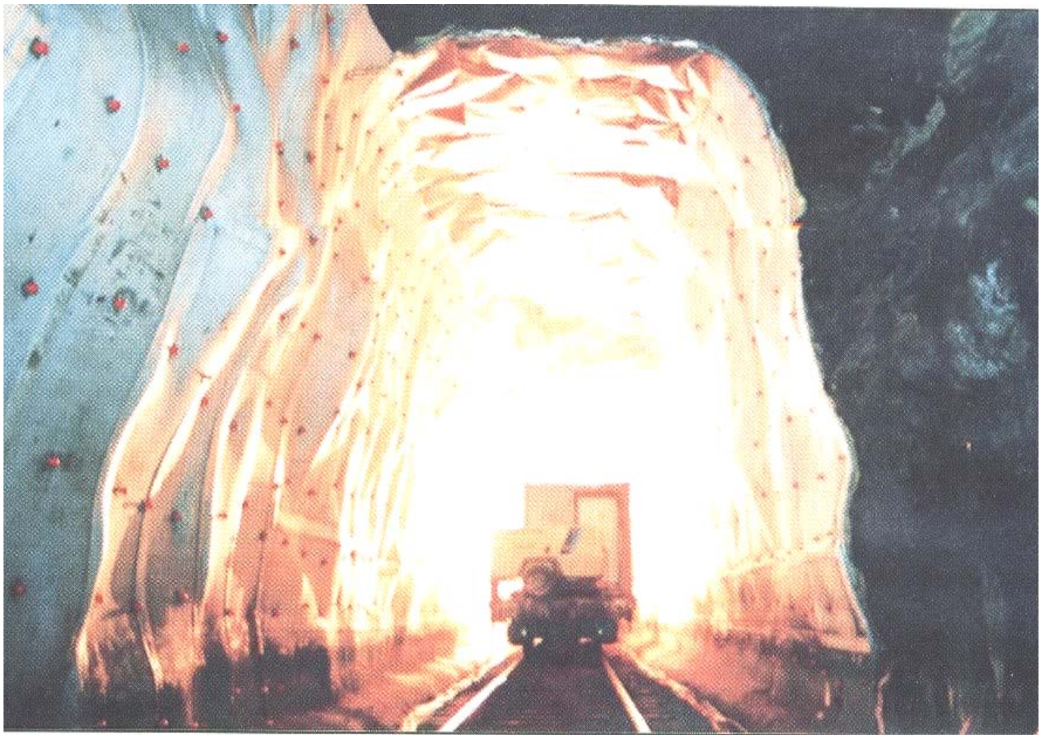


**Photo 9 –** Insulated panels used as a waterproofing lining to keep infiltrating water from freezing. (Photo courtesy of Tunnels & Tunnelling International) (FHWA, 2005)

**Photo 10 –** General view of tunnel arch ceiling above plenum slab where a cementitious coating has been applied to the underside of the arch in a Pennsylvania tunnel.

**Photo 11 –** Leakage at a construction joint through the cementitious coating that was applied on the underside of the tunnel arch in a Pennsylvania tunnel.

**Photo 12 –** Hydro demolition operations for removing deteriorated concrete in the Liberty Tunnel in Pittsburgh, PA.

**Photo 13 –** Using shotcrete to repair large areas in walls of Liberty Tunnel in Pittsburgh, PA.

**Photo 14 –** Using shotcrete to make overhead ceiling repairs in Liberty Tunnel in Pittsburgh, PA.

**Photo 15 –** Preparing 3’ x 4’ surface area on tunnel wall by installing ports and sealing grout lines with an epoxy gel prior to initiating a vacuum injection process.

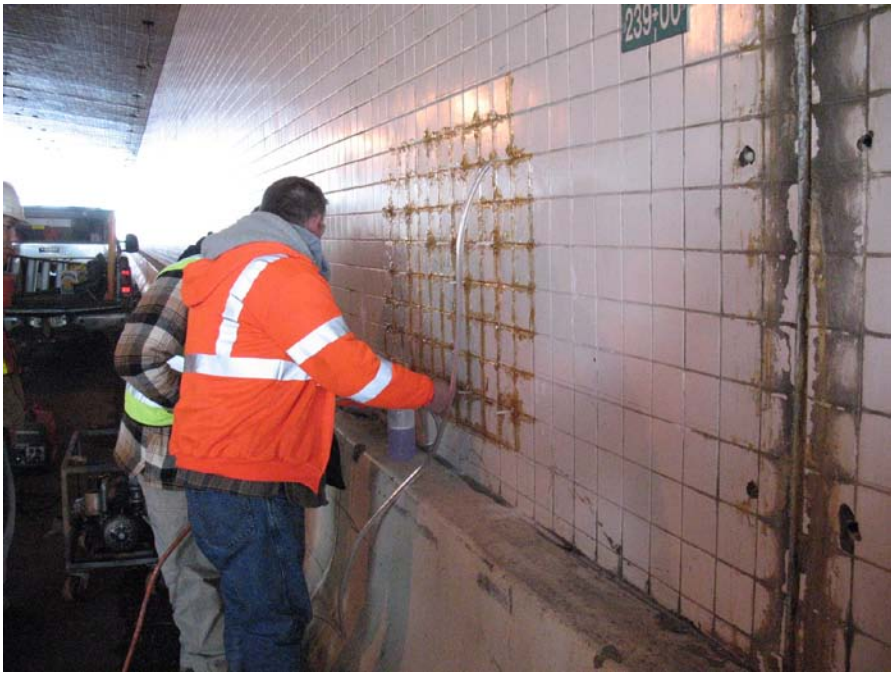


**Photo 16 –** Filling the injection ports with the methyl methacrylate as part of the vacuum injection process.

**Photo 17 –** 2” diameter core of region vacuum injected to validate that the methyl methacrylate filled the crack in the mortar. Please note that the red at the end of the core is the tile on the wall surface. Also, the bond between the mortar and the concrete substrate was sound, but debonded during the coring and extraction process.

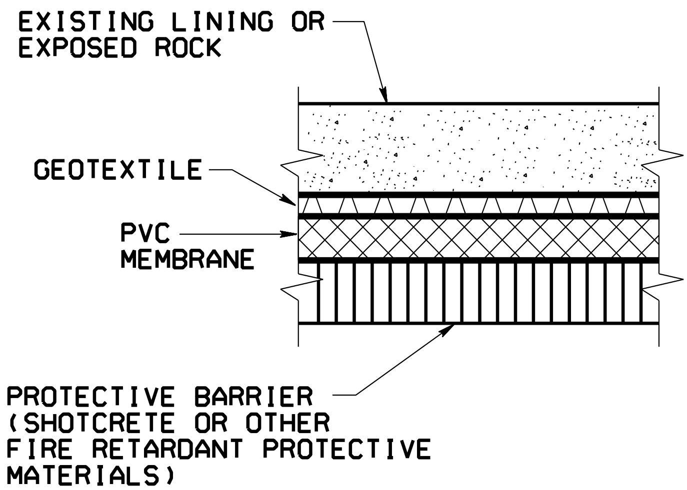



**Figure 1 –** Section of Membrane Waterproofing System (FHWA, 2005)

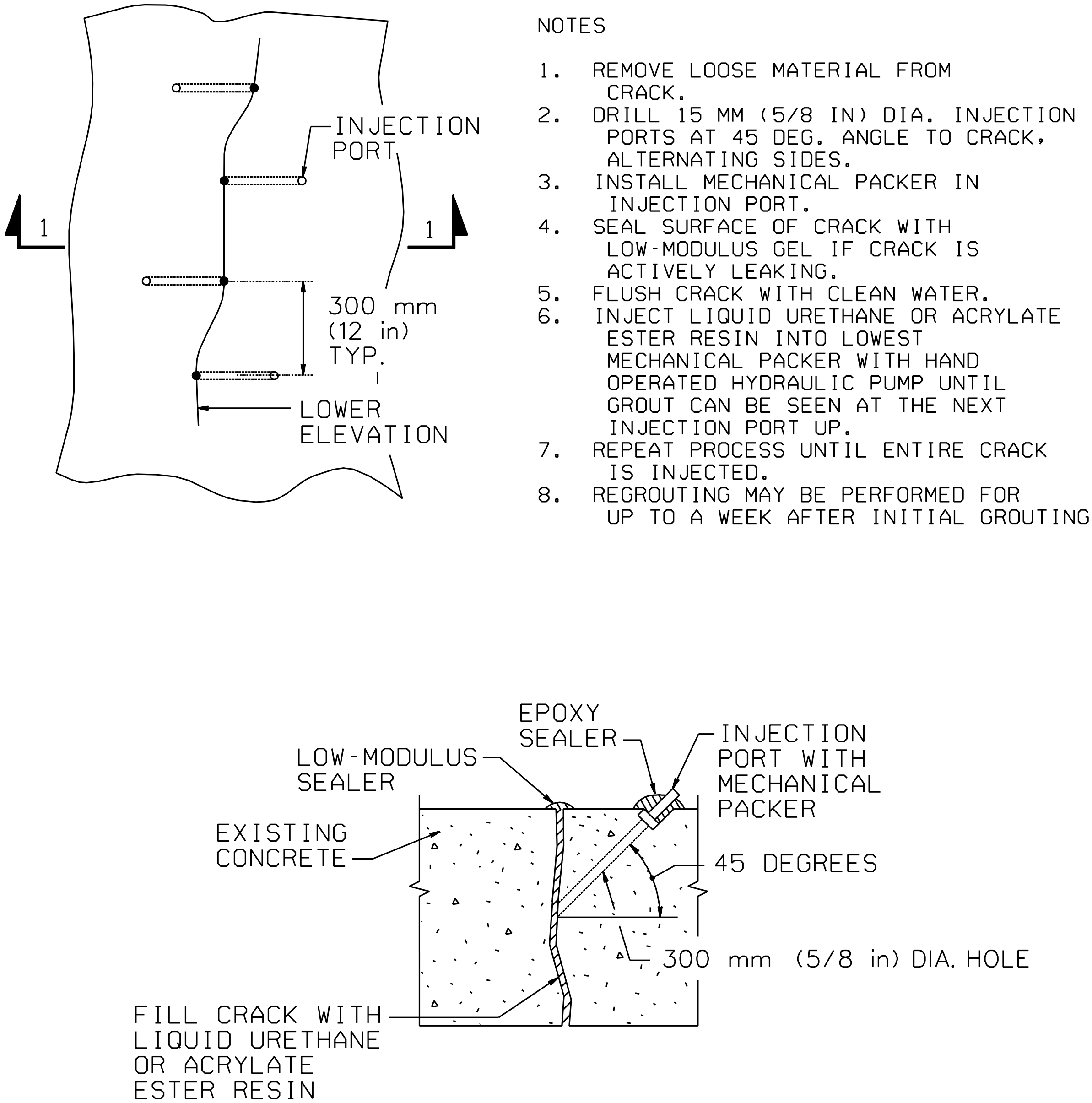



**Figure 2 –** Section 1-1 – Leaking Crack Repair Detail (For Leaking Crack, Vertical Surfaces) (FHWA, 2005)

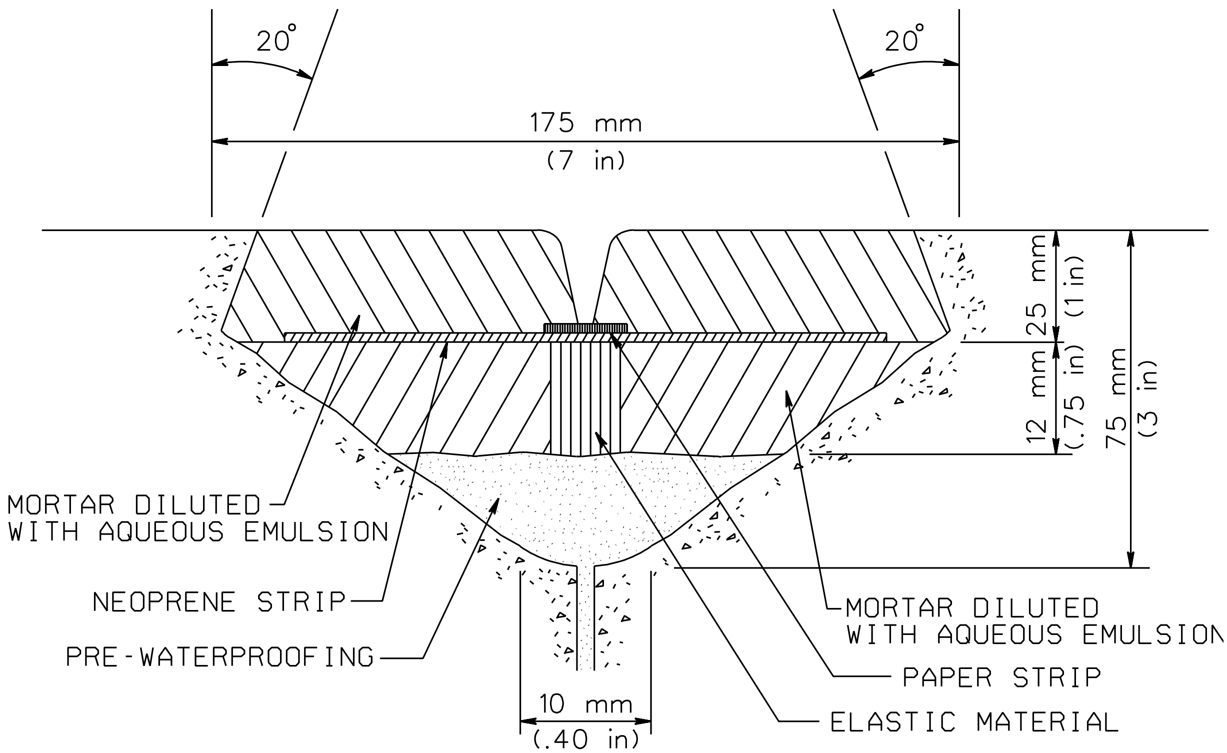



**Figure 3 –** Repair of a Concrete Joint or Crack by Inclusion of a Neoprene Strip (FHWA, 2005)

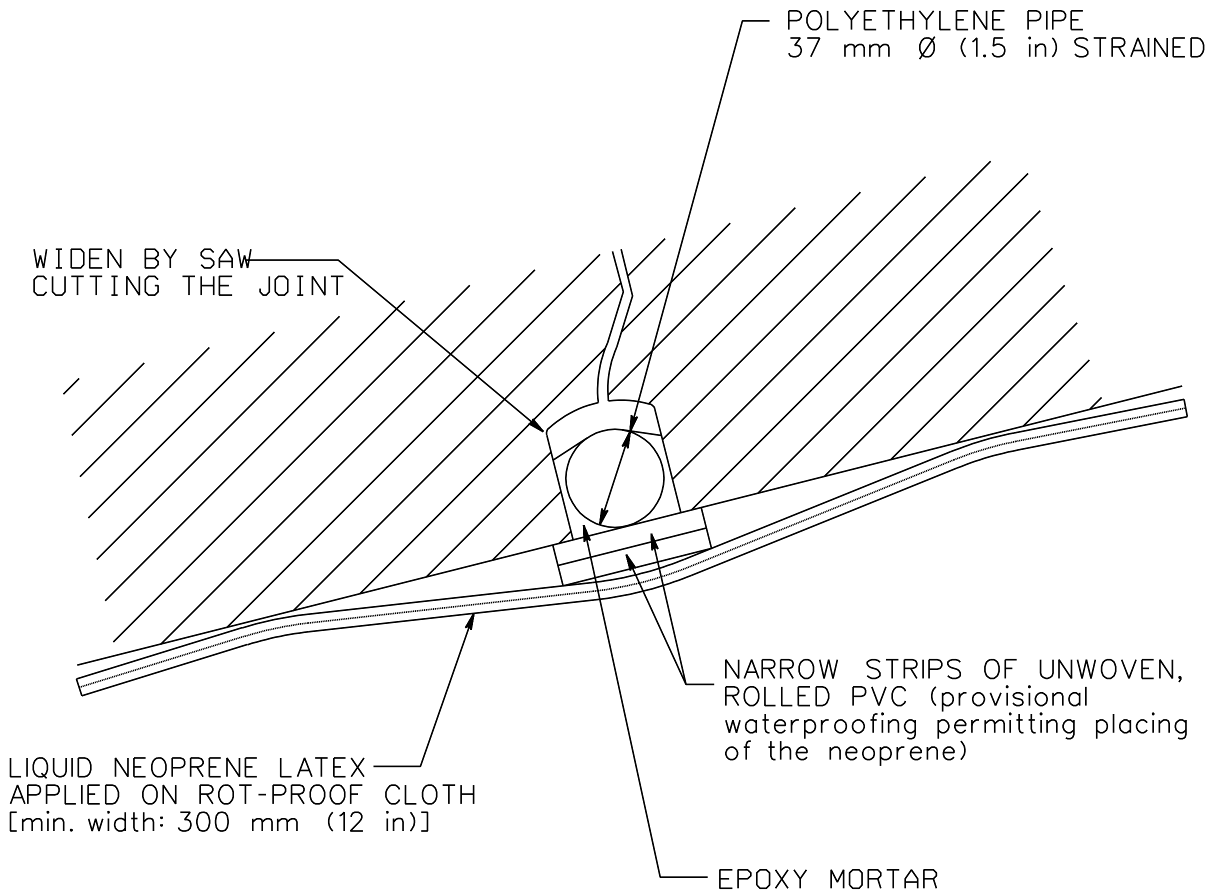



**Figure 4 –** Treatment of Cracks by Membrane Covering (FHWA, 2005)

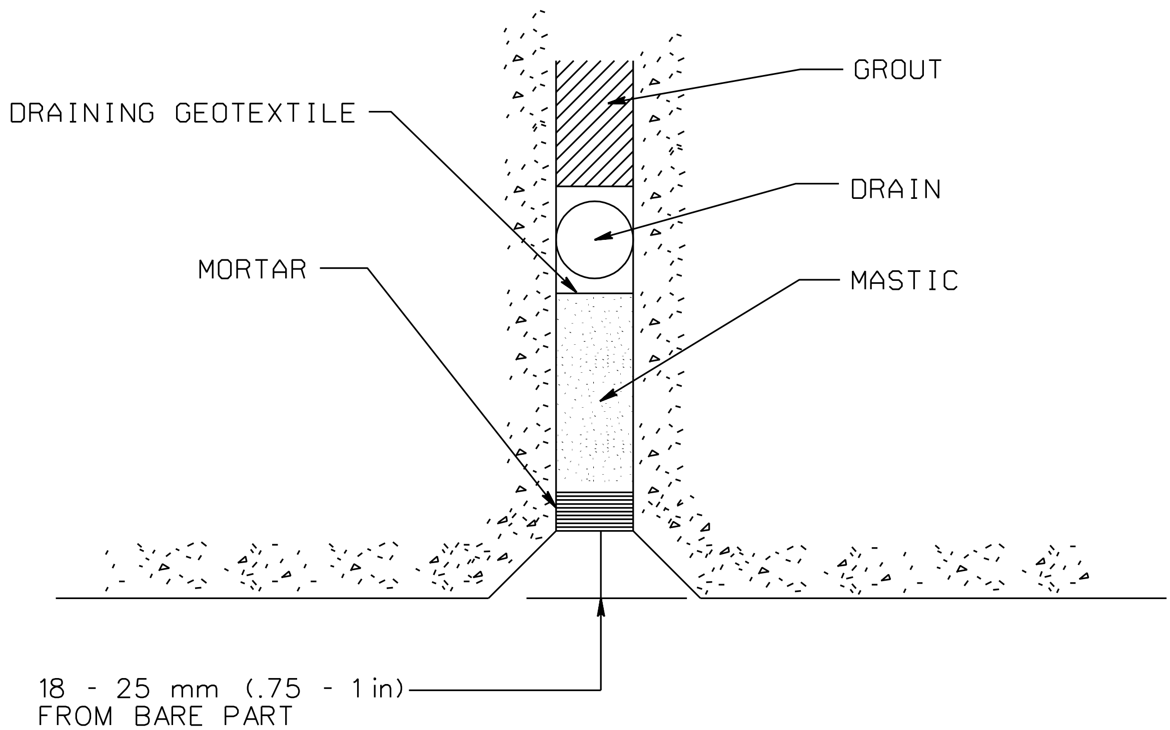



**Figure 5 –** Method of Repairing a Leaking Joint (FHWA, 2005)

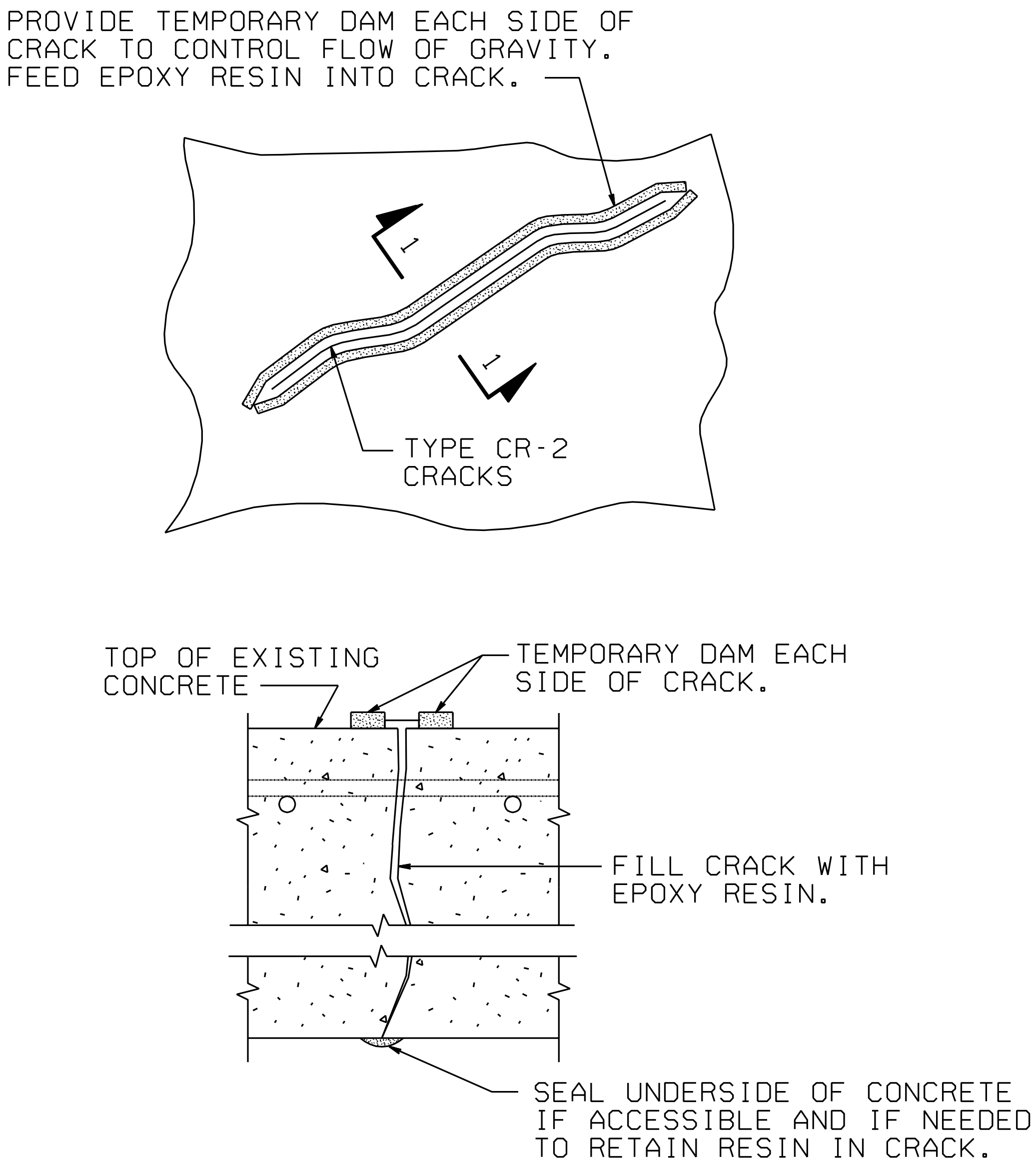
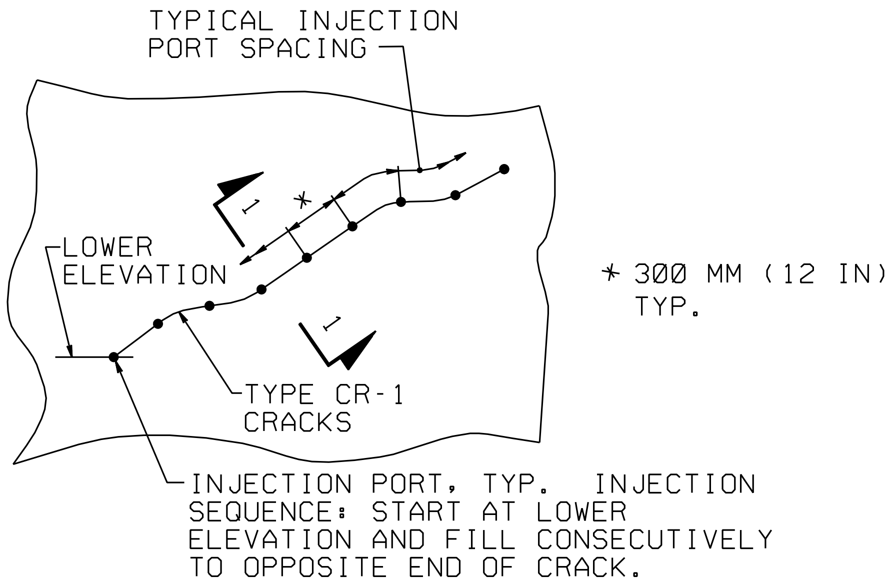



**Figure 6 –** Section 1-1 – Horizontal Surface Crack Repair Detail (for cracks 0.8 mm (1/32") wide and greater) (FHWA, 2005)



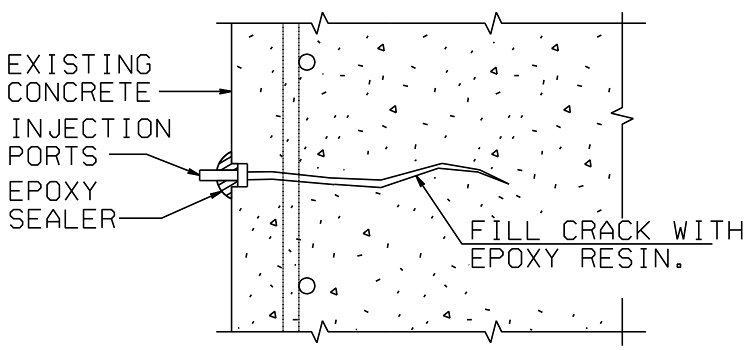




**Figure 7 –** Section 1-1 – Vertical/Over Head Crack Repair Detail (FHWA, 2005)

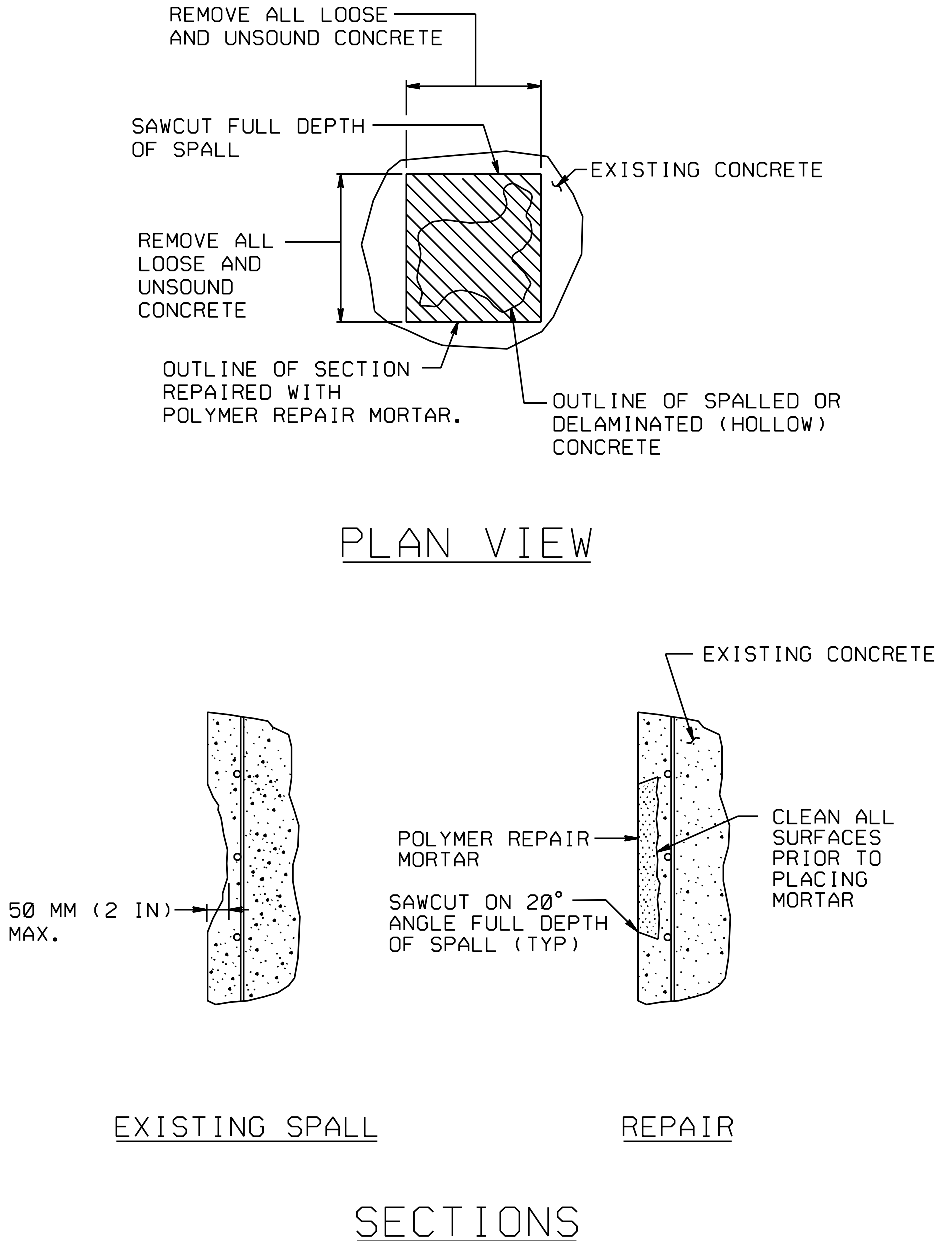



**Figure 8 -** Shallow Spall Repair Detail (shallow spall with no reinforcement steel exposed) (FHWA, 2005)

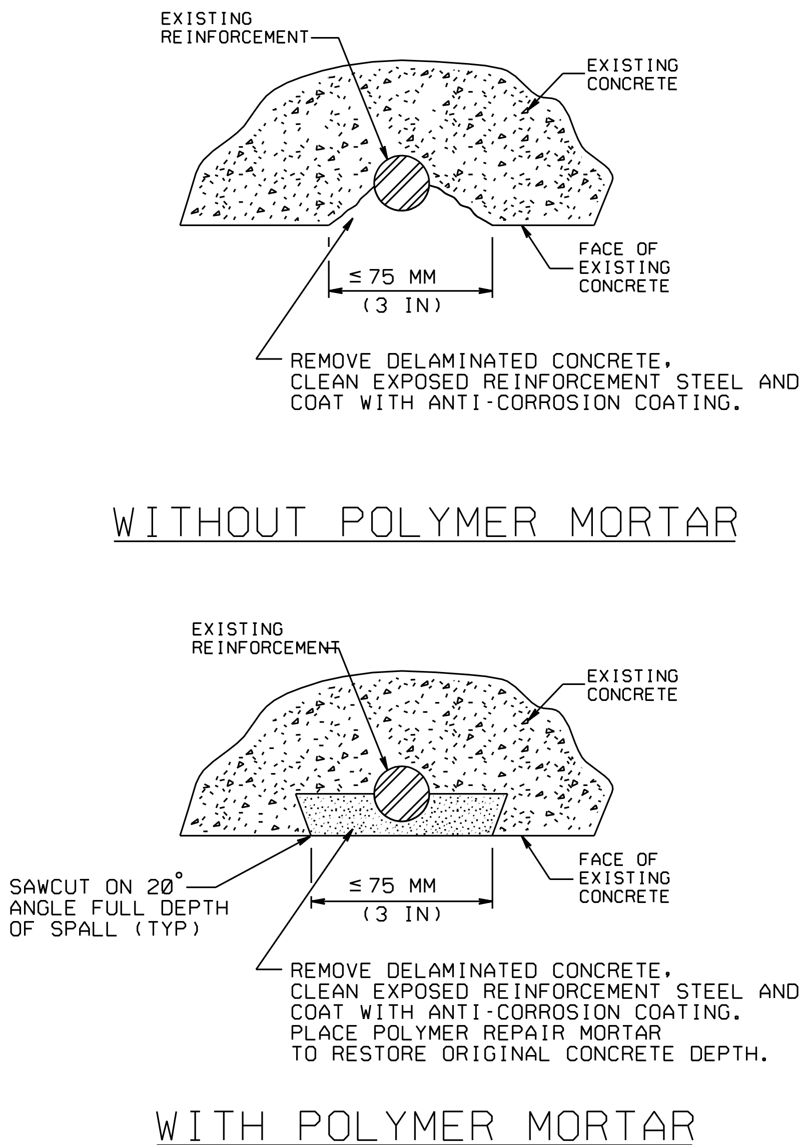



**Figure 9 –** Shallow Spall Repair Detail (shallow spall with reinforcement steel exposed) (FHWA, 2005)

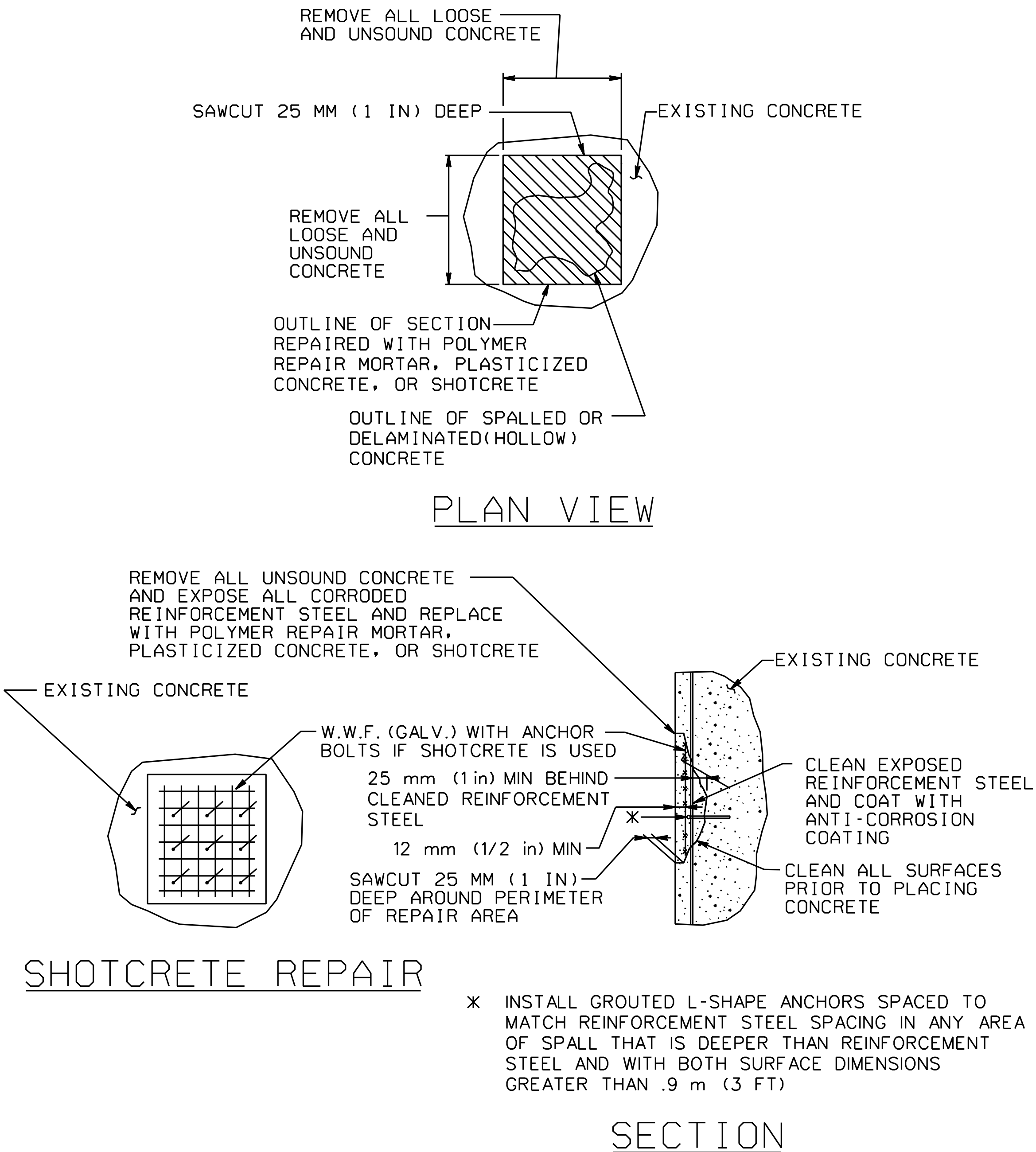



**Figure 10 –** Deep Spall with Exposed Adequate Reinforcement Steel (using polymer repair mortar, plasticized concrete or shotcrete) (FHWA, 2005)

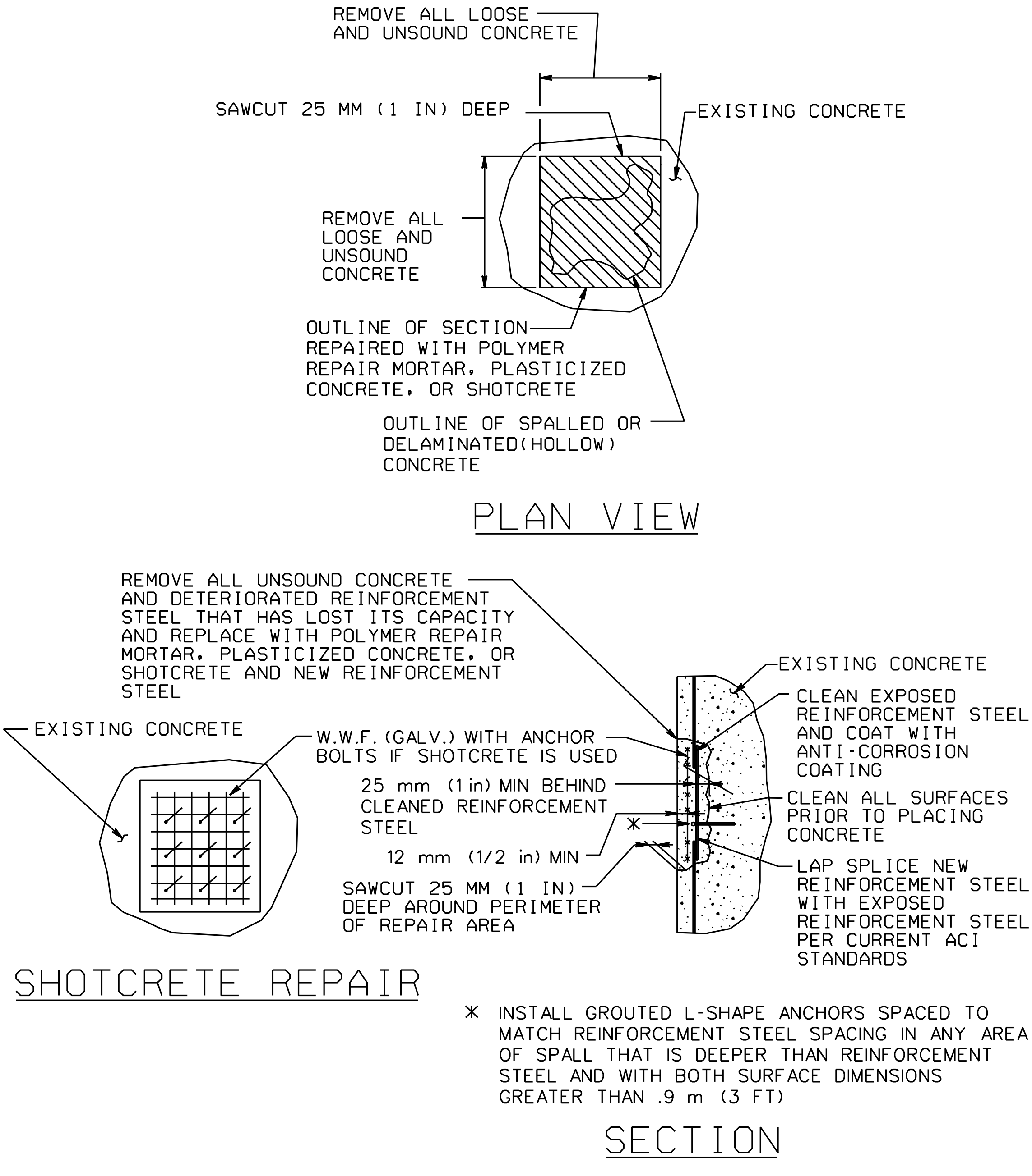



**Figure 11 –** Deep Spall with Exposed Inadequate Reinforcement Steel (using polymer repair mortar, plasticized concrete or shotcrete) (FHWA, 2005

# APPENDIX C

# TYPE A – CHANNELLING OF LEAKAGE WATER

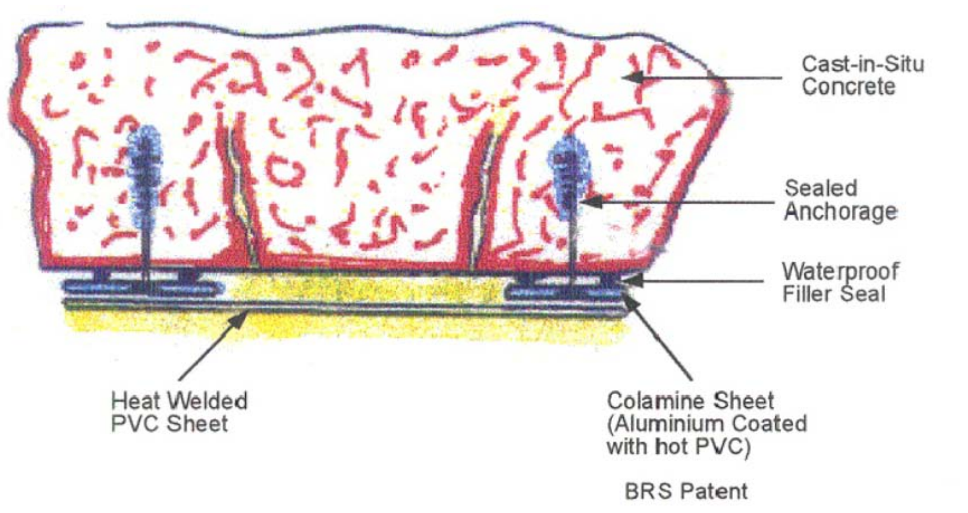



**Figure F5** (ITA, 2001)

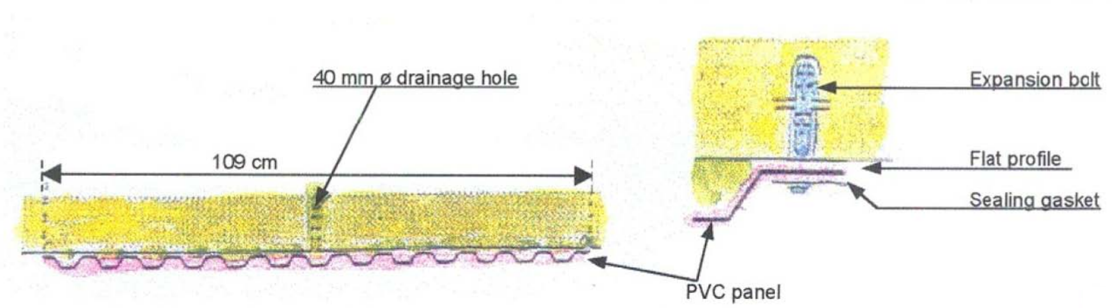



**Figure I8** (ITA, 2001)

# TYPE A – CHANNELLING OF LEAKAGE WATER

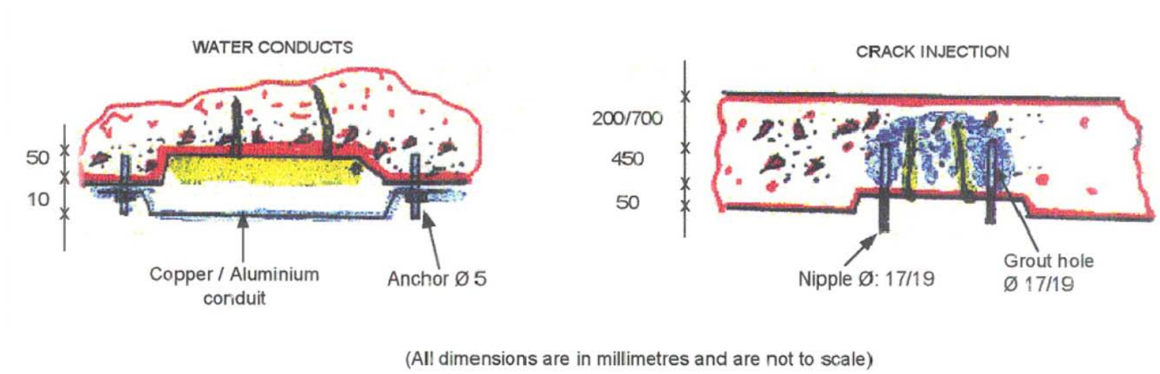



**Figure CU1** (ITA, 2001)

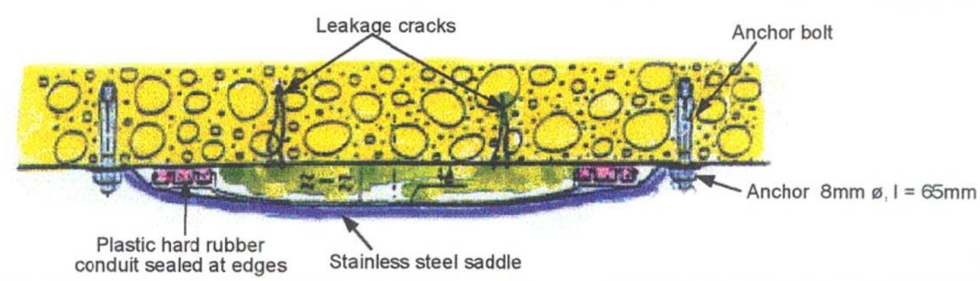



**Figure J1** (ITA, 2001)

## TYPE A – CHANNELLING OF LEAKAGE WATER

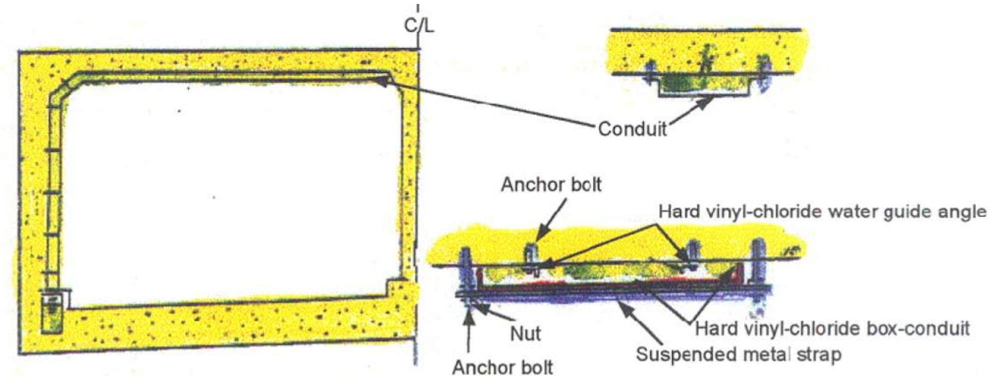



**Figure J2** (ITA, 2001)

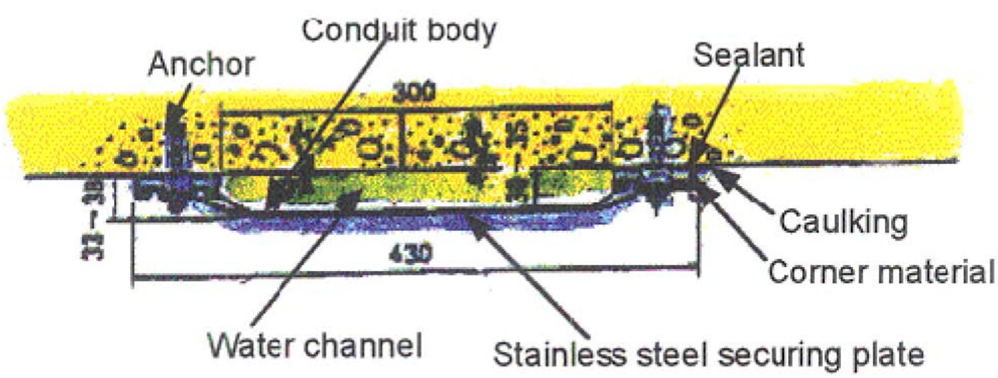



**Figure J3** (ITA, 2001)

# TYPE A – CHANNELLING OF LEAKAGE WATER

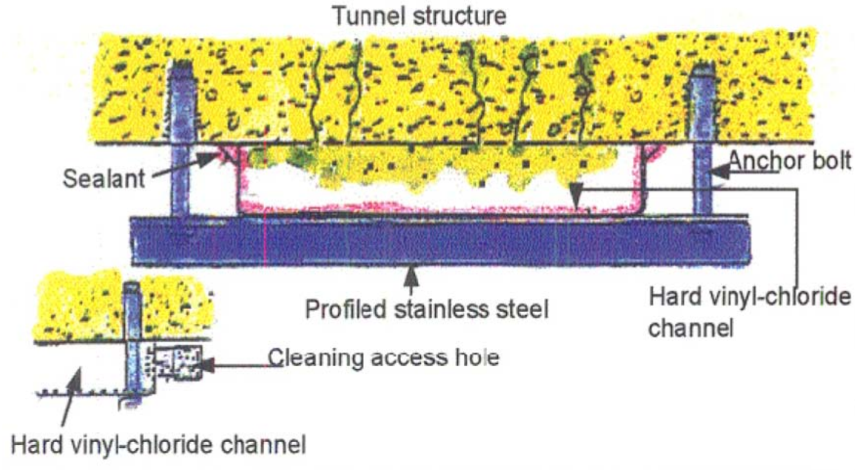



**Figure J4** (ITA, 2001)

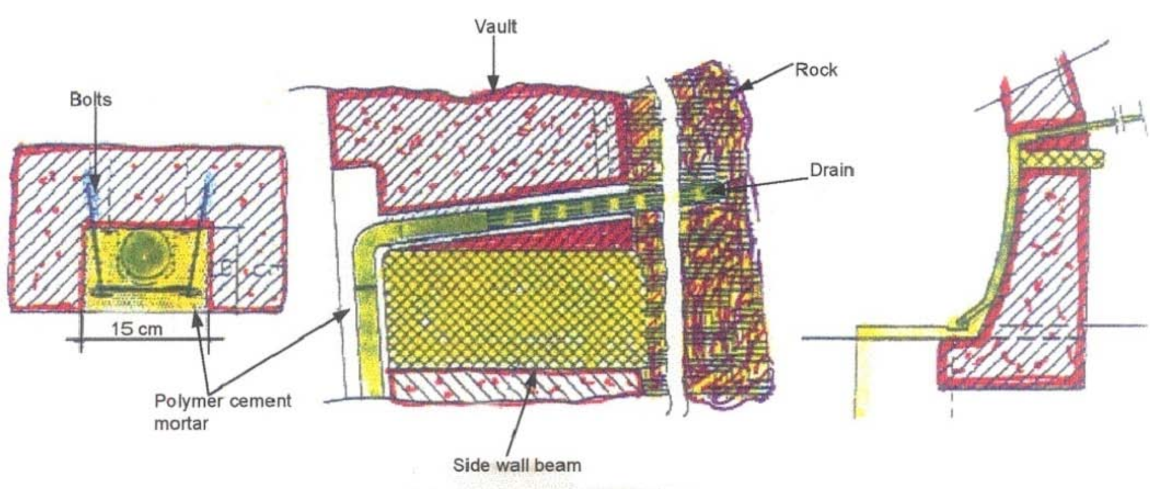



**Figure I4** (ITA, 2001)

# TYPE A – CHANNELLING OF LEAKAGE WATER

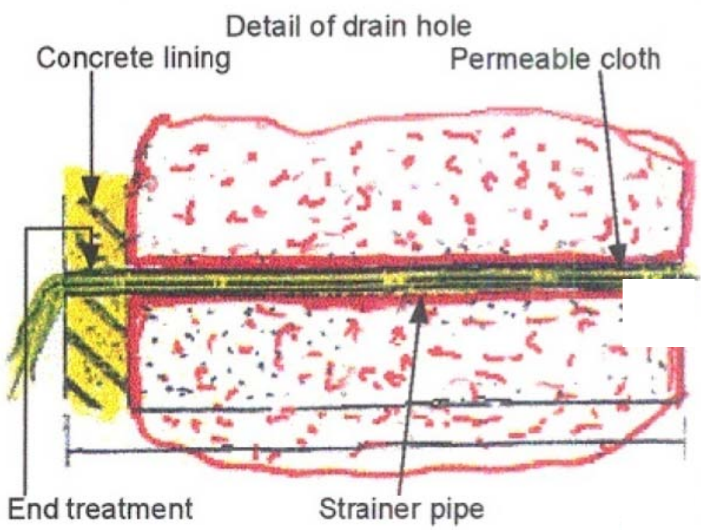



**Figure J22** (ITA, 2001)

## TYPE B – INNER SHELL

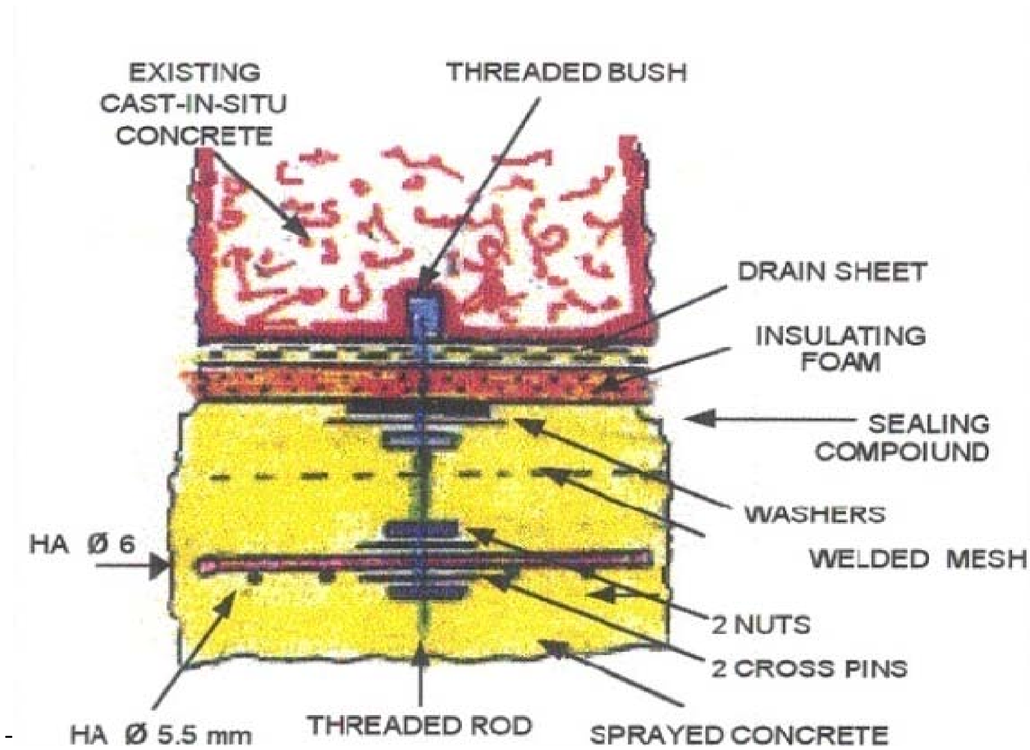



**Figure F1** (ITA, 2001)

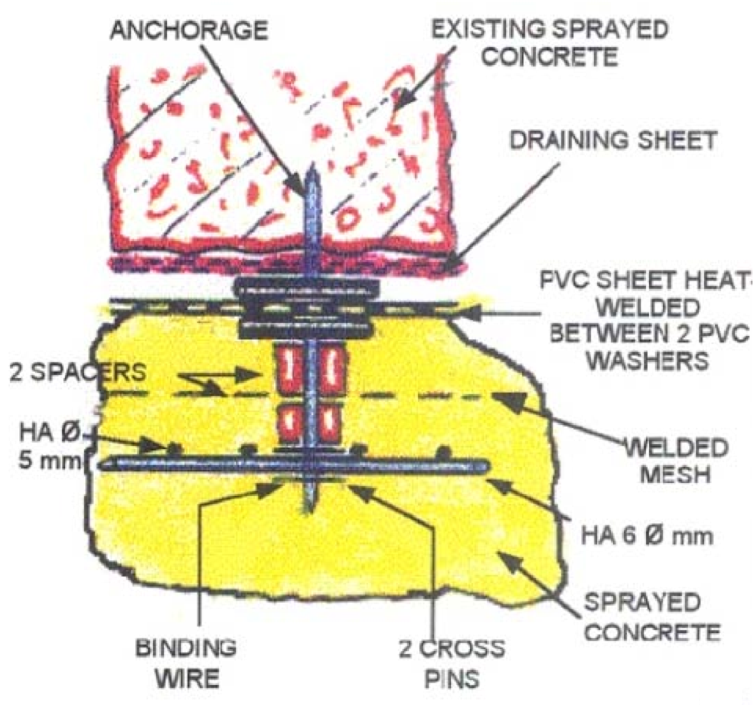



**Figure F4** (ITA, 2001)

# TYPE B – INNER SHELL

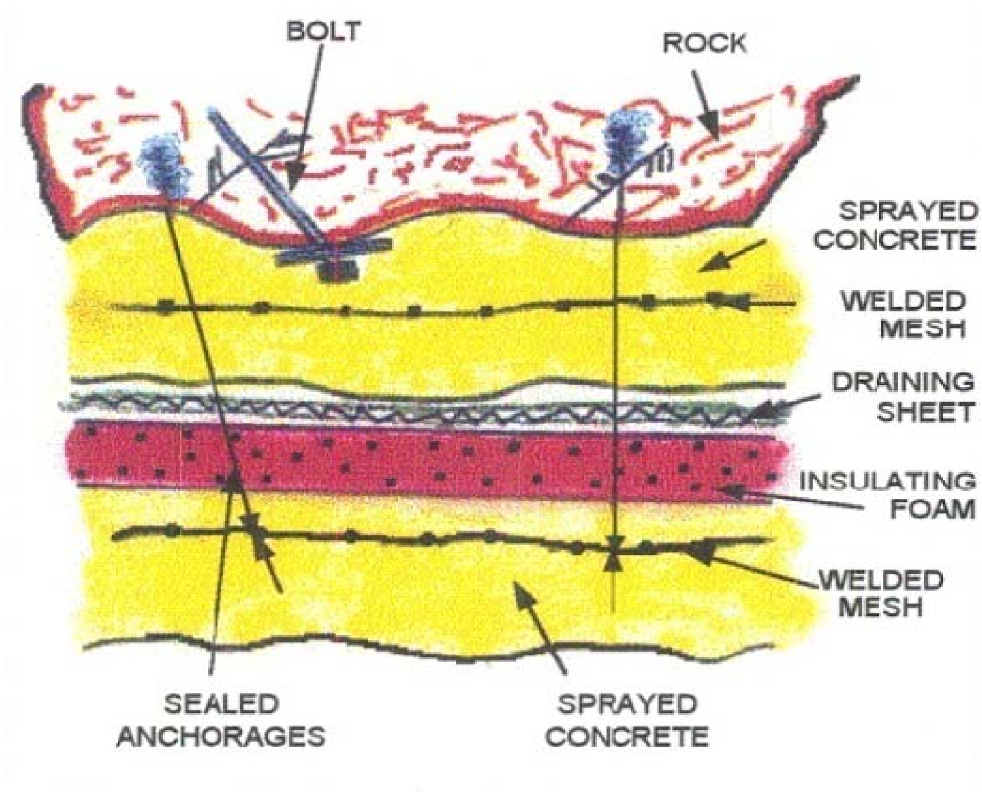



**Figure F6** (ITA, 2001)

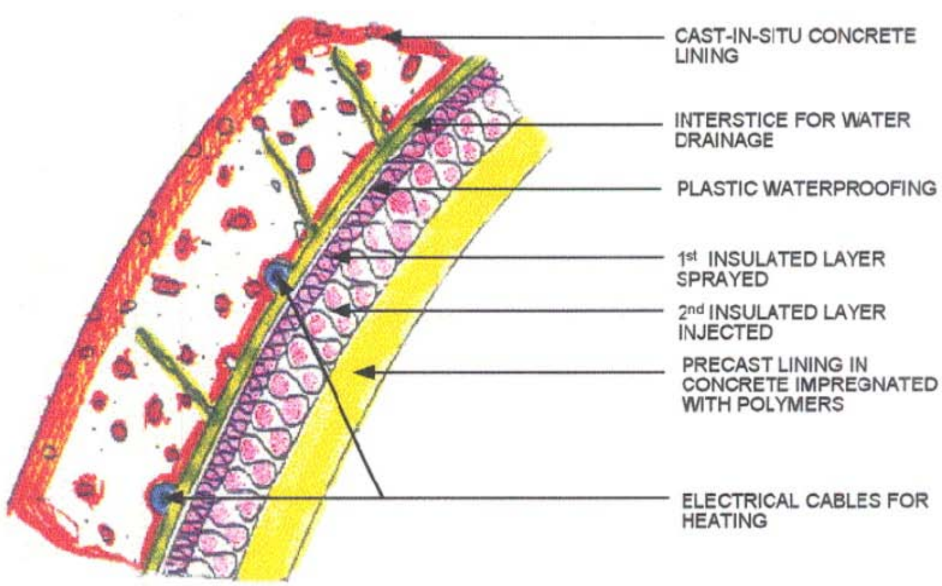



**Figure I9** (ITA, 2001)

# TYPE B – INNER SHELL

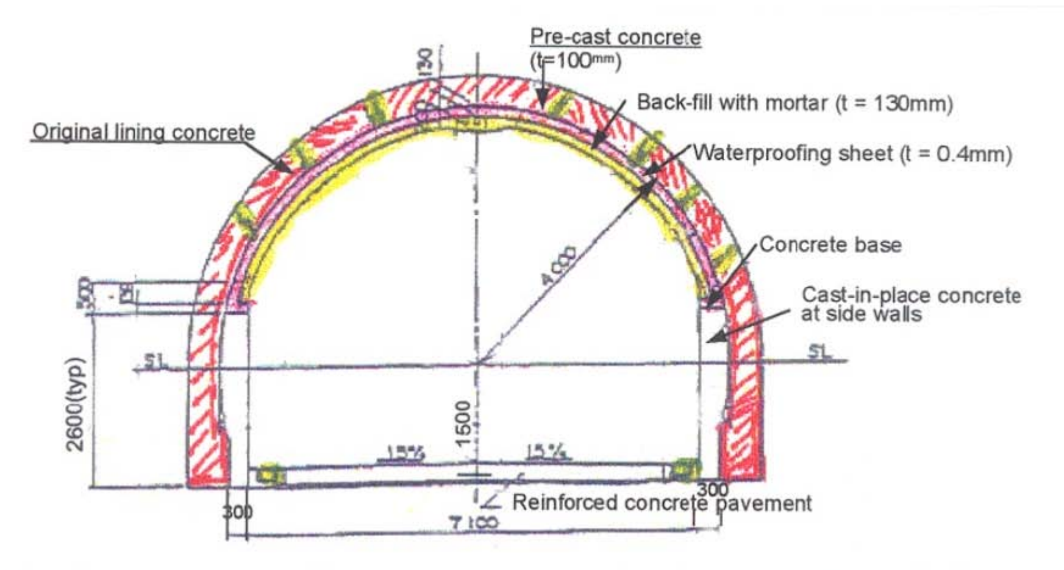



**Figure J18** (ITA, 2001)

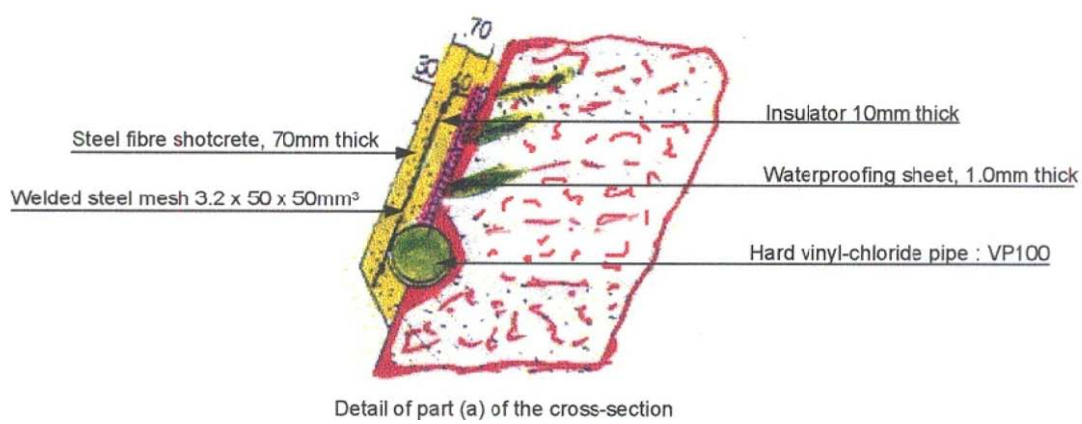



**Figure J27** (ITA, 2001)

## TYPE B – INNER SHELL

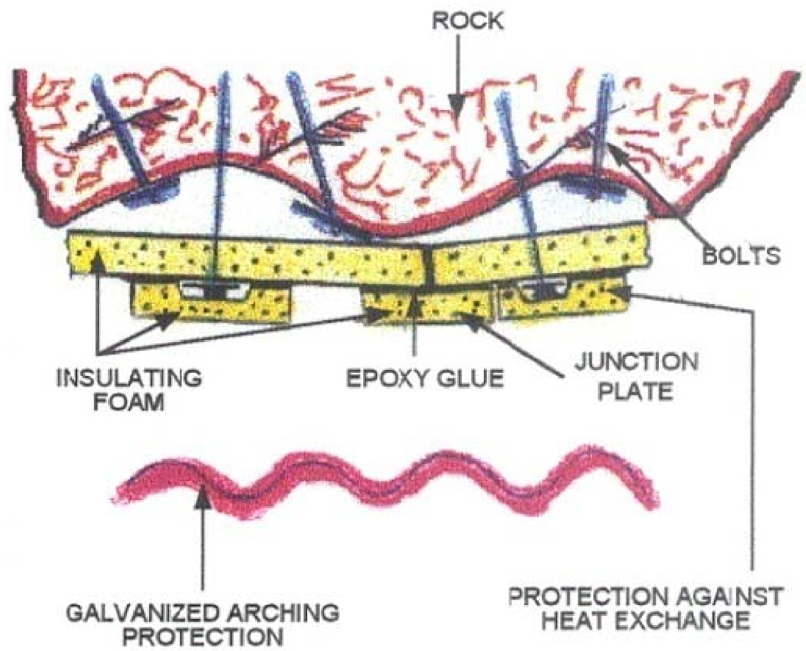



**Figure F7** (ITA, 2001)

# TYPE B – INNER SHELL (FREE STANDING)

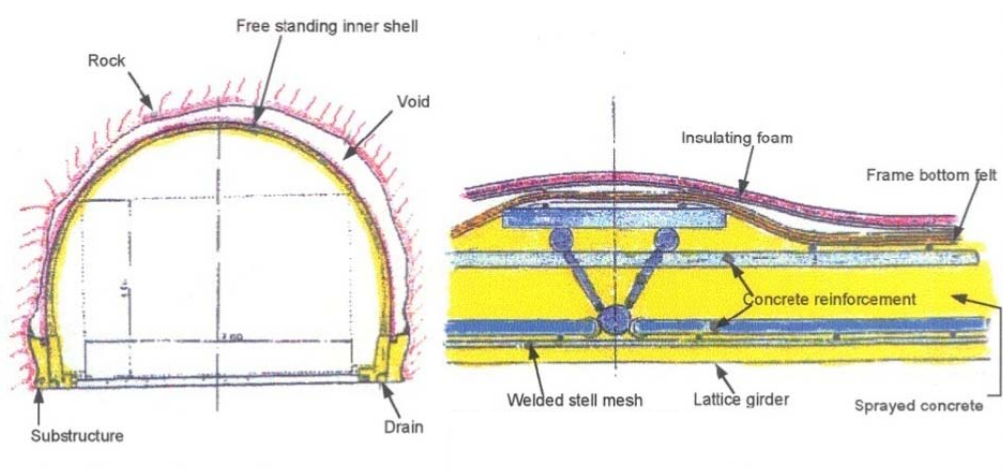



**Figure New Case F11** (ITA, 2001)

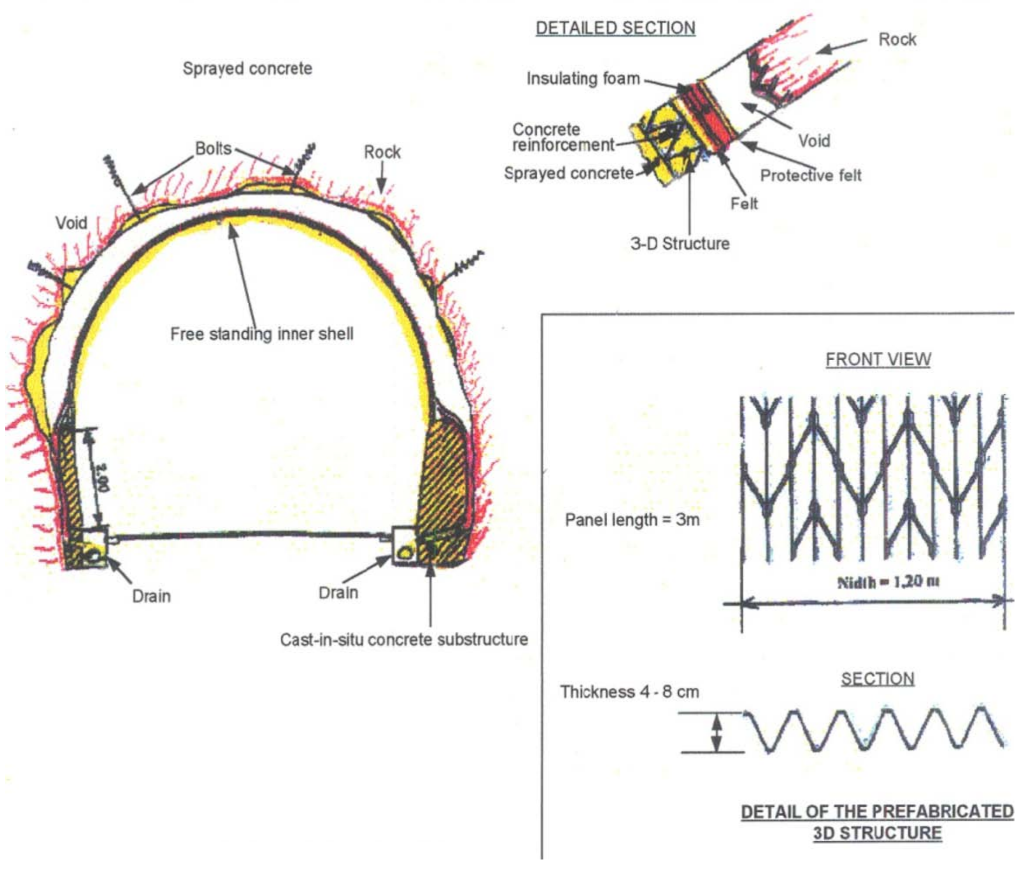



**Figure New Case F12** (ITA, 2001)

## TYPE C – SPRAYED MEMBRANE OR INNER LINING

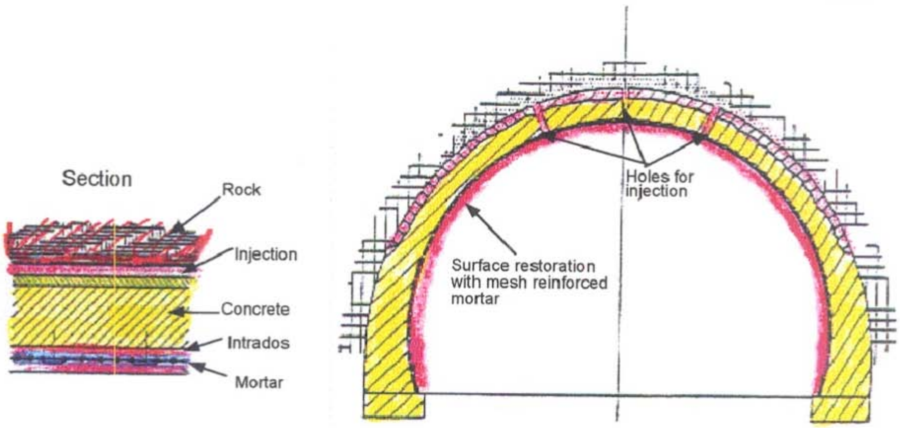



**Figure I3** (ITA, 2001)

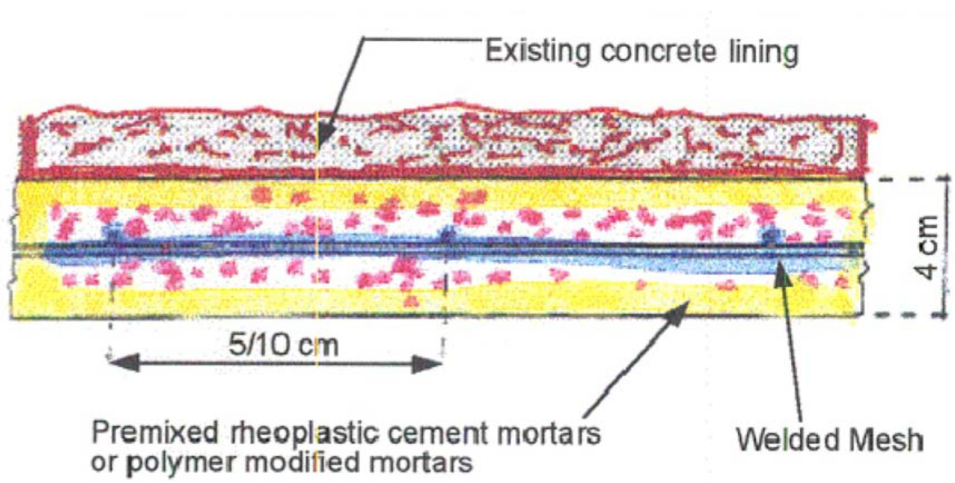



**Figure I6** (ITA, 2001)

# TYPE C – SPRAYED MEMBRANE OR INNER LINING

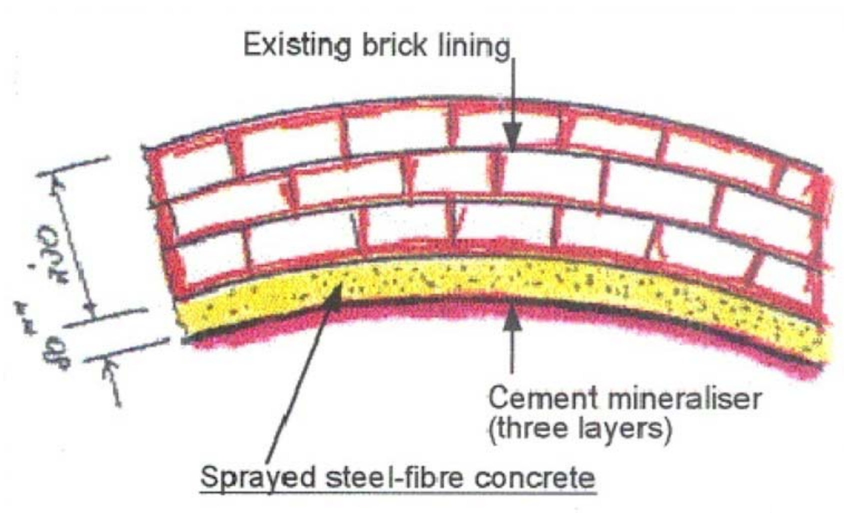



**Figure J20** (ITA, 2001)

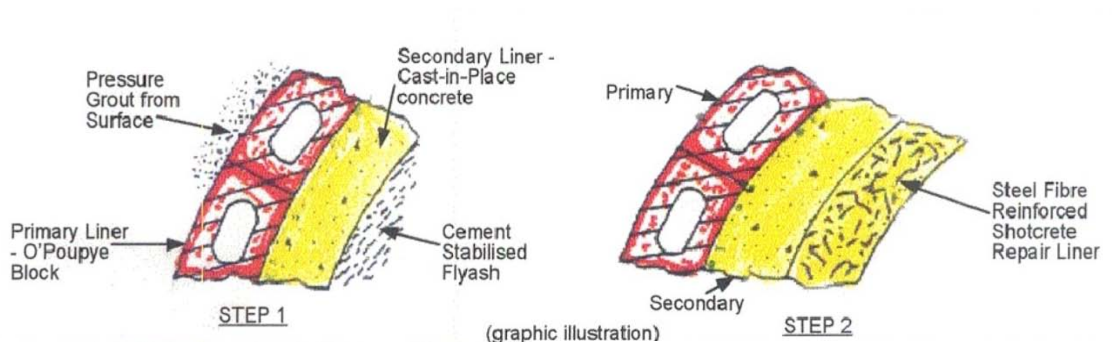



**Figure US3** (ITA, 2001)

## TYPE C – SPRAYED MEMBRANE OR INNER LINING

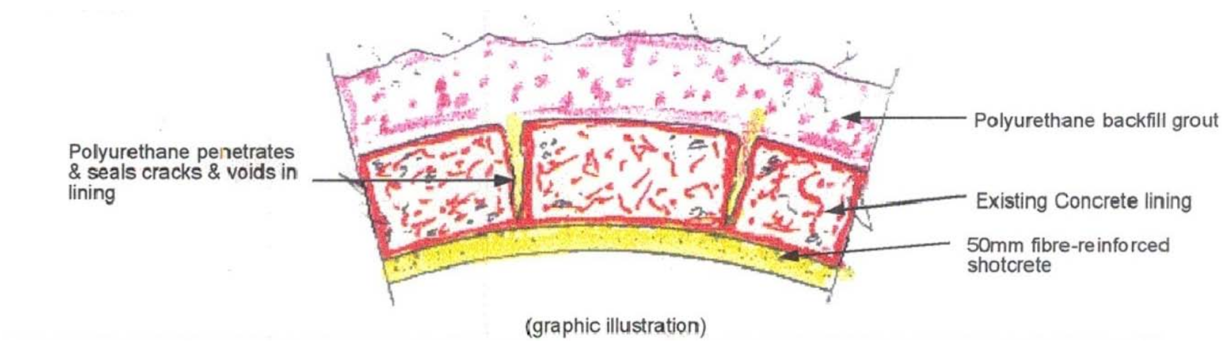



**Figure US7** (ITA, 2001)