

Guidelines for Waterproofing of Underground Structures



By

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1.00 Introduction

The purpose of this document is to discuss waterproofing options for the construction of underground structures, and to provide guidance to the designer for the selection of the proper waterproofing system for the particular type of structure to be built. The objective is to describe the benefits and deficiencies of each type of waterproofing system and to assist the designer in the selection of a waterproofing system that best suits the project conditions. It is important to remember that not one system is appropriate for all projects and this guideline identifies the waterproofing systems available at the time of writing and reflects PB's experience in the success or failure of each system.

Due to the soil and groundwater conditions it is critical that the structure be protected from groundwater infiltration and a suitable site specific waterproofing system be selected for the structure. The protection of an underground structure can be performed using a positive side (exterior) or negative (interior) waterproofing system. In general, the preferred system is a positive side waterproofing system that protects the structure from all types of attack while providing a tight waterproof membrane. Negative systems are typically used in rehabilitation systems where the exterior of the structure is not accessible. This document will address the various types of waterproofing systems including advantages and disadvantages of each system. In addition this document will discuss waterstops for penetrations and joints as well as remedial actions to be taken to control groundwater infiltration in the event that the waterproofing membrane has failed and is causing leakage into the structure.

Although this guideline is considered comprehensive it is possible that over time additional waterproofing systems will be developed and their effectiveness should be evaluated prior to the incorporation into PB documents.

2.00 Waterproofing: A System Approach

In order to understand the applications of waterproofing it is necessary to have knowledge of the principles of waterproofing below ground structures. It is important to understand the difference between waterproofing which is a coating or membrane that prevents the free passage of all water through a medium, while water-resistant prevents the limited passage of water vapor or water through a medium by the use of a membrane, coating or physical properties. For the purpose of this discussion we will focus on waterproof systems, with limited discussion on water resistant systems

The success or failure of a waterproofing system is often dependent on the owner's expectations for water tightness. Over the years tunnel designers have developed criteria for water tightness which is known as permissible (allowable) leakage. Permissible leakage is the amount of water that is acceptable to the owner for the safe operation of the tunnel. Permissible leakage is often identified as liters/day per square area of lining or as a point source leak in liters/day. These criteria should be established with the client, prior to the bidding to provide acceptance criteria for the waterproofing.

Once the criteria are selected for the permissible leakage attention must be drawn to the waterproofing selection criteria. The following are items necessary for the selection of a satisfactory waterproofing system:

- Type of structure
- Type of construction (bored, cut-and cover, etc.)
- Depth of burial of structure (lowest elevation of structure)
- Maximum Elevation of groundwater (after construction)
- Environmental conditions at the site (including Ph, hydrocarbons, and chemicals)
- Ease of installation
- Track record (successes and failures of the system)
- Construction Cost
- Long term maintenance (including costs)

In addition to the above a successful waterproofing system is dependent on the following:

- Site specific design for this type of structure and conditions
- Knowledgeable Designer familiar with this type of waterproofing and structure
- Proper Specifications and details
- Educated Owner
- Proper installation by experienced workmen
- Full time inspection during construction
- Warrantee
- Good track record

3.0 Waterproofing Systems

There are numerous waterproofing systems available in the market place:

- Liquid systems toweled or mopped
- Panel systems
- Sheet membranes
- Epoxy systems
- Sprayed systems
- Hybrid systems

It should be noted that epoxy systems, liquid and some of the hybrid systems can be applied by either spray or toweling. Some of the liquid systems and sprayed systems require the material to be heated prior to application.

3.10 Liquid Systems

Liquid systems have the longest track record and generally comprise the hot applied rubber, tar, polymers and asphalt emulsions. These systems are applied hot and require electric or propane fired kettles to raise the temperature of the material to approximately 100°C. The necessity for a kettle requires additional manpower and the materials are placed by hand with either mops or squeegees. Protection Board may or may not be required depending on the manufacturer.

Advantages

- Long track history
- Totally adhered
- Highly trained installers
- Good for Penetrations
- Easy to apply on horizontal surfaces
- No seams
- Known technology

Disadvantages

- Limited elongation usually less than 50%
- Requires heating (kettle)
- Attacked by hydrocarbons
- Requires a minimum 7 day concrete cure for application
- Requires dry surface
- Difficult to apply on vertical Surfaces
- Membrane thickness hard to control
- Safety issues
- Not self healing
- Requires protection board

Note: There are some cold applied liquid waterproofing systems, however, they are generally placed by spray methods and will be discussed later.



Hot Applied Polymer Rubber: note hot kettle

Comments: The hot applied membranes are good for penetrations and are an effective waterproofing membrane. However, poor elongation properties allows for it to separate from the substrate. The membrane requires the substrate to provide its ability to be continuous, if the substrate has any movement the membrane usually splits and is compromised. The heating kettles require additional personnel to operate and fire is a great risk during installation.

3.20 Panel Systems

Panel systems are those systems that use swelling Bentonite encapsulated either in a fabric roll or cardboard. The Bentonite must swell to create an effective waterproof barrier. This swelling occurs generally within 4 hours of contact with water. This system requires the panel to be placed in “the dry” and attached to the concrete. The locations of the attachments must be coated with mastic to seal the penetrations in the panel.

Advantages

- Quick installation
- Not attacked by hydrocarbons
- Good for flat surfaces

Disadvantages

- Penetrations difficult – often leak
- Requires penetrations for attachment
- Requires 7 day concrete cure
- Bentonite often separates within the panel – non continuous membrane
- Does not react (swell) in saltwater
- Seams difficult to seal
- Numerous seams
- Rigid system: no elongation

- Not self healing
- Requires protection board



Bentonite panel system: note nailing and poor seams

Comments: Bentonite panels are difficult to install correctly, often the Bentonite is segregated within the panel leaving undetected voids that allow leakage. The attachment to the concrete requires nailing, which must be surfaced sealed. The surface sealing is often poorly done allowing leakage. During installation, any rainfall or water leakage on site, the panels swell unconfined and lose their ability to provide an effective membrane. Penetrations are difficult and often not properly sealed. Note: Currently, Bentonite panels have been modified to be bonded to geotextile rolls and are installed as a hybrid system similar to sheet membranes and panels. These systems have similar properties to the Bentonite panels in performance and failure rates and should be avoided.

3.30 Sheet Membranes systems: Rubber, Neoprene, Rubber/HDPE

Sheet membranes systems are available in Rubber, Neoprene, high density polyurethane, (HDPE) and combinations of rubber and HDPE. They are provided as rolls usually approximately 2-3 meters in width and are self adhered. During application the roll is laid out flipped over and the backing removed. The sheet is placed onto the concrete with the adhesive in contact with the concrete and pressed into place. The sheets can be applied either as a blind side waterproofing against sheet piling or a temporary support system or can be applied after partial cure of the concrete. Blind side does not require protection board; however, normal installation requires the use of a protection board.

Advantages

- Quick to apply to flat surfaces
- Known technology
- HDPE resistant to hydrocarbon attack
- Few seams

- Good elongation 200-300%
- Available for blind side application

Disadvantages

- Neoprene/rubber attacked by hydrocarbons
- Seams difficult to seal
- Requires very clean dry surface
- Penetrations difficult
- Requires 7 days minimum concrete cure with primer
- Not self healing
- Mixed track history
- Not self healing
- Requires protection board



Self adhered sheet membrane: note backing at edges of sheet

Comments: Sheet membranes except for the HDPE systems are highly susceptible to Hydrocarbon attack the HDPE systems are susceptible to hydrocarbon attack if the seams are not properly sealed. Penetrations with all materials are very difficult and often leak. The seams are an overlap and require a very clean dry surface. Surface preparation is critical. Placement is difficult due to the self adhering properties of the sheets and the workmen must be very skilled in the applications.

3.40 Sheet Membrane Systems: HDPE, PVC

Sheet membrane systems used in the New Austrian Tunneling Method (NATM) for bored tunnels and for limited application in shafts, and are comprised of High Density Polyurethane (HDPE), or Poly Vinyl Chloride (PVC) sheet systems. These systems differ from the self adhered systems in that they are attached to the exposed rock, shotcrete liner of the tunnel or temporary walls for shafts. The Sheet Membrane system is often compartmentalized for repair after the casting of the final liner. This compartmentalizing allows for a location that has been

torn or compromised during construction to limit the direction of flow and allow for localized grouting to seal the liner. The seams of the system are heat sealed and are tested by air pressure to verify the seal. The liner is penetrated with attachment hooks, which have patch placed over the penetration to seal it.

These liners are installed as a closed or open bag system: a closed bag system does not allow any water to penetrate it and is watertight; an open bag system allows for drainage from the exterior of the liner to reduce hydrostatic pressure and is also watertight.

Advantages

- Excellent for bored tunnels and connecting shafts
- Not attacked by hydrocarbons
- Compartmentalized for repairs
- Known technology
- Good for areas of high hydrostatic pressure
- Good track history
- Needs no protection board
- Concrete cure time not an issue

Disadvantages

- Flammable: releases toxic fumes
- Rigid system: low elongation
- Seams often leak
- Difficult to repair
- Not self healing



HDPE Liner: note blue compartment gaskets

Comment: These sheet membrane systems are very costly and are difficult to erect due to the often irregular surface which they are attached. The attachments often leak and during construction the liner is often penetrated during the erection of the reinforcing steel. Testing of the seams is critical and time consuming. The system if proper installed is an excellent system but requires intensive inspection. During the period when the liner is exposed, caution must be exercised to protect the liner from fire. These materials when exposed to fire release toxic gases that can cause death therefore, personnel working in the tunnel must be trained in the use of self rescuers. This system is not particularly well suited for cut-and-cover construction.

3.50 Epoxy Liner Systems

Epoxy liner systems were first developed for use on bridge decks under railroad ballast. They are two (2) component systems and generally are produced in two (2) formulations: (1) one for horizontal surface and (1) one for vertical surfaces. The difference is that the vertical material is non-sag to better adhere to the vertical surfaces. The formulations are not interchangeable due to the requirement to have non sag for vertical surfaces to develop the required thickness. Typical installation of epoxy systems is performed by spraying the epoxy. All applications of epoxy systems and requires specialized personal protection equipment (PPE) including but not limited to respirators and in some cases self contained breathing apparatus.

Advantages

- Hard Finish: needs no protection board
- Relatively easy to apply
- Good for penetrations
- No seams
- No protection board required

Disadvantages

- Requires personal protection equipment
- Fumes toxic
- Low flash point: 4°C
- Offgasses and pinholes (voids in the membrane)
- Rigid no elongation or flexibility
- Requires 18 day concrete cure time
- Not self healing
- Limited track history
- Surface must be very clean and dry
- Limited applicators
- Requires Personal Protective Equipment (PPE)



Epoxy coating being applied: note respirator

Comments: A very dangerous product to use in a confined space or trench with the low flash point and vapor density four (4) times heavier than air, the material is very flammable and explosive. The material pinholes as it offgasses and cures and needs to be touched up after application, which requires extensive inspection. It is rigid and therefore any movement of the structure will cause a breach in the membrane. Also the different mix formulations require attention to application to ensure the non-sag is used on vertical surfaces.

3.60 Sprayed Coating Systems: Cold Applied Neoprene

Sprayed cold applied neoprene is a single component material that is sprayed onto the concrete surface immediately after the stripping of the concrete forms. The neoprene is a water based product that has been used as a gas barrier for methane for many years it is applied with a heavy duty airless sprayer and does not require a primer.

Advantages:

- Apply same day forms stripped
- No primer required
- Excellent elongation: 400%
- No seams
- Good for penetrations
- Does not require a heat source (kettle)
- Non-flammable
- Concrete surface may be moist

Disadvantages

- Blisters as concrete cures
- Attacked (dissolved) by hydrocarbons
- Not self healing

- Requires protection board
- Limited applicators
- Requires very clean surface
- Limited history



Cold Applied Neoprene: note protection board

Comment: The spray neoprene is aggressively attacked by hydrocarbons particularly petrol (gasoline). The hydrocarbon issue has seriously hurt the reputation of this material. It is very good for penetrations. It has a limited history in the tunnel industry and the formulations have changed often. Strict attention has to be made to the blistering issue where water vapor from the concrete is trapped and the blister traps water long term performance may be an issue track record too short to quantify.

Note: Within the last two years a latex cold apply spray material has been introduced. However it has only been used on one project in the U.S. and the performance has not been evaluated. Therefore this discussion will not cover this product.

3.70 Spray Coating Systems: Polyurea

Polyurea is a material that has been formulated for use as a waterproofing membrane. The polyurea is the same material used for automobile bumpers, however the materials formulated for waterproofing membrane is a more rigid material that must be heated to apply to the concrete surface. It bonds tenaciously to steel and concrete.

Advantages:

- Hard finish
- Rapid cure
- Good elongation
- Does not require protection board
- No seams

Disadvantages

- Requires very clean dry surface
- Material must be heated to apply
- Rapid cure time: 20-30 seconds
- Vapors highly flammable
- Requires special protective equipment
- Limited track history
- Few trained installers
- Not self healing



Polyurea Application: note protective equipment

Comment: Polyurea is fairly new to this market and therefore has a limited history. The manufacturers advertise 200 % elongation. However, our experience is that it is semi rigid materials that has very little elongation and has develop cracking due to surface shear. Application is difficult in hot climates due to the extensive personal protection equipment needed to install. The vapors are typically very flammable. The equipment is very costly and there are few experienced installers and the costs are very high compared to other systems.

3.80 Cementitious Waterproofing Systems

Cementitious waterproofing systems are a blend of co-polymers and Portland cement. These materials use the copolymers to reduce the pore size of the concrete to prevent the passage of the water molecule through the coating while allowing water vapor to pass. These coatings are generally used on the negative (interior side) of structure in rehabilitation projects where the exterior concrete surface is not accessible. However, it has been used on exterior surfaces of tunnels with success.

Advantages:

- Hard finish
- No protection board required
- Available in white and grey colors
- Rapid installation
- No seams
- Good track record
- Installed by plastering spray equipment

Disadvantages

- Rigid system no elongation
- Not self healing
- Applied day concrete forms stripped
- Not applicable to penetrations
- Rapid set time in hot climates



Tuscarora Tunnel before Cementitious Coating



Application of Masonry coating with hopper gun



Tuscarora Tunnel: After Cementitious Coating

Comments: The cementitious coatings have been used extensively for tunnel rehabilitation projects; however, have very limited use on the exterior of tunnels. This is a good product as a backup system for areas where exterior waterproofing has failed. This system is a rigid system and will crack and leak if the structure moves. Not recommended as an exterior coating.

3.90 Hybrid Systems: Poly Rubber Gel

Poly Rubber Gel system is a system that uses a mixture of recycled rubber and co-polymers to create a flexible membrane that remains plastic and is self healing. This product, while fairly new (10 years), has been used extensively in Asia and has had a very good track record. The material is placed either by spray or trowel as a cold mixture with the use of high pressure spray equipment or a rotary stator pump similar to that used for concrete mortars.

Advantages:

- Cold applied by traditional methods
- Not attacked by hydrocarbons
- Excellent elongation and flexibility
- Self healing
- Non flammable non-toxic
- Good for penetrations
- Applied same day as concrete forms are stripped
- No primer necessary
- Good track record
- No seams
- Non flammable
- Green Product: made from recycled materials
- Excellent track record

Disadvantages

- Requires a clean dry surface
- Requires protection board
- Requires special pump/ spray equipment



Poly Rubber Gel: note seals around penetrations

Comments: This material has little or no odor and is a very thick product which requires a special pump to apply. It is cold applied and therefore does not need a kettle. The gel is very “sticky” and is difficult to remove from areas where spilled. Has excellent resistance to hydrocarbon and sulfate and sulfite attack. It is an excellent product for pile or pipe penetrations. It can be injected through a wall to reinstate the liner. It has an excellent track record. Poly Rubber Gel is a proprietary system as of 2008, and as such requires justification for publicly funded projects.

3.91 Hybrid Systems: Waterproof Concrete

Waterproof Concrete systems are a blend of additives and Portland cement and aggregates. This type of concrete uses additives, particularly Calcium Sterite, to reduce the pore size of the concrete to prevent the passage of the water molecule through the coating, while allowing water vapor to pass.

The term waterproof concrete is a misnomer since concrete can be made to be water resistant but not waterproof. Concrete as it cures releases water vapor and continues to cure for years after casting. This curing process also creates shrinkage cracking. The co-polymers used to create waterproof concrete do not address the shrinkage or concrete or other cracking that is due to thermal activity or settlement. Waterproof concrete is primarily used in Asia and has been used in Singapore on the MRT.

Advantages:

Rapid installation
Works well in Arid Areas

Disadvantages

Does not bridge cracks
Not waterproof: it is water resistant
Rigid system
No elongation/flexibility
Poor for penetrations
Limited details available for penetrations and terminations
Questionable track record

Comments: Concrete cannot be made waterproof without a membrane. The use of co-polymers to reduce the permeability of concrete is effective but does not assist in the prevention of water infiltration through cracks or at penetrations. This material has been used in Singapore and the author observed two stations on the MRT that was constructed of water proof concrete and they both had cracking in the roof with water leakage.



Harbor Front MRT Station (Singapore): Note Leaking crack



Chinatown MRT Station (Singapore): Note Leaking crack

3.92 Cast-in-Place Concrete Diaphragm Walls

Cast-in-place concrete Diaphragm walls more commonly known as slurry walls provide their own waterproofing system by their specialized type of construction. The construction process is to install a concrete wall (either concrete panels or secant piles) prior to excavation of the underground structure. The installation of the concrete panel or secant pile is performed without permanent support system and relies on slurry to maintain the sides of the excavation open as it advances downward. The slurry is displaced by a tremie pour of concrete and becomes the structural wall. The structural wall can be temporary in which typical waterproofing techniques are used, or in the case of being used at the permanent structural wall the waterproofing from the slurry acts as the exterior waterproofing membrane. Traditional slurry walls have used pure Wyoming natural montmorillinate Bentonite for the slurry. The Bentonite clay penetrates the granular soils and membrane is created by the formation of a mud cake in which the void space of the granular soils filled with the slurry providing a waterproof barrier. It has been PB experience that Bentonite slurry has worked very well and is suitable for both granular and non-granular, soils and rock for providing a suitable waterproofing membrane. Polymers on the other hand, do not form a mudcake and do not provide a suitable membrane for a structure where the exterior face of the diaphragm or secant wall is to act as the waterproofing membrane. Polymers are not recommended for use in granular soils loose tills or rock and are only suitable for structures that are completely constructed in impervious soils. Any design work for concrete diaphragm (Slurry) walls consult the *Guidelines for Design and Construction of Concrete Diaphragm (Slurry) walls, published by Parsons Brinckerhoff 2008.*

Advantages

Holds trench open
Excellent waterproofing membrane
Long history of success

Disadvantages

More costly than polymer
Requires landfill disposal
Requires close Q/AQ/C of the density and Ph

4.00 Waterstops for Penetrations and Joints

Cold joints and penetrations are the most common cause of leakage in an underground structure. The lack of proper detailing and installation of proper gaskets or waterstops in the structure are the most common causes of ground water infiltration. The penetrations may take many forms. They typically consist of tie-down anchors, pipe penetrations, utility penetrations etc. All penetrations share the same commonality in that they breach the waterproof membrane and require special treatment to prevent the water from entering structure. In general the materials used for sealing penetrations and cold joints are referred to as waterstops. Some membrane systems, cold and hot applied rubber neoprene and poly rubber gels require minimal additional treatment to seal penetrations and cold joints. These materials due to the nature of their installation can be applied around the penetration and effectively seal the penetration and cold joints with the membrane material. The Poly Gel Rubber and cold applied Neoprene are the only products that do not require additional treatment for penetrations. However it is always good practice to add extra seals to all penetrations to ensure a tight structure. Sheet membrane, Epoxy and Bentonite membranes are the most difficult to seal and require additional materials and procedures to seal the penetration.



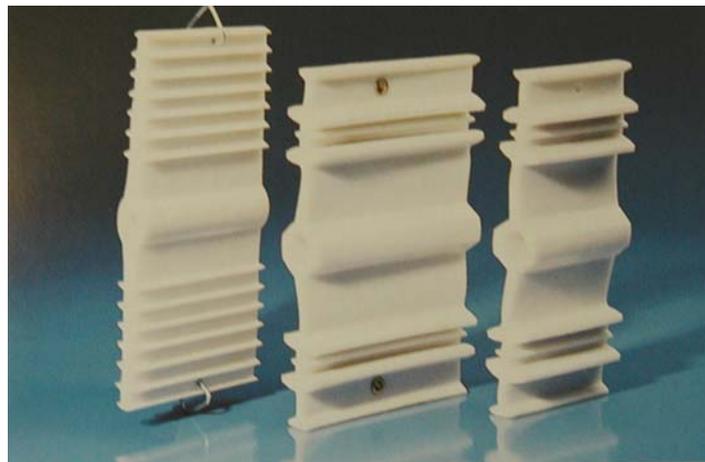
Sheet membrane: note lack of seals at penetrations



Poly Rubber Gel at pile penetrations

4.10 Vinyl or PVC Waterstops

The traditional waterstop for concrete cold joints is the traditional dumbbell (due to shape) waterstop made of vinyl, PVC or rubber. These waterstops are partially placed in the primary pour and are held in position in the subsequent pour. This placement is across the joint providing a second barrier to the inflow of water. These water stops rely on the ribs on the waterstop to create an arduous path for the water to follow thereby preventing the flow of water across the cold joint. These waterstops are often ineffective due to damage or displacement during the concrete pour and craftsmanship during installation. They are either torn or folded over themselves therefore defeating the purpose of the ribs. Dumbbell waterstops are not designed for membrane penetrations and should not be used for pipe or utility penetrations.



Typical vinyl or PVC waterstop: note ribs



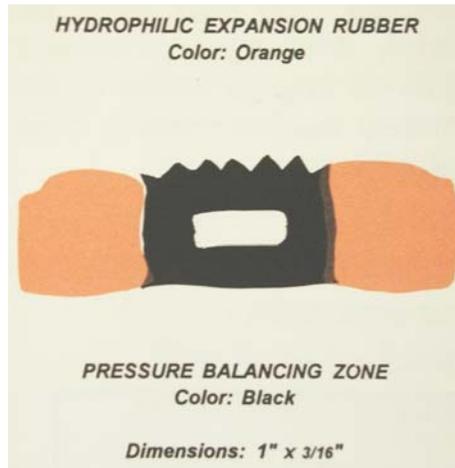
Typical installation of vinyl or PVC waterstop: Note end is folded over

Comment: The use of Vinyl or PVC Dumbbell (commonly referred to due to their shape) waterstops is only partially successful for preventing long term leakage. The installation is labor intensive and requires extreme care to prevent damage to the installation of the waterstop. The swelling Bentonite seals are also problematical for use in a humid climate in that they start to swell once exposed to air and if in contact with rainfall prior to final concreting. They are ineffective to preventing water flow across a joint. Of all options provided the swelling rubber waterstop is the most effective. The water stop requires minimal attention for installation it is generally Hilti nailed to the cured primary pour and requires 72 hours to swell. It is also extremely effective for pipe penetrations providing two seals are use form the gun grade material.

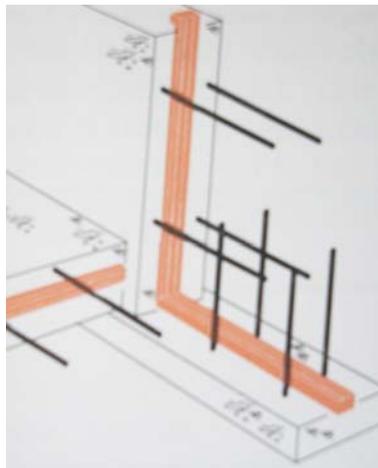
4.20 Swelling Rubber Waterstops

An alternative to the traditional water stop at cold joints is the use of swelling rubber waterstops which is also used for penetrations. The swelling rubber is a polymerized rubber that swells 300 % when in contact with water. The swelling rubberstop is better than the swelling Bentonite products for joints since it requires 72 hours for the material to swell thereby preventing premature failure of the waterstop as a result of the water stop material being wet from rainfall or other means during construction. Swelling rubber in both strip and gun grade is acceptable for pipe or pile penetrations.

The swelling rubber water stop is available in both a gun grade for pipe penetrations and as a strip for cold joints. The installation of the swelling rubber water stop must be at a minimum of five (5) cm in from the face of the concrete walls. This is necessary to prevent the swelling action of the rubber from spalling the concrete.



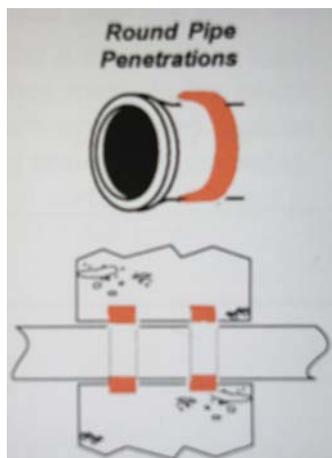
Typical swelling rubber waterstop



Typical detail of swelling rubber for cold joint



Typical installation of swelling rubber strip



*Typical detail of swelling rubber for pipe penetration
Note: double seals*



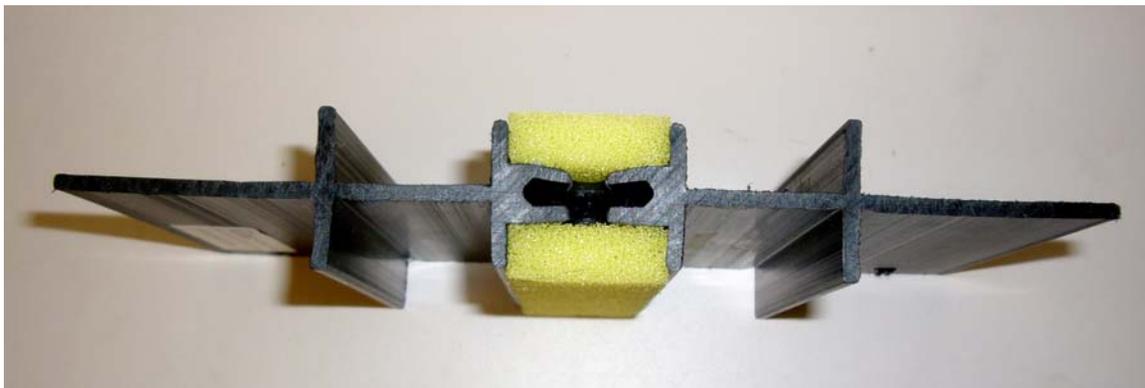
Typical installation of gun grade swelling rubber on pipe penetration



Gun grade swelling rubber water stop: Note irregular surface

4.30 Injection Waterstops

In addition the above are hybrid types of waterstops that allow the injection of a polyurethane, acrylate or Microfine cement to seal a leaking cold joint. The tube is placed in the joint, with junction boxes placed at intervals to allow for the j tube to be injected at a later time when the joint leaks. These hybrids are available as tubes and vinyl waterstops.



Traditional Vinyl waterstop with injection channel in centerline



Typical Injection Tubes for Joints

Comment: the use of injection tubes for waterproofing joints in walls and penetrations has had little success. In general they do not perform as the manufacturer's literature describes. They are extremely sensitive to the installation and in particular to the care taken in the installation. They must be protected from concrete infilling and are often only available for a one time injection. On a recent project the injection tubes had a 70% failure rate primarily due to poor installation. Due to their installation sensitivity injection tubes should be used as a backup system and not as a primary waterproofing of construction joints, Reinjectable grout tubes have not had a very successful history and should be avoided. FUKO Tube, a Reinjectable grout tube as manufactured by BBZ (Greenstreet) is not recommended due to the high failure rate on PB Projects.

5.00 Costs

5.10 Membrane Systems

In order to assess the effectiveness of a waterproofing system which includes the water stops, penetration seals and the membrane itself, numerous factors must be applied.

The initial cost of the materials, cost of installation and the long term cost of maintenance must be considered in the evaluation of a waterproofing system. Often installing the system that is the most economical to install results in extensive remedial repairs to eliminate ground water intrusion after the structure is in use. The following are tables that were developed for each type of system based on the short and long term costs of each system.

System	Difficulty in Installation	Initial Cost	Long Term Maintenance	Success Rating
Liquid Systems				
Hot Applied Rubber	4	2	3	3
Panel Systems				
Bentonite	4	3	5	1
Sheet Systems				
Rubber	3	3	4	3
Neoprene	3	4	4	2
HDPE	4	4	4	3
PVC	4	4	3	3
Sprayed Coating				
Epoxy	4	5	4	3
Polyurea	5	4	3	3
Neoprene	3	4	4	1
Cementitious Coating				
Polymer Cement	3	2	4	3
Hybrid Systems				
Poly Rubber Gel	2	2	1	5
Waterproof Concrete	2	4	5	2

Notes:

1. The scoring is as follows: 1 low; 2 below average; 3 averages; 4 above average; 5 high based on costs and ease of installation, etc. The higher the number the more successful the system.

Based on the aforementioned table the long term cost is as follows:

<i>System</i>	<i>Score</i>
Waterproof Concrete	5
Panel Systems; Bentonite	5
Sheet membranes; rubber/Neoprene/PVC/HDPE	4
Cold Applied Neoprene	4
Hot Applied rubber	3
Poly Rubber Gel	1

Notes:

1. Cementitious coatings are not included since this is not the proper material for this installation.
2. The long term cost scoring is as follows: 1 low; 2 below average; 3 averages; 4 above average; 5 high based on costs and ease of installation, etc. The higher the number the more successful

The success rate is a combination of installation success and long term maintenance costs. The results are as follows:

<i>System</i>	<i>Score</i>
Poly Rubber Gel	5
Liquid Systems: Hot Applied Rubber	3
Sheet System: HDPE/Rubber PVC	3
Sprayed systems: Epoxy/ Polyurea	3
Sheet systems Neoprene	1
Sprayed Systems: Neoprene	1
Panel systems: Bentonite	1
Hybrid Systems: waterproof Concrete	1

1. The Poly Rubber Gel system has the best success rating with the waterproof concrete and neoprene systems being the most susceptible to leakage while the other systems were average.
2. The long term cost scoring is as follows: 1 low; 2 below average; 3 averages; 4 above average; 5 high based on costs and ease of installation, etc. The higher the number the more successful

5.20 Waterstops

Waterstops were analyzed in the same manner as for membrane systems and the results of that analysis is as follows:

System	Difficulty in Installation	Initial Cost	Long Term maintenance	Success Rating
Vinyl& PVC Waterstops	3	3	4	2
Swelling Bentonite Strips	4	4	5	1
Reinjectable Waterstops	5	5	5	2
Swelling rubber Waterstops	4	2	1	5

The long term lowest cost maintenance of the waterstops is as follows:

<i>System</i>	<i>Score</i>
Swelling Rubber	1
Vinyl/ PVC waterstops	4
Swelling Bentonite	5
Reinjectable waterstops	5

1. The scoring for waterstops is as follows: 1 low; 2 below average; 3 averages; 4 above average; 5 high based on costs and ease of installation, etc. The higher the number the more successful
2. The swelling rubber waterstops have an excellent track record, while the other systems have not been very successful.
3. The success rating of the systems is similar to that for the cost with swelling rubber waterstops the leader with the others at a just below average as is clearly shown in the previous table.

6.00 Conclusions and Recommendations

Based on our knowledge of the waterproofing systems in the marketplace and this discussion, the following recommendations can be made:

- All buried structures must be waterproofed on the exterior (positive side) of the structure, even if at the time of construction there is no groundwater present.
- Waterproofing systems must accommodate the anticipated movement of the structure.

- All Installations of waterproofing materials must be performed by a qualified Contractor with experience in similar work.
- Waterproofing membranes in urban environments must be resistant to hydrocarbon, sulfates and sulfide attack.
- Swelling rubber waterstops should be used for all construction joints and penetrations and cut and cover bored and slurry wall construction dumbbell waterstops should be avoided.
- Water proof concrete should not be considered due to the potential for shrinkage cracking during curing, freeze thaw conditions, and the potential for tension cracking due to unequal loading of structural elements.
- Flexible membranes should be seamless and ideally suited for the type of construction and the environmental conditions of the site, including any chemical or hydrocarbon or salt attack
- Rigid membranes must closely match the modulus of the surface that they are waterproofing.
- Any membrane material used must comply with current Federal, state and local standards as to flammability and toxicity.
- At the cut and cover sections and the ventilation structures the membrane must be extended to ground surface. The invert slab should use this material to waterproof the connections between the piling and the invert slab and the invert slab.
- Attention must be given to the detailing of penetrations on the plans.
- A detailed review of the plans and specification must be performed by a knowledgeable person familiar with waterproofing systems prior to issuance of contract documents or tender.
- In all cases the Material Safety Data Sheet (MSDS) must be reviewed during the design and construction phases of the project to provide for proper health and safety issues to be addressed in the construction.
- Full time inspection by qualified personnel, of the waterproofing installation is required to ensure a proper installation
- The waterproofing is to be installed on the exterior of the concrete structure and any voids between the temporary support system and the completed structure should be filled with flowable concrete.
- Invert membrane for cut-and –cover structures should be installed on a mud mat and is to extend beyond the exterior walls to allow for lapping of the membrane after the casting of the walls.
- Any mud mat membrane is to be protected with protection board during the installation of the reinforcing steel.
- The waterproofing system should have a good history and track record in similar installations.
- Any Proprietary systems since it is propriety should have a 100% labor and material warrantee for a minimum of 3 years, guaranteed with a performance bond.
- Waterproofing for penetrations must be detailed on the contract drawings and easily buildable.
- All Bentonite products are to be avoided, due to their poor track record.

- Blind side waterproofing must be performed using a fully adhered mastic, or spray coating, sheet blindside waterproofing should be avoided due to poor track record.
- All waterstops are to be swelling rubber waterstops either strip or gun grade materials. Dumbbell type waterstops are to be avoided.
- In granular soils concrete diaphragm walls (slurry walls) should use pure Wyoming Bentonite for the trench support to allow for the formation of a mud cake to provide exterior waterproofing for the concrete diaphragm wall. Polymer slurry is to be only allowed for use in locations where granular soils are not present.
- Concrete diaphragm walls (slurry walls) should have plastic pipe installed in the location of the vertical wall joints to allow for injection of chemical grout if after excavation the wall joint leaks. See Guidelines for Design and Construction of Concrete Diaphragm (Slurry) Walls.
- Shelf adhering Bituthane or neoprene sheet membranes should be avoided due to their poor track record
- Panel systems should be avoided due to numerous penetrations for attachment to the structure.
- All materials must have a joint lap as recommended by the manufacturer and as specified.
- All specifications and contract documents must be strictly enforced by the designer and the inspection personnel with no exceptions.
- All expansion joints must be detailed to be watertight and designed to accept 150% elongation.
- All expansion joints must be designed for the anticipated movement based on the seasonal temperature changes to be experienced by the structure. (This is particularly important for highway tunnels).
- Spray epoxy and Polyurea coatings must not be used within tunnels and locations where air may become stagnant. (This is due to the toxicity and flammability of the material.)
- Injection tubes for grouting of joints or other locations are to be a secondary backup system. Reinjectable grout tubes are to be avoided due to a very poor track record.
- BBZ Fuko Tube is not recommended due to its' high failure rate on PB Projects
- Waterproofing membranes are to be installed by specialty contractors with experience in similar work
- All Sheet membrane systems HDPE/PVC shall have bulkheads to compartmentalize the membrane around the entire structure to provide areas for sealing future leaks in the membrane by chemical grouting. The compartments shall be no larger than 500SF.
- During the initial stages of the grouting a manufacturer's representative must be on site to advise the contractor on the proper use and application of their material
- Polymer Slurry is not recommended for concrete diaphragm wall construction in granular soils

In conclusion the selection of a waterproofing membrane system for any project must be site specific and performed as a complete system including waterstops. The installation of any waterproofing system must have a qualified contractor and experienced fulltime inspection personnel to ensure a quality product. These guidelines are based on PB experience over the

years and are guidelines and must be reviewed by any designer or specification writer at the inception of each project and should be part of the Project Implementation Plan. Any questions or inquiry as to the suitability of a particular waterproofing system for a project please contact Henry A. Russell P.E. via e-mail at Russell@PBWorld.com

7.00 Control of Structure leakage

7.10 INTRODUCTION

The section discusses the most common type of leakage encountered is that of water infiltration into structures that are used for underground structures, where the waterproofing system has been breached either by poor construction methods or by an aggressive environment such as hydrocarbons and or high or low Ph. The infiltration of water into the structure creates numerous operational problems to the operator of the facility. The primary problem is the loss of service of the structure during shutdowns due to corrosion, equipment failure, and possible structure failure. All of these problems cause increases in revenue costs and potential shortening of the life of the structure.

Rail Tunnels

Leakage in rail and transit tunnels causes tie deterioration, corrosion of rail, ice buildup on track or tunnel crown and its potential for derailment. In electrified tunnels, the electrolysis created by the stray currents can accelerate the corrosion of the electro-mechanical sub system.

Highway Tunnels

The presence of groundwater leakage in highway tunnels creates the potential for black ice to form on the roadway within the tunnel during the winter months. Road salts are often used by tunnel maintenance crews to counteract black ice formation. Road salts combined with groundwater infiltration accelerate corrosion of the structure by providing the vehicle for chlorides to penetrate the concrete elements of the roadway and tunnel lining. And deteriorate the reinforcing steel. In addition, the presence of water, in the exhaust plenum, creates the potential for the mixing of exhaust gases to create sulfate, and sulfite compounds that will attack the concrete tunnel lining, support steel elements including the ceiling support hangers and anchors.

7.20. STRUCTURE CONSTRUCTION

The quality of the materials used in the original construction is of primary importance in the water tightness of the structure. In lined tunnels, these materials usually consist of reinforced concrete, brick, steel, cast iron, or precast concrete segmental liners. It is very important to understand the state-of-the-art of underground construction for the control and construction methods for this type of work has changed dramatically over the last 100 years.

The quality of the workmanship in the original construction of underground construction is as important as the design and quality of the materials. Attention to detail and the subsequent quality assurance of the original construction are essential to develop a watertight durable underground structure. Understanding

the accepted practice in the industry at the time of construction is required to evaluate the overall conditions of the structure.

Currently there is no single standard for the identification of leakage into tunnels and underground structures. Permissible leakage is an allowable leakage that is determined by the engineer and the owner at the time of construction. The most important element in the determination of the water tightness of the structure is the cost associated with the development of a watertight structure that fulfills the operational requirements of the facility.

7.30 Identification of Leaks

It is important to identify the amount of leakage in standardized terms to facilitate communications between the Owner, contractor, manufacturer and PB personnel. For the last 10 years PB has been using the following identification parameters for degree of moisture at any one given point to assist in the proper identification of the groundwater inflow at a joint or crack or other structural defect.

PB. Descriptions of Tunnel Leakage

Term	Symbol	Description
Moist	M	Discoloration of lining surface, moist to touch
Past Moisture	PM	Area indicates previous wetness, water staining, calcification, rust staining, etc.
Glistening Surface	GS	Visible movement of a film of water across a surface
Flowing	F	Continuous flow of water from a structural defect, requires a quantity definition as to flow
Dry	D	A structural defect which illustrates no signs of moisture

The use of the aforementioned terms allows for all personnel to describe the leakage in definitive terms and assists in the selection of the set time for the grouts which is variable.



Typical tunnel leak

7.40 Leak Mitigation

The mitigation of leakage in underground tunnel/structures falls into two basic philosophies:

- Control of leakage
- Elimination of leakage

Control of leakage is a process by which the water infiltration into the tunnel/underground structure is diverted to the drain system of the structure and providing that the leak does not deteriorate the structure. This approach is often used, when the design of an older facility was intended to allow flow for leakage into the structure. In this case the elimination of the inflow of water may cause detrimental damage to the facility. Common methods for the diversion of leakage away from important elements of the underground structure are the use of pans, geosynthetic drains, false linings, and cavity walls.

The elimination of leakage is best performed by the injection of various grouts either into the leaking structural defect (cracks, joints or other defects) or by injection of grout behind the structure at the soil/rock interface. Various types of grout will be discussed here to provide a general understanding of the properties of grouts to be used and their application.

7.50 GROUTS

Particle grouts

Particle grouts consist of cementitious grouts using Type I/II and Type III Portland Cements, microfine cement and microfine silicates. All of the particle grouts have low toxicity and are non-flexible after curing. The lack of flexibility of the in-place grout after curing creates a potential for repairs to be short term. If any movements of the structure occur, particle grouts are often used to seal off tunnels/underground structures by injection of the material behind the lining and creating a “blister” type patch outside of the area that is leaking. Caution must be exercised in the injection of these materials so as not to overstress the structural lining.



Typical injection port for particle grout placement outside of the structure

Particle grouts are often injected by the use of small piston or worm type pumps. The mix for the injection is dependent on the size of the aperture of the opening or crack to be injected inflow rate of the leak and the head of water surrounding the structure. Injection ports are positioned in such a manner to create an overlap of the grout zone and to provide for an indication of grout return. The grout return is used as a means of determining if the area to be grouted has had adequate grout take.



Typical portable mixer and injection pump for particle grout

Chemical grouts

Chemical grouts vary greatly in regard to toxicity and include the following:

- Acrylamides – Highly neurotoxic, low viscosity grout
- Acrylates – A non-toxic, equivalent to Acrylamides, low viscosity, semi rigid grout, with a very good track record in the USA, extensively used on PB projects with an excellent track record.
- Lignosulfates and Aminoplasts – Highly toxic and costly grout – not generally used – old technology
- Polyurethane – Non-toxic, low to medium viscosity hydrophilic and hydrophobic grouts. High success rate, extensively used by Transportation Agencies, Contractors and PB with an excellent track record.
- Sodium Silicate – A low toxicity, medium viscosity grout with a high degree of shrinkage.

Chemical grouts have the most success in the sealing of construction joints and shrinkage cracks, which exist in concrete structures. These grouts have various degrees of flexibility after curing. The use of a particular grout is site and application specific. Hydrophilic grouts are those which will react in the presence of water and do not need a catalyst to create the reaction. Hydrophobic grouts do not react well in the presence of water and require the addition of a catalyst and the use of special metering equipment.

In general the polyurethanes and acrylates have shown the best success rate, since they are generally flexible and exhibit a good degree of elongation. Recent developments have resulted in new non-flammable and low viscosity single component polyurethane grouts have greatly enhanced the

adaptability of these hydrophilic grouts. Acrylate grouts have over the last 5 years become a grout of choice for many applications which formally used Polyurethane grouts. The Acrylate grout manufactured by BBZ (Greenstreet) must be avoided due to its extensive failure rate. Chemical Grouts manufactured by Green Mountain Grout, DeNeef , and Avanti have been used extensively by PB and have an excellent track record and performed as required.



Typical single stage polyurethane chemical grout piston pump

7.60 Grout Selection

The selection of the grout to be used is dependent on the type of material, comprising the liner, and the width of the crack or defect to be grouted. The width of the crack is important in determining the viscosity of the grout to penetrate the full depth of the crack or defect to be injected.

The water flow from the area to be injected will strongly influence the “gel” or set time. Environmental conditions at the site of the leak, strongly effect the selection of material. Many leaks in transit tunnels occur at locations where the ambient temperatures are allowed to cause structural movements as a result of expansion and contraction from seasonal temperature changes. Typical locations include stations, vent shafts, and portals. In highway tunnels the most of the structure is subjected to these changes due to the ventilation system inducing ambient air into the tunnel structure during seasonal temperature changes, thereby causing the same type of movements. All of these locations require a flexible grout with a high degree of bond strength to the substrate. Leaks in tunnel/underground structures which are not effected by temperature changes or other ground movements, may be injected with particle grouts or other non-flexible chemical grouts. A comparison of various grouts is included in the following table.

Comparison of Grout Materials (Welsh 1987)

Description	Viscosity	Toxicity	Strength	Remarks
<i>Particle Grouts</i>				
Type I/II Cement**	High (50cps- 2:1)	Low	High	Nonflexible, only for Large cracks
Type III Cement**	Med. (15cps-2-1)	Low	High	Nonflexible, only for Large cracks
Microfine Cement**	Low (8cps-2:1)	Low	Med.	Nonflexible, penetrates fine cracks
Microfine Cement/ Silicates**	Low (10cps-2:1)	Low	Med.	Nonflexible, penetrates Fine cracks
<i>Chemical Grouts</i>				
Acrylamides*	Low (1-2 cps)	Very High	Low	Flexible, penetrates Very fine cracks
Acrylates	Low (1-15cps)	Low	Med	Semi-rigid to rigid, penetrates fine cracks, water soluble
Silicates**	Low (6cps)	Low	Med.	Nonflexible, penetrates fine cracks.
Lignosulfates*	Low (8cps)	High	Low	Flexible, penetrates fine fine cracks
Polyurethane (MDI)	Med. (100-300cps)	Low	High	Flexible, penetrates fine Cracks, non-flammable
Polyurethane (TDI)	High (300-600cps)	Low	High	Flexible, penetrates Large cracks
Epoxy Resin*	Low (60-200 cps)	Low	High	Nonflexible for structural rebonding
Silicone Rubber*	High (500 cps)	Low	Low	Flexible, weak bond

Notes: * Not to be used for injection into underground structure liners.

** For injection at he soil/rock structure interface (outside of the structure)

Closed cell polyurethane is preferred for injection wide joints, cracks and defects in concrete and brick liners. Acrylates are to be injected into fine to medium width (1/16 – ¼ inch) joints and cracks and defects. Acrylamides are not to be used due to their high neurotoxin issue; contains high concentrations of cyanide.

7.70 Costs

The cost of particle and chemical grouts vary significantly depending on the type of grout the following table illustrates the relative cost of the most commonly used particle and chemical gouts used.

System	Difficulty in Installation	Initial Cost	Long Term maintenance	Success Rating
Particle Grout Type I/III cement	4	1	5	3
Microfine Cement	4	5	5	3
Acrylate chemical grout	3	3	1	5
Polyurethane closed cell grout	2	2	1	5

The scoring for grouts are as follows: 1 low; 2 below average; 3 averages; 4 above average; 5 high based on costs and ease of installation, etc.

The installation of chemical grout is typically injected into a structural liner in the following manner:

- Identify the location to be grouted
- Drill injection holes along the crack or defect to be grouted. Locate the hole spacing not more than the full thickness of the structure to be injected. Drill the injection holes at a 45 degree angle to the face at one half the thickness of the structure away from the crack. The hole size to be determined by the selection of the grout injection packer to be used.



Typical Injection ports with Zerk fitting for chemical grout

- Insert the packer into the hole and flush the drill hole with water to clean the crack and hole. This also insures that the drill hole intersects the crack or defect.
- Pump the Chemical grout at a rate recommended by the manufacturer that allows for adequate grout penetration and provide observation of the return of the grout from the crack.

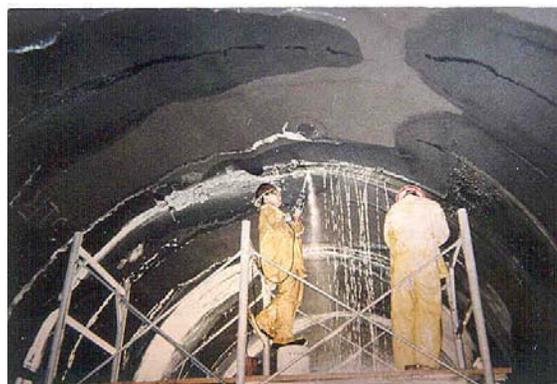


Injection of chemical grout for sealing a construction joint



Injecting a chemical grout in a horizontal joint note the grout return from joint

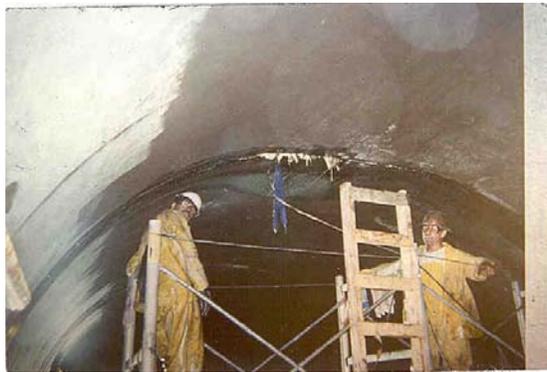
- After observing the grout “gel” or set return from the crack, move to the next port



Grouting crack leak from the top down



Continuing on same crack from top down



Completed crack injection from the top down

- Once the initial injection port is grouted continue the procedure from the top most hole down to the invert/floor of the structure. Starting at the top port location is contrary to cement grouting technique. This procedure allows for a leak that cannot be sealed to be diverted to drains away from any equipment or other facilities in the main part of the structure.

7.80 Conclusions and Recommendations

The attached specifications describe in full the procedures and materials required for the injection of chemical and particle grout for the control of groundwater intrusion. Based on PB experience the following conclusions and recommendations are as follows:

- Particle grouts should only be used for exterior grouting of leaks in underground structures at the contact between the structure and surrounding soil/rock.
- Chemical grouts (polyurethane; acrylates) are to be used for the sealing of cracks, joints and other defects in underground concrete, brick, and masonry structures.
- Grouts manufactured by BBZ (Greenstreet) are not be used due to the poor record on previous PB projects
- Grouts manufactured by Green Mountain Grout, DeNeef Construction Chemical company,, Avanti International and Minerva are acceptable manufactures of chemical

grout to be used on PB Projects,. Other manufactures may be considered based on the track record on similar applications.

- The proper selection of the grout type must be site specific and consideration must be given to the Ph, environmental conditions of the project, degree of leakage, temperature of substrate at time of injection, and properties of the grout.
- The manufacturer of the selected type of c grout must be consulted to insure that the grout selected is suitable for the project.
- The selection and design of a grouting program must be performed by a qualified person who has extensive experience in the application of grouting programs.
- The Inspection of the installation of the particle or chemical grout must be full time and performed by a qualified person.
- The grout selected should have a good history and track record in similar installations.
- Any proprietary grout or grouting system should have a 100% labor and material warrantee for a minimum of 3 years, guaranteed with a performance bond.
- A detailed review of the plans and specifications must be performed by a knowledgeable person familiar with grouting programs prior to issuance of contract documents or tender.
- In all cases the Material Safety Data Sheet (MSDS) must be reviewed during the design and construction phases of the project to provide for proper health and Safety issues to be addressed in the construction.
- Under no circumstances are any Acrylamides to be used on any PB project.
- Grouts to be used an in urban environments must be resistant to hydrocarbon, sulfates and sulfide attack.
- Any grout material used must comply with current federal, state and local standards as to flammability and toxicity.
- The particle or chemical grout must be installed as recommended by the Manufacturer and the specifications must be fully adhered to insure a successful application of the grout.
- During the initial stages of the grouting a manufacturer's representative must be on site to advise the contractor on the proper use and application of their material

In conclusion the selection of a grouting program for any project must be site specific and performed as a complete system and be compatible with the chosen waterproofing system. The installation of any grouting program must have a qualified contractor and experienced fulltime inspection personnel to ensure a quality product. Specifications for remedial grouting of the waterproofing membrane must be included in any underground project to provide a backup system in the event that the waterproofing membrane is breached and need to be repaired after installation. These guidelines are based on PB experience over the years and must be reviewed by any designer or specification writer at the conception of each project and should be part of the Project Implementation Plan. Any questions or inquiry as to the suitability of a grout or grouting program please contact Henry A. Russell P.E. @ Russell@PBworld.com.