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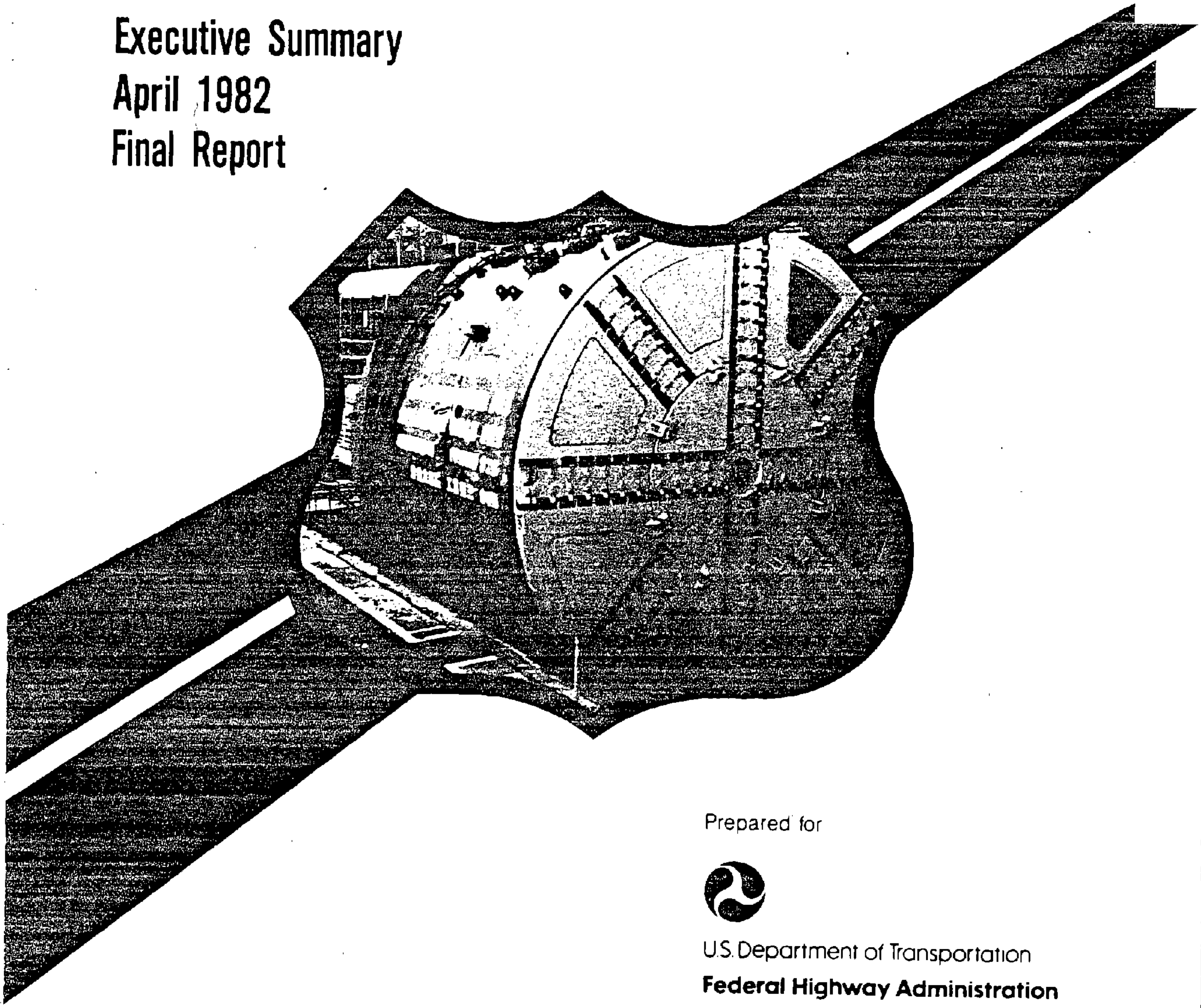
GROUNDWATER CONTROL IN TUNNELING

Executive Summary
April 1982
Final Report



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FOREWORD

This brief summary volume reviews the main groundwater problems associated with underground construction and it provides key tables of recommended control measures. Greater detail is given in the three volume report listed in the abstract section on the opposite page.

Sufficient copies of the report are being distributed to provide two copies to each regional office, one copy to each division office, and two copies to each State highway agency. Direct distribution is being made to the division offices.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

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16. Abstract

This Executive Summary briefly describes a three-volume report on Groundwater Control During Tunneling and in Completed Tunnels.

The three volumes include:

Volume 1: Groundwater Control Systems for Urban Tunneling (FHWA/RD-81/073)

Volume 2: Preventing Groundwater Intrusion Into Completed Transportation Tunnels (FHWA/RD-81/074)

Volume 3: Recommended Practice (FHWA/RD-81/075)

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EXECUTIVE SUMMARY

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1.00 INTRODUCTION

Proper control of groundwater can be the most important factor influencing the success or failure of a tunneling project, especially in urban areas. Seepage into an excavation can impede the excavation process by making it difficult for men and machinery to work efficiently; large flows can, and often do, halt construction. Seepage can lead to excavation instability and cause ground loss with subsequent surface settlement.

After completion of a tunnel, provisions must be made to exclude groundwater throughout the life of the project. This becomes especially important in urban transportation tunnels where the smallest amount of leakage may prove hazardous to vehicles and require expensive continuting maintenance.

This series of reports which describe these considerations includes:

Volume 1: Groundwater Control Systems for Urban Tunneling (FHWA-RD-81-073)

Volume 2: Preventing Groundwater Intrusion Into Completed Transportation Tunnels (FHWA-RD-81-074)

Volume 3: Recommended Practice (FHWA-RD-81-075)

These volumes contain discussion of the parameters which should be defined prior to design of a groundwater control system, the technical feasibility of a number of well-known, as well as innovative groundwater control techniques, the criteria which govern the final selection of a system, and the practical aspects of physically implementing and maintaining that system.

Conceptually, the principles of groundwater control are relatively simple. However, in practice this is often not true because the study of the interaction of soil and interstitial water; the science of geohydrology; deals with highly variable materials. Basic paramaters such as soil or rock permeability may vary over eight to ten orders of magnitude. The amount of geohydrologic data which can be obtained has practical and economic limits, and thus interpolation between widely spaced explorations and in-situ tests must often suffice. The resulting situation is one where extensive subsurface information, may not fully disclose the variability in subsurface conditions. Successful groundwater control requires thorough analysis and interpretation of all existing information, tempered with experience. This requirement for extensive experience has resulted in the establishment of firms that are highly specialized in the various groundwater control methods, i.e., dewatering, grouting, freezing, etc.

1.10 PROBLEMS ASSOCIATED WITH INADEQUATE GROUNDWATER CONTROL

Poor management of groundwater control can affect a tunneling project from initial design, through construction and performance of the finished structure. In the best case, inadequate groundwater control may only require minimal sumping. In the worst case, large soil and water flows may endanger lives and bury machinery. The actual consequences of inadequate groundwater control will probably lie somewhere between these two extremes. During the design phase, proper assessment of the groundwater control effort is important, for evaluation of project feasibility and for preparation of cost estimates. The consequences of not fully appreciating the importance of the groundwater control method during the design phase will probably be contract extras, disputes and construction delays.

During construction, effective groundwater control is a prerequisite for high productivity. Improper handling of even small flows can result in loss of productivity, ground runs into the excavation and subsequent surface settlement, or face instability. In less severe cases, water entering the excavation can hamper mobility, and make it difficult to install liners or place concrete.

The effects on property and people adjacent to the construction area are typically related to ground movement or changes in stresses near existing foundations. Groundwater control by predrainage may result in detrimental consolidation of finer grained soils and possible deterioration of wood piles or timbers. Ground loss into the excavation may lead to subsequent ground loss below adjoining building foundations, resulting in building damage. Obviously, these problems are more serious in congested urban environments.

Environmental impact associated with groundwater control results from treatment and disposal of water removed from the ground, plus recharge, where required, for groundwater replenishment. Inadequate attention to the quantity and quality of water removed may lead to problems such as depletion of local water supplies, or contamination of surface water with construction water. Contamination of groundwater can also occur as a result of altering previous flow patterns.

Seepage may occur into completed tunnel sections years after construction and cause a variety of operational problems. The sudden appearance of small amounts of seepage may result from nearby construction activity, changes in ground loads on the liner, changes in groundwater conditions, or deterioration of the primary waterproofing system. The consequences of the seepage range from harmless staining of walls or tiles to dangerous corrosion of reinforcing steel, piping and loss of ground above the tunnel.

1.20 EVALUATION OF SUBSURFACE CONDITIONS

A thorough knowledge of geohydrologic conditions is essential for design and installation of successful groundwater contol systems. Key parameters which should be evaluated are:

- Groundwater levels, directions of flows and gradients
- Permeability of the soil or rock formation
- Geometry and character of the aquifer
- Gradation of cohesionless soils
- Density of cohesionless deposits
- Compressibility of cohesive or organic deposits
- Groundwater Chemistry.

In general, the tunnel and the groundwater control method will be designed with limited geohydrologic information. With more care and preparation in developing, executing and interpreting the subsurface exploration program, fewer unforeseen conditions will be encountered.

Preliminary field investigations may consist of widely spaced borings and a review of available information concerning general soil conditions, groundwater levels, bedrock elevations and existing surface and subsurface structures along the alignment. Design phase field investigation will obviously be more involved and include detailed explorations, sampling and in-situ tests. A typical design phase exploration and testing program may include many of the following:

(1) Closely spaced borings with continuous sampling from tunnel arch to invert

(2) Installation of observation wells and piezometers to establish groundwater levels, fluctuations, direction of flows, etc. In addition, they can help to monitor the effectiveness of the groundwater control system.

(3) Geophysical surveys to establish general trends in subsurface conditions at depth. The most frequently used are resistivity, seismic refraction, and seismic reflection.

(4) Borehole permeability testing in soil and pressure testing in rock

(5) Pumping tests

(6) Groundwater sampling and chemical analysis

Laboratory investigations may include grain size analyses, permeability tests, Atterberg limits (index test), shear strength and compressibility tests and water quality tests.

More detailed investigations for design of groundwater control systems include large scale pumping tests, water treatment tests (where required), detailed environmental analyses or full-scale test sections of the primary groundwater control options. These investigations would typically represent the final and most useful test of the dewatering system prior to construction. Table 1 is a summary of site investigation techniques for evaluation of groundwater control.

Subsurface investigations should not terminate during the design phase, but continue, and even intensify, during installation of the system and actual tunnel excavation. Variations in subsurface conditions encountered during construction should be reflected in modifications in the groundwater control system (if possible) to insure adequate water control. As examples, changes in soil gradation may require changes in well spacing, grout consistency, or bentonite concentration. Continuous system re-evaluation is necessary to insure proper groundwater control and to maximize excavation productivity.

2.00 GROUNDWATER CONTROL DURING CONSTRUCTION

Eight groundwater control methods are discussed including extraction and exclusion methods. Table 2 is a summary of the methods considered.

TABLE 1. SUMMARY OF SITE INVESTIGATION TECHNIQUES FOR EVALUATION OF GROUNDWATER CONTROL

WORK PHASE	GEOLOGIC CONDITIONS	EXPLORATORY PROGRAM GUIDELINES							NOTES
		BORINGS AND WATER OBSERVATIONS				LABORATORY TESTS		SPECIAL TESTS	
		SPACING	DEPTH	TYPE	O.W./Pz.	SOIL/ROCK	WATER		
PRELIMINARY	SOIL	1,000 ft. (305m.) to 2,000 ft. (610m.)	A minimum of 2 tunnel diameters below probable invert	2 1/2 in. (6.4 cm.) dia wash boring, split spoon samples. ----------- Continuous Bx size rock core	In every completed boring (See Note 3) if groundwater is encountered or expected to be encountered.	Limited number of soil classification tests. ----------- Engineering properties can be approximated from Alterberg limit data.	Use available data. If none available, a limited number of tests may be required for evaluation of corrosion and encrustation potentials.	Usually none required.	1. Research all existing data. See Table 2 for sources of information. 2. Full-time qualified observation of explorations is essential. 3. Observation wells with surface seals are normally adequate. If perched water or a confined aquifer is suspected, install piezometers in critical horizons.
	ROCK	See above	See above	3 1/2 in. (8.9cm) diameter wash boring in soil, split spoon samples. ---------- Continuous NX size rock core	See above	Usually no laboratory tests of rock cores required.	See above	See above	

TABLE 1. SUMMARY OF SITE INVESTIGATION TECHNIQUES FOR EVALUATION OF GROUNDWATER CONTROL (continued) 2/3

WORK PHASE	GEOLOGIC CONDITION	EXPLORATORY PROGRAM GUIDELINES							NOTES
		BORINGS AND WATER OBSERVATIONS				LABORATORY TESTS		SPECIAL TESTS	
		SPACING	DEPTH	TYPE	O.W./Pz.	SOIL/ROCK	WATER		
DESIGN	SOIL AND ROCK	300 ft. (91.5m.) to 500 ft. (152.5m.) (See Note 3)	A minimum of one tunnel diameter below probable invert.	• 3 1/2 in. (8.9 cm.) dia. wash boring. split-spoon samples. (See Notes 1 & 2) • Continuous NX size core in rock.	• Installed in completed borings at spacings on the order of 1,000 ft. (305m.) • A minimum of two at each station or major underground chamber.	• Classification tests of every major soil unit. • Engineering property tests of fine grained soft compressible soils. • Certain sedimentary rock susceptible to solution may require mineralogic testing to identify soluble components, i.e., carbonates	• Total hardness • Total Fe • Total Ng • Alkalinity • Chlorides • Sulphates • Nitrates • pH • Hydrogen sulphide • Carbon dioxide • Dissolved oxygen • Total dissolved solids • Silica	• Falling and constant head borehole permeability tests in soil to identify major differences in soil permeability. Special care required in test interpretation. • Packer tests in rock. Limited objective pumping tests. • Long-term pumping tests to investigate significant aquifers. • Special performance tests to evaluate innovative groundwater control techniques. • Geophysical techniques may prove helpful in augmentation of boring program, but should be used with particular care in urban areas.	1. Continuous soil sampling advisable at tunnel depth to identify stratification. 2. Undisturbed samples of soft compressible soils should be obtained from each major soil unit. 3. Closer spacing on the order of soft 50 ft. (15.m) to 200 ft. (61.0m.) may be required in station areas. 4. Full-time qualified field observation of explorations is essential.

TABLE 1. SUMMARY OF SITE INVESTIGATION TECHNIQUES FOR EVALUATION OF GROUNDWATER CONTROL (continued) 3/3

WORK PHASE	GEOLOGIC CONDITION	EXPLORATORY PROGRAM GUIDELINES							NOTES
		BORINGS AND WATER OBSERVATIONS				LABORATORY TESTS		SPECIAL TESTS	
		SPACING	DEPTH	TYPE	O.W./Pz.	SOIL/ROCK	WATER		
DESIGN	SOIL AND ROCK							• If unusual water quality parameters are measured, special treatment tests may be necessary. • If water is discharged into surface water, special tests may be required to evaluate effect of discharge water on aquatic life in receiving waters.	

TABLE 2 SUMMARY OF GROUNDWATER CONTROL METHODS DURING CONSTRUCTION (Sheet 1 of 3)

METHOD	APPLICATION IN TUNNEL DEWATERING	ADVANTAGES	LIMITATIONS
<u>Predrainage</u>			
Deep wells	- Sand and gravel	- Wide spacing - Large volumes pumped	- May result in pumping a greater quantity than necessary
Well points	- Sand and gravel	- Spot control possible - Minimize quantities pumped	- Lift limited to 15 - 20 feet
Ejectors	- Sand, silty sand		- Inefficient - Susceptible to encrustation
Vacuum wells	- Silty sand, sandy silt	- Increase yield when gravity drainage is slow	- Difficult to maintain - Complex
Pumping within Tunnel	- In stable water-bearing strata	- Inexpensive - Simple	- Can lead to unstable soils due to seepage pressures.
<u>Cutoffs</u>			
Steel sheeting	- Nearly any pervious or semi-pervious soil through which it can be driven	- Materials reusable - Easily installed - Effective in pervious soils	- Sheeting must be driven intact - Cobbles or obstructions may damage sheeting - Seepage thru interlocks can limit effectiveness in semi-pervious soil

TABLE 2 SUMMARY OF GROUNDWATER CONTROL METHODS DURING CONSTRUCTION (Sheet 2 of 3)

METHOD	APPLICATION IN TUNNEL DEWATERING	ADVANTAGES	LIMITATIONS
Slurry walls	- Any soil which will contain slurry, i.e. gravelly sand to clay	- Wall can be used as part of structure - Leaks can be repaired during excavation - Many variations in basic technique	- Boulders difficult to excavate - Messy operation
Slurry trench cutoffs	- Any soil	- Inexpensive - Able to withstand lateral movements	- Proper construction required to avoid non-homogeneous backfill
Thin wall cutoffs	- Any soil through which probe can be driven	- Economical	- Must penetrate impervious stratum - Thin cutoff
Recharge	- Sand and gravel	- Minimizes settlement outside excavation	- Encrustation of pipes - Entrained air in pipes - Must be monitored
Grout	- Gravel to sandy silt	- Very effective in eliminating flow into tunnel - Stabilize soils unstable due to seepage pressures	- Difficult to monitor - Environmental concerns with chemical grouts

TABLE 2 SUMMARY OF GROUNDWATER CONTROL METHODS DURING CONSTRUCTION (Sheet 3 of 3)

METHOD	APPLICATION IN TUNNEL DEWATERING	ADVANTAGES	LIMITATIONS
Compressed air	- Pervious sands, silty sand - Sandy silt	- Very effective silt and fine sands - Limits settlement outside tunnel	- Large air losses in very pervious soils (gravels) - Strict regulation of working environment - Limited work shifts in pressures over 12 psi - Possible "blowout"
Slurry Shields	- Silt and silty sand - Granular soils with no large cobbles	- Stable in water bearing sands - Minimizes surface settlement - Minimal tunnel hazards - Accurate tunnel alignment	- Problems in mixed face conditions - Large cobbles a problem - Cohesive soils a problem
Electro-osmosis	- Very fine grained silts, sandy or clayey silts	- Reverses seepage in open cuts - Stabilizes runny or sloughing soils - Consolidates and increases strength near cut - Useable where gravity or vacuum drainage is too slow	- Expensive - Requires continuous power - Difficult to assess power requirements

2.10 DEWATERING

Dewatering is typically accomplished using deep wells, ejectors, or wellpoints and has been used extensively for years.

Deep wells are individual extraction units which employ a submersible pump installed below the water level and powered by an electric motor. These wells typically have large pumping capacities depending on soil characteristics and pump size and are installed at relatively large spacings. They are typically used in pervious soils where moderate to large drawdowns are required.

Wellpoint systems consist of a series of screened wells connected to a common suction header which is evacuated by a pump. Wellpoint systems are relatively inexpensive to install but have lift limitations of 15 to 20 feet (4.6 to 6.1 m). Multiple stages can be installed where greater drawdown is required, but this installation often interferes with other construction operations and is not practical for dewatering of deep bored tunnels.

Ejector wells utilize a water driven jet pumped to extract groundwater from the soil mass. They are capable of removing water to large depths, but they are inherently energy inefficient. Ejectors are most practical in soils of moderate to low permeability where the volumes to be pumped are small, i.e. 5 to 10 gpm (0.3 to 0.6 l/s).

Pumping from within the tunnel is a common method of dewatering in soil profiles which are difficult to pre-drain completely. Sump pumps and systems of piping are usually easily installed in the excavation and can be modified to adjust to changes in inflows. Sumping is only practical where the soil or rock is stable under the flow of water. It is often used as a secondary method of dewatering to handle minor residual seepage not controlled by the primary system.

2.20 RECHARGE

Recharge systems are used wherever original groundwater levels outside of the excavation must be maintained. Uncontrolled groundwater lowering can cause settlement due to soft compressible soils, rotting of wood foundations, depletion of local water supplies or saltwater intrusion. Recharge systems replenish water to the aquifer to avoid these problems. Recharge is often difficult due to problems with encrustation and entrained air clogging or choking the recharge system.

2.30 CUTOFFS

Vertical cutoff walls and trenches are techniques of groundwater exclusion which form an artificial barrier between the excavation and the surrounding saturated soil mass. Cutoffs are used primarily in cut-and-cover tunneling as combined seepage barriers and lateral support systems, producing considerable economy where properly constructed. Steel sheeting is a common form of cutoff which is most effective in pervious soils through which the members can be driven without being damaged. Although not completely impervious due to seepage through the interlocks, sheeting walls can be economical if used in conjunction with a secondary groundwater control method such as sumping.

Slurry walls and diaphragm walls are newer techniques which use a bentonite suspension to hold open a narrow trench into which tremie concrete is placed. Variations on the slurry wall technique include precast slurry panels, soldier pile and tremie concrete (SPTC) walls, and bored secant or tangent pile walls. A great advantage of these latter techniques is their ability to be used subsequently as finished structural walls within the tunnel.

Slurry trenches are a variation on the slurry wall principle which uses bentonite, bentonite-cement, or bentonite-soil mixtures as backfill material in the trench. The resulting walls typically have very low permeabilities and little structural capacity. To date, these types of cutoffs have been used primarily as seepage barriers in earth dams and cofferdams or as a means of groundwater isolation and pollution control rather than for groundwater control in tunneling.

2.40 GROUTING

Grouting of soil and rock involves the injection of any one of a number of substances into the ground to plug all spaces and prevent groundwater movement. These methods may have been used primarily outside of the United States, but are being used more frequently in the U.S. for groundwater control in tunneling and it is expected that this trend will continue. A variety of grouts are currently available for injection into a wide range of soil grain sizes and rock openings. The bases for choosing a waterproofing grout are its ability to permeate the soil (viscosity), effectiveness as a waterproofing agent, cost, and possible toxicity. Other factors which may be involved are local experience and cost.

2.50 FREEZING

Freezing is an effective temporary means of groundwater control which can be used in nearly all types of soil and rock. The process involves the pumping of a calcium chloride brine or liquid nitrogen through pipes inserted at predetermined spacings within the soil mass. The coolant removes heat from the ground and freezes the pore water to form a continuous frozen zone. This process is typically expensive, but is becoming more cost competitive with other groundwater control techniques, especially in difficult soils or where the frozen earth structure serves as a shaft lining or cofferdam.

2.60 COMPRESSED AIR

Tunneling under compressed air is a technique which has been in use for over a hundred years and is still used today. Air pressure in an airtight compartment at the tunnel heading offsets the hydrostatic pressure exerted by the groundwater. The necessity for air locks and decompression chambers can slow the rate of progress at the tunnel heading considerably. In certain instances, a limited dewatering program can be used in conjunction with compressed air to reduce the working pressures.

2.70 SLURRY AND EARTH PRESSURE BALANCE SHIELDS

Relatively recent innovations in Japan and Europe have produced tunneling shields which stabilize the face with confined earth, water or slurry pressure and allow laborers to work in free air. These specialized machines; slurry shields and earth pressure balance shields, can be used in water bearing soils with very little cover. Maintaining the stability of the face using slurry or earth pressure excludes water from the tunnel, provides stability at the heading and limits settlements above the tunnel.

2.80 ELECTRO-OSMOSIS

Electro-osmosis is a unique process for stabilizing clays and running silts which cannot be effectively drained by other methods. The technique involves the application of an electric current into the soil mass which pulls water towards a negatively charged cathode where it can be mechanically withdrawn. The induction of electro-osmotic flow can be expensive because of the constant power requirements. Although it has never been used as a groundwater control method in tunnel construction, it is potentially useful in extreme situations to stabilize silts and clayey silts adjacent to cut-and-cover operations.

2.90 METHOD SELECTION

The selection of a groundwater control method is based upon technical and economic considerations. The technical questions to be addressed deal primarily with the characteristics of the soil and groundwater system. Soil parameters include grain size, stratification, stratum thickness, permeability and location of an interface with respect to the tunnel alignment. In a fractured rock profile, the most meaningful properties are fracture width and orientation. Characteristics of the groundwater environment which should be investigated include the nature, permeability and extent of the aquifer, barrier boundaries, variation in groundwater level, sources of recharge and groundwater chemistry.

Final choice among equally competent alternatives will probably be based upon economics. Cost criteria are different at various locations depending upon site specific variables and the experience of the local contractors. Factors to consider in the evaluation of relative costs are mobilization charges installation costs (drilling, labor, materials, etc.) and operational costs (labor, duration of groundwater control, maintenance costs, power costs, system safeguards, etc.)

3.00 LEGAL AND CONTRACTURAL CONSIDERATIONS

Since the cost and performance of groundwater control systems are vulnerable to variations in the geohydrologic environment, difficulties may, and often do, arise during construction. Acknowledging that risk is always embodied in groundwater control, it becomes the function of the legal and contractual arrangements for the tunneling project to determine how the several parties to the tunneling project shall share the burden of these risks. The contract documents can reduce the contingencies generally associated with implementing a groundwater control system by the following means:

- Disclosure of all subsurface exploration data, both factual and interpretive.

- A clear statement of the responsibility of the contractor with respect to groundwater control.

- Utilization of the contractor's ingenuity in developing groundwater control schemes

- Provisions to insure that groundwater is given proper consideration and to insure that system designs are competent.

- Providing a mechanism for monitoring the groundwater control system and implementing any necessary changes.

- Clear statement of the procedures for identifying and compensating contract extras

The contract documents should clearly specify the results expected and how the contractor will be compensated for his work. This will help to eliminate unreasonable bids and encourage contractors to design a satisfactory system. Where more than one dewatering technique is feasible, the contract documents should allow for ingenuity on the part of the contractor. A two-stage submittal process allows for review of the contractor's groundwater control scheme by the engineer both before and after installation.

Risk is typically allocated among the owner, the engineer and contractor. It is defined as the potential for damages which may increase the cost of the tunneling project. Since tunneling is a complex construction activity and which occurs in a high risk environment, the question of who bears the risk of system failure is an important one.

In current practice, the potential risks can be divided into three categories. Environmental risks are those related to the construction site and are typically assumed by the owner. These risks include the potentials for unexpected groundwater conditions and harm to third parites. They can be reduced by investing in an adequate subsurface exploration program, full disclosure of all available subsurface information and a mechanism to provide for changed conditions should they be encountered.

The Engineer usually assumes the risks of communications, i.e., insuring that the parties involved are aware of their responsibilities and understand fully the intent of the contract documents. Interpretation and review of documents and proper consideration of all aspects of the job may also be delegated to the engineer. Clarity and effectiveness of communication are his primary means of reducing risk.

The procedural risk associated with design, implementation and operation of the groundwater control scheme usually fall with the contractor. Improper attention to the procedures for proper dewatering may result in delays and added costs to the contractor. His risks can be reduced by competent explorations, testing, and system design to arrive at the most economical and flexible system.

4.00 GROUNDWATER CONTROL IN COMPLETED STRUCTURES

Permanent groundwater exclusion is essential to the proper performance of transportation tunnels. The method of groundwater control must therefore be reliable and durable. If leaks should develop due to tunnel liner deterioration or changes in soil or groundwater conditions surrounding the tunnel, remedial measures should be possible without major difficulty. The amount of allowable leakage into the tunnel is dependent upon its intended use and the hazards involved in allowing this leakage. Table 3 is a summary of common methods of controlling groundwater leakage into completed transportation tunnels.

4.10 CAST-IN-PLACE CONCRETE

One of the most frequently used methods of groundwater control and tunnel support is the cast-in-place concrete liner. These liners are typically made of high quality impervious concrete and placed using stringent controls to avoid concrete segregation, honeycombing, shrinkage, etc. Joints between concrete pours are waterproofed using any number of plastic, metal or rubber waterstops. The advantage of cast-in-place liners is their flexibility with respect to liner configuration and the development of unique and innovative techniques for concrete mix design, placement and curing.

4.20 WATERPROOFING MEMBRANES

Waterproofing membranes are impervious barriers applied to the tunnel liner to resist groundwater intrusion and resulting deterioration of the concrete or steel liner. The membranes are currently applied using a variety of methods such as hot applied bituminous materials, synthetic rubber sheeting, preformed multli-layered boards, bentonite sheets or spray, cold liquid applied membranes, cementitious coatings or thin metal sheeting membranes. These materials can be selected for application in a particular tunnel based upon required resistance to temperature variations, chemical attack, microbiological reactions or ground movement. They are most easily applied in cut-and-cover tunnels but have been used as secondary groundwater control methods in bored tunnels.

4.30 SEGMENTED TUNNEL LINERS

Combined structural-waterproofing properties make the use of segmented tunnel liners attractive in bored tunnel construction. The liners can be made of cast iron, steel or pre-cast concrete. The cast iron segments are corrosion resistant, but combinations of steel and some protection system (membrane, cathodic protection) see widespread use. Joints between segments

TABLE 3. SUMMARY OF METHODS TO EXCLUDE WATER FROM COMPLETED TUNNELS

METHOD	ADVANTAGES	DISADVANTAGES	COMMENTS
<u>Cast-in-Place Concrete Linings</u>	Resistant to environmental deterioration Joint spacing can be easily adjusted Defects can usually be repaired Flexibility to deal with special situations in the field: - regulated set times - expansive agents - mix strengthening by additives - reinforcement with fibers	Difficult to place in confined or wet environment Good concrete placement procedures required to: - minimize shrinkage - minimize segregation - insure impermeability Must resist earth pressures as well as hydrostatic pressures Proper concrete curing is essential	More efficient and easier to control in cut and cover applications
<u>Waterproofing Membranes</u> General:	Most easily applied in cut and cover jobs	Can be punctured during installation or backfilling	Often used where primary and secondary liners are installed Should be flexible to move with adjoining structures without leaking
- Bituminous Materials			
Brick in asphalt mastic	Considerable previous experience	Expensive	Infrequently used at present
Built up membrane	Long term stability	Difficult to apply on vertical surfaces Susceptible to damage from downdrag forces if adjacent soil settles	Particularly effective on exterior of cut and cover tunnels
Preformed multi-layered board	Quick installation process Variable number of plies possible	Concrete surfaces must be clean and intact	
Cold applied bituminous material	Easily applied by brush or spray	Limited effectiveness	Considered a "damp proofing" method

TABLE 3. SUMMARY OF METHODS TO EXCLUDE WATER FROM COMPLETED TUNNELS (continued) 2/6

METHOD	ADVANTAGES	DISADVANTAGES	COMMENTS
- Plastic/Synthetic Rubber Sheeting			
General	Resistant to chemicals, aging puncture Lightweight Flexible, with good elastic properties Electrical resistance Self-healing to some degree		Often single layer systems
Polyethylene sheets	Nearly any size or shape	Sheets may be damaged by adjacent construction activity	
Polyvinyl Chloride Sheeting			Similar to polyethylene
Butyl Rubber Sheeting	Great flexibility Does not stiffen with age Self-healing properties Abrasion resistant Sheets easily spliced Most impervious of synthetics		Most frequently used synthetic in U.S.
Hypalon Sheeting	Large elongation before rupture Can withstand large differential movement	Expensive	
Neoprene Sheeting	Properties can be altered to suit the job		Properties vary with additives
- Cold, liquid applied waterproofing	Usually more economical than sheeting Can typically be sprayed, rolled or troweled into place	Difficult to apply uniformly and adequately Mutiple coating may be necessary	Typically reserved for remedial waterproofing One or two component systems
- Bentonite panels/sprays	Expands when wet to fill voids/crack	Susceptible to degradation by chemicals in groundwater	
Panels	Effective at any temperature	Must be installed on smooth surface and protected from damage and moisture	
Spray	May be applied to irregular surfaces		

TABLE 3. SUMMARY OF METHODS TO EXCLUDE WATER FROM COMPLETED TUNNELS (continued) 3/6

METHOD	ADVANTAGES	DISADVANTAGES	COMMENTS
- Cementitious coatings	Can be applied directly on wet surfaces	Coatings must be moist cured Expensive	
	Leaks can be easily repaired	Requires skilled hand labor	
- Aluminum sheeting	Relatively inexpensive materials	Susceptible to degradation by certain chemicals	
<u>Segmented Tunnel Linings</u>			
General	Typically combined support and waterproofing system in one	Results in more numerous sources for leaks at joints	
- Cast iron segmented linings	Highly resistant to chemical and electrolytic corrosion	Limited availability in U.S.	Lead caulking between segments, provides waterproofing
- Fabricated steel segments	Effective waterproofing, commonly used in U.S.	Subject to corrosion and must be protected	Lead caulking used between installed segments can be used with secondary
- Precast concrete segments	Potential for savings over other segmented linings	Possible sources of leaks in poor or damaged concrete	Adhesive sealers useable for low water pressures
	Flexible with respect to segment configurations	Heavier segments are difficult to handle	Caulking or gasket seals for higher pressures
	A variety of seals available to waterproof between segments	Segment are brittle and easy to damage during transport or installation	
- Segmented linings or rock tunnels	Rapid progress using pre-cast segments with tunnel boring machines	See notes above Limited flexibility to deal with unanticipated conditions	
<u>Chemical Grouting</u>			
General	Temporary as well as permanent waterproof	Requires extensive field investigation	
	Can strengthen as well as impermeabilize soil surrounding tunnel	Requires expertise to choose proper grout type, set time, infection pressure	Frequently used in Europe as a primary treatment for waterproofing
	Does not require enlarging of tunnel to accommodate waterproofing material	Difficult to monitor success of grouting process	

TABLE 3. SUMMARY OF METHODS TO EXCLUDE WATER FROM COMPLETED TUNNELS (continued) 4/6

METHOD	ADVANTAGES	DISADVANTAGES	COMMENTS
- Silicate-based grouts	Wide range of viscosity, setting times and strengths Weak solution can still penetrate fine sands Least expensive of chemical grouts	Possible syneresis	One-shot injection process most common in U.S.
- Plant-product grouts			
- Lignin grout	Wide range of setting times Relatively inexpensive Non-petroleum based Low viscosity	Reactant is toxic Imparts little strength to soils	
- Colophane	Non petroleum based	Only for waterproofing	
- Forfural	Non petroleum based	Little experience	
- Acrylamides	Well controlled set time Low viscosity	Very expensive Possible toxic effects	No longer in general use in U.S.
- Resins			
- Phenoplasts	Low viscosity; non petroleum based	Individual components are toxic	Used for strengthening as well as waterproofing
- Aminoplasts	Relatively low cost Non petroleum based	Require an acid medium to gel	
- Polyurethane foams	Good waterproofers	Two-shot injection process Toxic ingredients before setting Expensive	
- Emulsions	Non toxic Good long term stability Useful in fine and silty fine sands	Grout coagulation difficult to control	Does not strengthen soil
- Bituminous asphalts	Effective in controlling flowing	Must be heated before injection	Seldom used, little experience
- Vulcanizable oils		Expensive High initial viscosity Long set time	Seldom used, little experience
- Reactants	React directly with groundwater	Limited application	

TABLE 3. SUMMARY OF METHODS TO EXCLUDE WATER FROM COMPLETED TUNNELS (continued) 5/6

METHOD	ADVANTAGES	DISADVANTAGES	COMMENTS
Consolidation Grouting (Rock)			
General	Inexpensive Widespread experience A variety of materials and additives available to meet job needs	Possible segregation Admixtures needed to cope with groundwater flows	Typically done using particulate cement grouts or cement-clay grouts
Annular Space and Contact Grouting			
- Annular space grouting	May reduce need for extensive grouting or waterproofing	Not always a reliable method for waterproofing completely	Grout pumped into voids of gravel packed into annular tunnel space
- Contact grouting	May reduce need for extensive grouting or waterproofing		Backfilling of voids between primary and secondary liners with grout
Diaphragm Walls			
General	May be incorporated into final structure Constructed in any soil which can be held open by slurry	Must penetrate impervious stratum Joints require sealing or water-stops	Cut and cover project Temporary or permanent water barrier May be structural as well as water barrier
- Cast-in-place concrete	Waterproof as well as structural	Expensive if not used as permanent wall	Most common type
- Cast-in-place soldier piles and tremie concrete	Waterproof as well as structural	Slurry or concrete may become contaminated with loose soil along piles Leakage at concrete/steel interface	
- Precast concrete	Good quality concrete Good waterproofing abilities Slurry behind panels increases waterproofing ability	Wall depths limited May be expensive Less flexibility to deal with unanticipated conditions	Limited use outside of Europe

TABLE 3. SUMMARY OF METHODS TO EXCLUDE WATER FROM COMPLETED TUNNELS (continued) 6/6

METHOD	ADVANTAGES	DISADVANTAGES	COMMENTS
Permanent Ground-Water Lowering	Eliminates need for extensive waterproofing	Usually impractical Adverse effects on adjacent structure Requires long-term maintenance	Never been used to date
Sunken Tube Tunnels			
General	Very long tunnel segments (few joints)	Very strict waterproofing necessary Joints are sealed underwater	Used under bodies of water (channels, harbors, etc.)
- Steel shells	Steel provides primary waterproofing membrane	The steel must be protected from corrosion, etc.	Typically welded joints; secondary concrete liner may be used
- Reinforced concrete tubes	Joint flexibility possible	Requires dense, high quality concrete	Usually covered with steel or asphaltic membrane Joints sealed with gaskets

are sealed using lead caulking and liner bolts with grommets or gaskets. Pre-cast concrete segments have more flexibility with respect to segment configuration and are sealed with a variety of techniques including epoxy, gaskets or O-rings. In general, the specification of segmented liners is attractive for future applications in bored tunnels because of current innovations and research in prefabricating and sealing segments.

4.40 OTHER METHODS

Other methods of permanent groundwater control include grouting of the soil mass or rock fissures, contact grouting or annular space grouting behind tunnel liners, diaphragm or cutoff walls or permanent groundwater lowering. In general, these techniques are not as commonly used as the three previously mentioned, though some are used as secondary groundwater control methods along with waterproof tunnel liners. Grouting of soil is a specialty process which has been used both to reduce seepage and strengthen loose or running soils prior to excavation. Grouting behind tunnel liners is a method for both filling voids left by the tunneling process (therefore reducing ground movement) and as a secondary waterproofing aid. Cutoff walls are very attractive for temporary and permanent dewatering of cut-and-cover sections. They can be utilized as combined lateral support systems and finish tunnel wall. Permanent lowering of the groundwater table is a technically feasible process which has yet to be used on any major dewatering project.

4.50 SUNKEN TUBE TUNNELS

Sunken tube tunnels are used primarily below large bodies of water such as harbors or channels. Fabricated of steel or dense concrete, they are typically very long and must be towed and sunk into place. Very strict waterproofing measures must be used in sunken tubes due to the presence of a virtually infinite supply of water above the structure.

4.60 SELECTION CRITERIA

The selection criteria for permanent groundwater control are very similar to those for control during construction. Technical feasibility is, of course, a primary consideration which is based upon the hydrogeologic characteristics of the profile. One additional technical factor to be considered is the long term durability of the groundwater control system. Trade-offs may be considered between potentially expensive permanent techniques and less durable methods which require occasional maintenance over the life of the structure. Cost considerations for physically implementing a permanent groundwater control method may be the deciding factor when choices can be made among two or more competent systems. Cost differentials will arise from variations in cost for mobilization of materials and machinery as well as actual system installation. These costs will in turn depend upon site specific variables and local experience.

5.00 MONITORING OF GROUNDWATER CONTROL SYSTEMS

Even the best designed groundwater control method may have shortcomings due to unforeseen groundwater or soil conditions. A monitoring system can be an effective way to observe the performance of the dewatering system and its effect on the soil mass and structures near the excavation.

For purposes of groundwater control, the most useful instruments are piezometers or observation wells placed at strategic locations along the tunnel alignment. These instruments can determine the effectiveness of drainage systems ahead of the tunnel excavation or verify that water levels in recharge areas or outside of cutoff walls are maintained. To ascertain the effects of the groundwater control method (and excavation method) on the soil mass adjacent to the tunnel, a number of devices are available to monitor surface movement, settlement at depth, and lateral soil movement (See Table 4). These instruments are especially useful when tunneling in congested urban areas where even small movements may cause distress to buildings, streets or utilities. Special monitoring techniques can be implemented to observe the progress of unique groundwater control systems such as freezing or grouting.

The costs for developing and interpreting a monitoring system (usually less than one percent), are small compared with the potential cost of an interuption of mining progress or an excavation failure. Substantial benefits can be realized verifying design assumptions, instilling confidence in the construction process and signalling the onset of problems before they become critical. Proper use and interpretation of instrumentation data can result in future savings in groundwater control, ground support (bored tunnels), lateral support systems (cut-and-cover tunnels) and underpinning of adjacent structures. The systems must have the flexibiity to handle unexpected subsurface conditions during the course of the project.

6.00 MAINTENANCE CONSIDERATIONS

6.10 DURING CONSTRUCTION

Maintenance requirements for groundwater control during tunnel construction are typically not great. Cutoffs and grouting

TABLE 4. SUMMARY OF GROUNDWATER CONTROL MONITORING INSTRUMENTS

	Instrument	Use
1.	Piezometers and Observation Wells	- Measurement of piezometric levels associated with all groundwater control methods. (See Figure 3)
2.	Surficial Settlement Measurement	- Measurement of surface settlement resulting from groundwater control. Usually monitored by optical survey, but can be done with water level devices and pneumatic settlement systems.
3.	Deep Settlement Devices	- Measurement of settlement at depth. Can be a single deep anchor device (Figure 8) or a multi-point system (Figure 9).
4.	Lateral Movement Devices	- Measurement of lateral movement adjacent to open cuts and bored tunnels in soil and rock (Figure 10).
5.	Thermocouples/ Thermistors	- Measurement of temperature in the ground for evaluation of freezing processes (Figure 30).
6.	Accoustic Emission Monitors	- Measurement of grout travel in soil and rock. A method still in research.
7.	Resistivity	Measurement of chemical grout travel in soil. A method still in research.

are passive systems which do not require postconstruction maintenance. Predrainage and recharge systems will require pump maintenance cleaning of wells and screens if they operate for extended periods of time. Recharge operations are particularly susceptible to clogging and encrustation and so may require backflushing of the system or chemical treatment of the recharge water.

Maintenance of compressed air, freezing or slurry shields involves usual efforts associated with keeping compressors, pumps, conveyors and hydraulic systems operating properly. Failure of any components of these systems will undoubtedly bring the excavation process to a halt.

6.20 PERMANENT MAINTENANCE

Since even the most carefully designed and installed waterproofing system may allow seepage at some point over the life of a structure, the cost of maintenance must be considered in initial system selection. In some instances it may prove economical to install a backup waterproofing system to reduce maintenance costs later on.

Preventive maintenance measures can resolve minor leaks into the tunnel before the situation deteriorates. These measures include periodic inspection of bolts, nuts, grommets and washers in segmented tunnel liners or interior protective coatings on fabricated steel segments. Where lead caulking is used to seal the joints between segments, re-caulking should be carried out when leaks appear.

Repair of major leaks in the tunnel liner will probably depend upon access to the zone of seepage. Concrete liners may be patched using fresh concrete applied to a properly prepared surface or with the aid of sythetic epoxy or bituminous materials. Access to waterproofing membranes and subsequent repair is more difficult; fortunately, some membranes are self-healing if the puncture or tear is not too large.

Nearly all types of tunnel leaks can be repaired by the injection of a chemical grout behind the liner. The application of this technique depends upon the groutability of the soil mass. As with a primary grouting program, considerations include the soil permeability and grain size as well as the presence of flowing water which could wash the grout into the tunnel before it has the opportunity to set.

Unusual maintenance requirements may be required if the tunnel has been damaged by excessive water inflow, fire, vehicular accident or neglect. In these situations the maintenance and repair may include structural work which will call for costly tunnel shutdown and waterproofing.

7.00 RECOMMENDED AREAS FOR ADDITIONAL STUDY

7.10 OVERVIEW

Most groundwater control methods employed during construction have been practiced for many years and are well understood. Possible exceptions to this general statement include the newer specialized soft ground shields, certain grouting techniques, and ground freezing. For groundwater control in completed tunnels, the basic methods, i.e. high quality concrete, grouting and some of the older applied membrane methods are well understood, however, certain technical details do require further study, such as use of the newer membrane materials and certain gasketing materials and details.

Groundwater control, both during construction and in completed structures, continues to be much of an art and this situation will probably continue for the foreseeable future. Advances will probably be made in small steps through method variations on individual projects and case history information will, therefore, be invaluable to the advancement of the state of practice. Engineers must be encouraged to publish detailed, yet concise, case histories of successful and unsuccessful applications of groundwater control methods. It is particularly important to publish those case histories where significant problems were encountered, and it could be said that first attempts at groundwater control failed.

During the course of this investigation, numerous individuals involved with groundwater control in the tunneling were interviewed. Based on these discussions plus the experience of the principal authors, areas for potentially fruitful additional study were identified.

7.20 SPECIALTY CONTRACTOR INVOLVEMENT IN DESIGN

Much groundwater control is practiced by specialty contractors who are not generally consulted in detail during the design process because of potential conflicts due to vested interests in a particular method. Detailed consultation with specialty contractors during the design process, including the development of project specifications and contract provisions, can be extremely helpful. It is believed that with the proper use of available expertise, significant savings and smoother running contracts can be realized. Detailed study of fair contractual mechanisms which permit a specialty contractor to participate in design, yet not be excluded from bidding, needs to be conducted, supplemented with case studies.

7.30 PROBLEM IDENTIFICATION

There also needs to be continuing study to make both designers and contractors aware of new, innovative groundwater control methods and what they can accomplish. Many smaller tunnel projects, i.e. tunnels on the order of 8 to 12 feet (2.4 to 3.6m) in diameter, are built by medium sized to small contractors who, rather than trying an innovative method, will fight the water with resultant loss of ground and surface settlement. Designers should identify anticipated groundwater problems in the contract documents and require the contractor to take a positive approach to the problem rather than just allowing him to fight it.

7.40 PRE-QUALIFICATION

There needs to be additional studies of the advisability of developing specification language which would prevent unqualified contractors from attempting tunnel constuction under difficult groundwater conditions, and which would also prevent unqualified subcontractors from attempting specialty techniques. Development of fair and equitable prequalification provisions can be difficult to achieve. It is felt that publication of case studies of where it has been attempted plus discussion with both engineers and contactors would prove enlightening in this regard.

7.50 SUBSURFACE EXPLORATION

Improved subsurface exploration is a continuing area of study in the tunnel industry. It is recommended that a study be considered to identify that information which is most meaningful to contractors for evaluation of groundwater control. It is not believed that major new exploratory techniques need to be studied, but rather the information which it typically provided to contractors can be reviewed and contractors interviewed in a systematic manner to identify a general perception of what information is most useful and whether or not there needs to be additional information of a particular kind provided.

7.60 IMPROVED GROUTING TECHNIQUES

Areas which are being studied in some detail in the grouting industry include development of more economical chemical grouts such as economical silica grouts plus monitoring of grout migration and the effectiveness of grouting programs. Several techniques have been tried, including various geophysical methods. One of the most promising at this time is the accoustic emission technique. It is suggested that this work continue and that it is an area for fruitful additional research.

7.70 APPLICABILITY OF SLURRY AND EARTH PRESSURE BALANCE SHIELDS

The new soft ground shields, i.e. slurry and earth pressure balance shields, have been used extensively in Japan and to a lesser degree in Germany, England, and the United States. While there has been considerable work done primarily by the Japanese on the development of this equipment, there is still some concern relative to evaluation of proper ground conditions under which each type of shield works most effectively. In particular, the optimum conditions for slurry or earth pressure balance shields are different and additional work is required to more clearly define these optimum conditions. This is an rea for further study with much of it again being involved through case history information.

7.80 SUITABILITY OF GROUNDWATER CONTROL METHODS IN COMPLETED TUNNELS

This is an area where there is probably not a need for major new research or development of new techniques. Rather, the most productive area of study would be to conduct a systematic evaluation of these methods in common use today and their effectiveness. It is suggested that case studies of groundwater control methods commonly used in the United States be prepared and that the information be presented in a very concise format with proper references to allow readers to obtain specific details on each method if desired.

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

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1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

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* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.