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Water Intrusion Problems in Transit Tunnels

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16. Abstract

This report presents the findings of five case studies in which an in-depth analysis was made of tunnel water intrusion problems in transit tunnels. Water intrusion parameters of transit systems in Atlanta, Boston, Buffalo, New York and Washington, DC, relating to geologic, hydraulic, design, construction and leakage problems which may be associated with tunnel water intrusion are examined. Special emphasis is placed on grouting applications to leaking and the recommended practices derived from past and current experiences. The report attempts to systematically analyze tunnel leakage problems and potential causes across several diverse transit systems. The results suggest that choices of remedies and maintenance control may relate to design and construction considerations, particularly those associated with original concrete processes and applications. Cost factors and comparisons, while systematically pursued, produced fewer insights than were expected.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	[*]2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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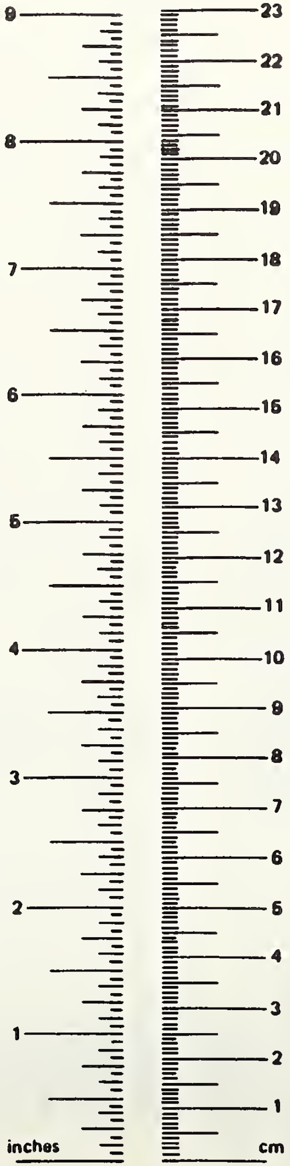
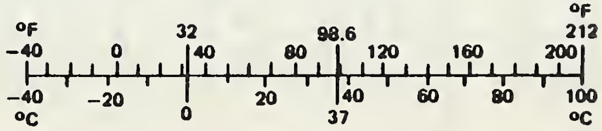
[*] 1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This report was prepared by Paul Parks and Associates, Inc., Boston, MA, between October 1983 and October 1984. The work was sponsored by the U.S. Department of Transportation, Urban Mass Transportation Administration (UMTA), under Contract No. DTUM60-83-C-71217.

Howard Evoy of UMTA and James Lamond of the Transportation Systems Center (TSC) technically monitored the tasks and made necessary arrangements for visits to the various construction sites and subway systems, and meetings with members of the construction community.

The objective of the contract was to perform case studies of five subway systems (Buffalo; Atlanta; Washington, DC; New York, and Boston) by collecting data on the geologic, hydraulic design, structural and construction parameters as they may relate to tunnel water intrusion, and to develop recommended practices.

During the work, the detailed review of major grouting methods and technique was presented by Wallace Hayward Baker, Ph.D. His work and cooperation are gratefully acknowledged.

The cooperation of the transit properties personnel listed below, who gave their time and assistance to the work performed, is greatly appreciated. They are:

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Also acknowledged is the assistance of the technical staff of Paul Parks and Associates, who provided typing, editing and compiling of the final report.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

Section Page

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

EXECUTIVE SUMMARY

This is a study of water intrusion problems at five subway systems in five major cities: Atlanta, GA; Boston, MA; Buffalo, NY; New York, NY; and Washington, DC. The objective of this effort is to assist the Urban Mass Transportation Administration in developing a data base for waterproofing existing tunnels and establishing a recommended approach to tunnel waterproofing by gathering and documenting case history information on water intrusion and remedial techniques from several transit systems.

The study included: (1) a technology review of the state-of-the-art in waterproofing techniques including current data from on-going grout programs and particular concentration on grouting methods and experience; (2) identification and development of the different parameters causing and/or affecting water leakage and analyzing their relationships; (3) development of a data collection questionnaire and case study format based on the parameters; and (4) collection and analysis of data from five transit systems in a case study format through review of files, reports, interviews, history and on-site investigations.

The study has produced the following key material and results:

1. The definition of seven parameters for evaluating water intrusion in transit tunnels as follows:

   (a) Geological setting,
   (b) Hydraulic conditions,
   (c) Design,
   (d) Underground structure,
   (e) Construction methods,
   (f) Post-construction experience,
   (g) Conclusions. (See Tables 2.1 to 2.7 on pages 5 through 8.)

2. A state-of-the-art bibliography of grouting techniques and methods (Appendix B).

3. The codifying of parameters into key words and sub-routines for a computer-based literature search and reference for water intrusion in transit tunnel research.

4. Five case studies of water intrusion problems in transit tunnels (Chapter 5 through Chapter 9).

5. An overview of water intrusion problems based on the correlation of data and findings of the five case studies (Chapter 3) including a summary chart of groundwater control methods and water intrusion treatment during tunnel construction.

The overview correlation summarized the results of the study by four major approaches:

- Paths of Water Infiltration into Tunnels

  From the analysis of the five different subway systems it can be concluded that the major paths of water infiltration into tunnels and underground stations are: shrinkage cracks in concrete lining; construction joint in concrete lining (where waterstops did not work or were not used); channels and ducts in concrete as the result of concrete deterioration and structural failure; and other types of water paths such as through ventilation shafts, pipe systems and concrete and steel structural elements, though the latter represents minor contributions to water inflow.

- Problems Caused by Water Intrusion in Tunnels and Stations

  Information collected during construction site visits at five different subway systems allows classification of the problems into the following categories: (1) total failure of structures; (2) deterioration of tunnel walls and ceilings due to calcification and precipitation (when calcification infiltration occurs it causes fouled trackway drainage, reduced drain pipe cross sections and greatly increased pump impellar replacement requirements); (3) corrosion of steel structural elements and concrete steel reinforcement; (4) deterioration of rail tracks, trackbed and other track components, and (5) invert and architectural finish deterioration.

- Remedial Measures to Control or to Stop Water Leakage

  The various methods of water control being used in all five investigated subway systems can be classified according to the following categories: (1) grouting; (2) crackfilling with waterproofing materials; (3) channeling water through trough and pipe drains; (4) pumping running or standing water from the trackbed area; (5) complete reconstruction of tunnel invert and (6) installing waterproofing panels.

- Costs

  Study of the five transit systems produced very little cost information which could be analyzed across all systems. Prospective and systemic cost data specifically related to water intrusion require special cost studies. One example of cost data, developed by the MARTA system through contract, related costs per linear foot of leaking cracks. The cost per linear foot included all overhead, labor, supervision, tools, equipment and supplies. The cost range varied according to complexity of application from $42.66 to $46.24 per linear foot of cracks.

Finally, structural leaks through concrete floors, walls, and ceilings have been observed in almost all the subway tunnels and stations studied. The amount of water inflow varied depending on age of tunnels, degree of invert deterioration and the magnitude of underground water pressures.

However, since water intrusion has been observed even in new tunnels and stations and the major factors which allow water inflow through a structure are cracks in the concrete lining, it becomes apparent from these studies that the principal approach to the solution of water intrusion problems may depend on improving the quality of initial concrete construction.

The recommendations therefore would include research into all possible measures of quality control to obtain an impervious tunnel lining during the time of its construction; and the study of special admixtures to reduce or prevent concrete shrinkage. Decades of experience in subway constructions show that it is more cost-effective to prevent water intrusion in the earliest phases of tunnel construction than to treat the problems later.

1. INTRODUCTION

1.1 OVERVIEW

Water intrusion affects all underground structures to varying degrees. In most cases, the amount of leakage is controllable; existing drainage systems are generally adequate to remove water from the structure. In the case of transportation tunnels, water intrusion can be particularly troublesome to the efficient operation of the rail system. The presence of water is the initial cause of many structural and track related problems. Clogged drains, calcification, corrosion, third rail arcing, track component deterioration, stray currents and pump failures are directly related to water inflow. Structural deterioration - such as spalling and cracking concrete; corrosion of steel reinforcement, columns and beams; rusting bolts and invert deterioration - would generally not occur in a dry environment.

If the intrusion of water into transit tunnels can be eliminated, or even reduced, the severity of other tunnel and track-related problems would also be lessened. This, in turn, would reduce the maintenance cost of operating the transportation system.

1.2 PURPOSE

The Urban Mass Transportation Administration (UMTA), through the Transportation Systems Center (TSC), has initiated the research in the area of transit underground structures, directed toward reducing the cost of tunnel maintenance and rehabilitation. The primary effort consists of the documentation of a series of case histories of transit properties' experiences and attempted solutions to the problem of water intrusion.

The objective of this effort was to assist UMTA in developing a data base for waterproofing existing tunnels and to establish an UMTA/TSC recommended approach to tunnel waterproofing by gathering and documenting case history information on water intrusion and remedial techniques from several transit systems. The data gathered are to serve as a basis for the collection and dissemination of waterproofing technology and information about the industry's products for waterproofing of tunnels.

1.3 SCOPE AND METHODOLOGY

The study proposes to evaluate the specifics of water leakage in a tunnel by coming to an understanding of the different parameters causing and/or affecting tunnel water leakage, and the interrelationships among these parameters. The methodology and approach to the study therefore consist of: (1) a technology review in order to obtain the state-of-the-art in waterproofing techniques; (2) parameter identification to evaluate specific areas of data on geologic, hydraulic, tunnel design, construction, and water leakage aspects for analysis and (3) case studies of specific transit properties (in Buffalo, Atlanta, New York, Boston, and Washington, DC) for transit water intrusion and waterproofing problems and solution experiences.

Each of the subway systems chosen for a case study has been selected to provide a different example of the ongoing practice of water control, depending on ground water conditions, construction experience and maintenance.

The Niagara Frontier Transportation Authority (NFTA) is in the process of constructing a Light Rail Rapid Transit (LRRT) system in Buffalo, NY. As work progresses, the extensive dewatering system that was in use during major construction of the twin rock tunnels is being deactivated. As a result of the geologic and groundwater conditions, water inflow in excess of that allowed by the design specifications is occurring in sections of the tunnels where the dewatering system has been shut down. Remedial actions are being taken at this time to control the inflow. This effort will provide a unique opportunity to study a major ongoing program of corrective tunnel waterproofing.

The New York City Transit Authority (NYCTA) is experiencing invert deterioration problems that are related to an unusual rise in the water table applying additional water pressure on the inverts, which were not designed to counteract loads of such extreme magnitudes. Invert reconstruction as well as other waterproofing efforts were observed and documented.

The newly constructed Metropolitan Atlanta Rapid Transit Authority (MARTA) tunnels are experiencing water leakage. An evaluation has been made of the waterproofing measures required to bring the tunnels into compliance with the specifications.

An ongoing UMTA grant to Washington Metropolitan Area Transit Authority (WMATA) is funding a study of the effects of calcification and acid water environment on WMATA structures. In addition, waterproofing procedures at WMATA were investigated.

The Massachusetts Bay Transportation Authority (MBTA) Subway System in Boston is the oldest in the United States, and its age predetermined many water intrusion problems which are specific to its geological conditions, an urban environment in close proximity to sea water. The new section of the MBTA Subway, the Northeast Extension of the Red Line, can also contribute useful information on the state-of-the-art in waterproofing technique.

All the data collected in the case studies have been analyzed and evaluated with the aim of developing recommended practices of water control in future and existing subway systems.

2. TECHNOLOGY REVIEW AND LITERATURE ANALYSIS

2.1 PURPOSE

The purpose of this chapter is to review and analyze the water leakage problems being experienced by transit systems and the maintenance practices employed to control or alleviate water leakage.

2.2 PROCEDURE

In order to evaluate the specifics of water leakage in a tunnel and to understand the different parameters causing and/or affecting water leakage, all available literature sources containing useful information about water intrusion problems and their treatment in tunnels and during tunnel construction were reviewed. Different parameters causing and/or affecting water leakage were considered, analyzed and constructed in the formats depicted in Tables 2.1 through 2.7. Through selected parameters, basic sets of conditions for water intrusion were developed under the following headings: geological setting, hydraulic conditions, design relating to water control, types of underground structures, construction experience, post-construction experience and conclusions of water treatment difficulties and effectiveness. Appendix B contains literature references in grouting technique.

2.3 COMPUTER-BASED LITERATURE FILE

A system of kew words was developed relating to the selected sets of parameters. A computer-based file utilizing this system is proposed as a means to perform a literature search for necessary information on water intrusion problems. The file, based on such key words as shown in Table 2.1, is represented by a computer menu format developed for a master file reference of article title, author, publisher, etc.

TABLE 2.1 WATER INTRUSION PARAMETERS - GEOLOGICAL SETTING

Set 1	Geological Setting	Key Word: GEO
A.	Subsoils	GEO/A
1.	Category	GEO/A/1
2.	Origin	GEO/A/2
3.	Characteristics	GEO/A/3
a.	grain size	GEO/A/3/a
b.	permeability	GEO/A/3/b
c.	stratification	GEO/A/3/c
B.	Bedrock	GEO/B
1.	Category	GEO/B/1
2.	Attitude	GEO/B/2
3.	Discontinuities	GEO/B/3
C.	Mix-faced condition	GEO/C
D.	Special problem materials	GEO/D

TABLE 2.2 WATER INTRUSION PARAMETERS - HYDRAULIC CONDITIONS

Set 2	Hydraulic Conditions	Key Word: HYDCON
A.	Groundwater	HYDCON/A
1.	Typical depth, artesian, perch levels	HYDCON/A/1
2.	Recharge conditions	HYDCON/A/2
3.	Control and limitations	HYDCON/A/3
4.	Dissolved constituents	HYDCON/A/4
5.	Physio-chemical properties	HYDCON/A/5
6.	Corrosion and pollutants	HYDCON/A/6
B.	Surface water	HYDCON/B
1.	Surface flooding	HYDCON/B/1
2.	Seasonal fluctuations	HYDCON/B/2
3.	Direct recharge of groundwater	HYDCON/B/3
4.	Open water-affecting systems	HYDCON/B/4
C.	Water carrying utilities	HYDCON/C
1.	Leakage or drainage	HYDCON/C/1
2.	Influence on construction activity	HYDCON/C/2
D.	Additional costs for intensive investigations of geological and hydraulic conditions (test borings, borehole permeability tests, test shafts, pumping tests, etc.)	HYDCON/D

TABLE 2.3 WATER INTRUSION PARAMETERS - DESIGN

Set 3	Design Relating to Water Control	Key Word: DRWC
A.	Hydrostatic pressure resistant	DRWC/A
	1. Liners: materials and thickness for various shapes	DRWC/A/1
	2. Concrete liners: precast versus cast-in-place admixtures	DRWC/A/2
	3. Steel liners	DRWC/A/3
	4. Types of joints and details	DRWC/A/4
	5. Water collector systems, panning, drains, chases	DRWC/A/5
	6. Exterior and interior waterproof coating	DRWC/A/6
	7. Special measures - grouting, joint filling	DRWC/A/7
	8. Criteria for satisfactory watertightness	DRWC/A/8
	9. Assumption of exterior water pressure	DRWC/A/9
B.	Hydrostatic pressure relieved	DRWC/B
	1. Materials and thicknesses for various shapes	DRWC/B/1
	2. Permanent drainage arrangements: pannings and collectors	DRWC/B/2
	3. Types of joints and details	DRWC/B/3
	4. Expected total flow and provisions for disposition: sumps and pumps	DRWC/B/4
	5. Assumptions of exterior water pressure	DRWC/B/5
C.	Costs of alignment of tunnels versus GWC systems provided	DRWC/C

TABLE 2.4 WATER INTRUSION PARAMETERS - TYPES OF UNDERGROUND STRUCTURES

Set 4	Types of Underground Structures	Key Word: TYPSTR
A.	Running tunnels	TYPSTR/A
	1. Types in soils	TYPSTR/A/1
	a. materials	TYPSTR/A/1/a
	b. cross-section	TYPSTR/A/1/b
	2. Types in rock	TYPSTR/A/2
	a. materials	TYPSTR/A/2/a
	b. cross-section	TYPSTR/A/2/b
	3. Mix-faced conditions	TYPSTR/A/3
	a. materials	TYPSTR/A/3/a
	b. cross-section	TYPSTR/A/3/b
	4. Subaqueous	TYPSTR/A/4
B.	Underground chambers	TYPSTR/B
	1. Stations	TYPSTR/B/1
	a. cross-section	TYPSTR/B/1/a
	b. materials	TYPSTR/B/1/b
	2. Ancillary buildings	TYPSTR/B/2
	a. cross-section	TYPSTR/B/2/a
	b. materials	TYPSTR/B/2/b
C.	Structures open to surface	TYPSTR/C
	1. Shafts	TYPSTR/C/1
	a. materials	TYPSTR/C/1/a
	b. cross-section	TYPSTR/C/1/b
	2. Entrances	TYPSTR/C/2
	a. cross-section	TYPSTR/C/2/a
	b. materials	TYPSTR/C/2/b

TABLE 2.5 WATER INTRUSION PARAMETERS - CONSTRUCTION EXPERIENCE

SET 5	Construction Experience	Key Word: CONEX
A.	Methods of excavation	CONEX/A
	1. Mining	CONEX/A/1
	2. Supported excavation	CONEX/A/2
	3. Open excavation (cut-and-cover)	CONEX/A/3
	4. Stabilization procedures	CONEX/A/4
B.	Problems of water control	CONEX/B
	1. Flow conditions during construction	CONEX/B/1
	2. Dewatering methods	CONEX/B/2
	3. Special measures: grouting, air pressure	CONEX/B/3
	4. Surface water control and flooding	CONEX/B/4
	5. Effects on property and people	CONEX/B/5
	6. Effects on the environment	CONEX/B/6
C.	Costs of dewatering systems	CONEX/C
D.	Costs of water protection measures	CONEX/D

TABLE 2.6 WATER INTRUSION PARAMETERS - POST CONSTRUCTION EXPERIENCE

Set 6	Post-Construction Experience	Key Word: PCE
A.	Water problems	PCE/A
1.	Leaking in cracks and joints; nature of cracking; quantity of flow	PCE/A/1
2.	Character of seeping water	PCE/A/2
a.	precipitates	PCE/A/2/a
b.	corrosive	PCE/A/2/b
c.	fine particles in suspension	PCE/A/2/c
3.	Change in exterior water pressure, loss of ground	PCE/A/3
4.	Efficiency of drainage arrangements	PCE/A/4
5.	Structural effects	PCE/A/5
a.	progressive damage or deterioration	PCE/A/5/a
b.	effect on surrounding structures	PCE/A/5/b
6.	Effects on electrical systems and operations	PCE/A/6
7.	Progressive changes with time	PCE/A/7
B.	Remedial measures	PCE/B
1.	Interior leak control: crack filling and sealing	PCE/B/1
2.	Waterproofing treatment, brushed coating	PCE/B/2
3.	Exterior leak control: grouting, excavation and patching, drawdown of groundwater, utilities repair	PCE/B/3
4.	Interior drainage provisions, cleaning or supplementary drains	PCE/B/4
5.	Altering electrical or interior utilities	PCE/B/5

TABLE 2.7 WATER INTRUSION PARAMETERS - CONCLUSIONS ON WATER LEAKAGE PROBLEMS

Set 7	Conclusions on Water Leakage Problems	Key Word: WATDIF
A.	Source of difficulties	WATDIF/A
1.	Design	WATDIF/A/1
2.	Construction and workmanshlp	WATDIF/A/2
3.	Ground Conditions	WATDIF/A/3
B.	Effectiveness of remedial measures	WATDIF/B
1.	Leak control	WATDIF/B/1
2.	Waterproofing	WATDIF/B/2
3.	Drainage measures	WATDIF/B/3
C.	Recommendations	WATDIF/C

3. OVERVIEW OF WATER INTRUSION PROBLEMS

3.1 INTRODUCTION

The objective of this study is to assist UMTA in developing a data base and a recommended approach for waterproofing of tunnels by gathering case history information on water intrusion and remedial technique from the following five transit systems:

- Buffalo Light Rail Rapid Transit System at NFTA (Buffalo, NY);
- Massachusetts Bay Transportation Authority (MBTA), Boston, MA;
- New York City Transit System Authority (NYCTA), New York, NY;
- Metropolitan Atlanta Rapid Transit Authority (MARTA), Atlanta, GA;
- Washington Metropolitan Area Transit Authority (WMATA), Washington, DC.

A detailed description of each case study is given in Chapters 5 through 9 of the report.

A correlation summary and the data analysis are presented below, according to the following aspects:

- Major paths of water intrusion in tunnels and stations;
- Problems caused by water in tunnels and stations;
- Remedial measures to control or to stop water leakage.

3.2 MAJOR PATHS OF WATER INTRUSION IN TUNNELS AND STATIONS

After analysis of the five different subway systems it can be concluded that the major paths of water infiltration into tunnels and underground stations are: shrinkage cracks in concrete lining; construction joints in concrete lining (where waterstops did not work); and channels and ducts in concrete as a result of concrete deterioration and structural failure.

3.2.1 Shrinkage Cracks

Leakage through shrinkage cracks which occurred during the concrete hardening process is one of the most common types of water intrusion in tunnels. The PPA site visit team has observed numerous leaks of that type in all subway systems investigated. The photos taken by the PPA team demonstrate various cases of water infiltration through shrinkage cracks. Those photos can be found in the chapters corresponding to the case studies.

- Figure 5.3 - water infiltration through the concrete walls.
- Figures 7.4, 7.7, 7.10, 7.14, 7.15 - large areas of calcification around shrinkage cracks in concrete walls, large stalactites grown due to water infiltration through the cracks (South Station, Red line, Aquarium Station of Blue Line, Boylston-Arlington tunnel of Green line of the MBTA system).
- Figures 8.6, 8.7 - calcifications and precipitations caused by leaking water and wet areas of walls with shrinkage cracks.
- Figures 9.7, 9.17 through 9.20 - water infiltration through shrinkage cracks and the deterioration effect of water leaks, i.e., calcification and settlements around cracks.

3.2.2 Construction Joints in Concrete Lining

Construction joints in concrete lining are also good paths for water intrusion. Such leaks were observed in large quantities in all five cases and are shown in the photographs of the corresponding case studies:

- Figure 6.5 (MARTA) - water infiltration through the construction joints in the station roof.
- Figure 7.6 (MBTA) - deterioration of paint on Aquarium Station walls due to leakage through construction joints.
- Figures 8.3, 8.4, 8.8 (WMATA) - leaks through precast and CIP concrete walls in the area of structural joints.
- Figure 9.8 (NYCTA) - leaks through wall joints.

3.2.3 Concrete Deterioration and Structural Failure

Channels and ducts in tunnel concrete walls and floors caused by concrete deterioration and structural failure are the most dangerous and intensive paths of water intrusion. These types of leaks were observed in many old tunnels of the New York City and Boston Subway Systems (Case Nos. 3 and 5). These systems have been operating for many decades and their underground structures have been subjected to ground water pressure and to the action of chemically aggressive soil components, which cause severe deterioration and failure of concrete lining and floors. Disintegrated blocks of concrete walls and floors allow the water to infiltrate in large quantities. This type of water intrusion is shown on Figure 9.10, Case No. 5, NYCTA, where the water inflow between the blocks of disintegrated tunnel floors washed out the trackbed ballast and resulted in deterioration of railtracks and trackbed. Figures 7.11, 7.12 and 7.13, Case No. 3, MBTA, and Figures 9.4, 9.5 and 9.8, Case No. 5, NYCTA, also show the water infiltration through the disintegrated tunnel walls and floors with the deteriorative effect of water intrusion on rail and trackbed.

3.2.4 Other Types of Water Intrusion Paths

Water can infiltrate into the tunnels through ventilation shafts, pipe systems and in the areas of contact between the concrete and steel structural elements, such as beams, columns, arches, etc. These possible ways of water leakage are minor contributions to the water inflow, as compared to those paths mentioned in previous paragraphs. At the same time the leaks through pipes, shafts, etc., can create some serious problems, as happened, along with shrinkage cracks, in the large multi-leveled 63rd Street Station in the New York City Subway System.

3.3 PROBLEMS CAUSED BY WATER INTRUSION IN TUNNELS AND STATIONS

Water intrusion into tunnels and stations creates many serious problems for tunnel structural and operating conditions. The information collected during construction site visits of five different subway systems allows us to classify the problems into the following categories:

- Total invert failure of structures - see Figure 9.10 of Case No. 5.
- Deterioration of tunnel walls and ceilings due to calcification and precipitation - see Figure 6.4, Case No. 2; Figures 7.4, 7.5, 7.7, 7.10, Case No. 3; Figures 8.6, 8.7, 8.8, Case No. 4; and Figures 9.11, 9.12, 9.16, 9.21, Case No. 5.
- Deterioration of rail, trackbed and other track as shown on Figure 6.4, Case No. 2.
- Pump Deterioration.

3.4 REMEDIAL MEASURES TO CONTROL OR TO STOP WATER LEAKAGE

The various methods of water control being used in all five investigated subway systems can be classified into the following categories:

- Grouting. The objective of the grouting method is to pump, under high pressure, cement or any other hardening solvent into empty spaces behind the tunnel lining, combining, in this way, an invert structure with the surrounding grounds. It is the oldest and the most developed method of water control used in tunneling. Chapter 4 of the report is fully devoted to grouting technique, its application, advantages and limitations for various ground water, geological and construction conditions.
- Crack Filling With Waterproofing Materials. This method is also widely used to seal cracks and spallings in a concrete lining.
- Channeling Water Through Pipe Drains. This procedure is used to prevent water from intruding onto tracks and beds. Channeling technique is shown in Figures 6.7, 7.5 , and 9.12. It uses drain pipes to direct infiltrated water to a water collector where the water can be pumped out.
- Pumping the Running or Standing Water From Track Bed Area. This is done whenever water has collected in large quantities.
- Complete Reconstruction of Tunnel. Unavoidable when floors and walls of tunnels have deteriorated severely as in some old tunnels of the New York Subway System (see Figure 9.6).

3.5 OVERVIEW OF CASE STUDIES

A tabular summary of goundwater control methods and water intrusion treatment during tunnel construction is shown for each case study site in Table 3.1.

A summary of groundwater control methods and water intrusion treatment in completed tunnels is shown in Table 3.2.

TABLE 3.1 SUMMARY OF GROUNDWATER CONTROL METHODS AND WATER INTRUSION TREATMENT DURING TUNNEL CONSTRUCTION

NIAGARA FRONTIER TRANSIT AUTHORITY (NFTA), BUFFALO, N.Y.

Tunnel Environment and Method of Excavation	Type of Construction Work	Type of Water Problem	Method of Water Control	Comments
Soft face, cut-and-cover	Soil excavation	No special problem	Regular waterproofing above groundwater level	Conventional techniques proved to be sufficient
	Placement of concrete lining	No special problem	Waterstops in construction joints	
Rock, TBM driven	Tunnel boring and muck excavation	Previously estimated amount of water inflow	A dewatering system of several deep wells	During the time of operation, the system adequately controlled the water
		Unexpected localized heavy water inflow in a 300-ft section of tunnel	Two additional deep wells and a treatment plant for water purification	
	Placement of concrete lining	Heavy water inflow (as a combined effect of decreased yield of deep wells plus heavy rains)	The invert drainage system (consisted of deep sump 6x6 ft and pump)	Effectively controlled the water during concrete pouring process
	Upon completion of concrete lining	Water leakage through the shrinkage cracks in concrete lining	Chemical grouting	Chemical grouting is most effective. However, it is expensive
			Cement grouting	Cement grouting met water tightness specifications

TABLE 3.1 SUMMARY OF GROUNDWATER CONTROL METHODS AND WATER INTRUSION TREATMENT DURING TUNNEL CONSTRUCTION (CONT.)

METROPOLITAN ATLANTA RAPID TRANSIT AUTHORITY (MARTA), ATLANTA, GA.

Tunnel Environment and Method of Excavation	Type of Construction Work	Type of Water Problems	Method of Water Control	Comments
Mix-faced tunneling, shield driven tunnels; Rock tunneling with drill-and-blast tunnels	Boring of shallow tunnels and soil removal	Estimated amount of groundwater inflow	Well point dewatering	Adequately controlled water inflow
	Placement of concrete lining	Numerous leaks through construction joints and shrinkage cracks		Were not sufficiently waterproof
				Was not sufficient
	After installation of concrete lining	Leaks through the lining	Envelope grouting with chemical grouts Drip pans	Labor intensive but worthwhile

TABLE 3.1 SUMMARY OF GROUNDWATER CONTROL METHODS AND WATER INTRUSION TREATMENT DURING TUNNEL CONSTRUCTION (CONT.)

MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA), BOSTON, MA.

Tunnel Environment and Method of Excavation	Type of Construction Work	Type of Water Problem	Method of Water Control	Comments
Cut-and-cover tunneling	Placement of concrete lining	Water infiltration through structural joints and shrinkage cracks	"Injecto-Method" for sealing construction joints of concrete lining	New and not widely used in the U.S.A.
Underground tunneling (shield driven)				Round shield buckets allow for better excavation and for better inside tunnel surface, which in turn allows for better quality of concrete lining

TABLE 3.2 SUMMARY OF GROUNDWATER CONTROL METHODS AND WATER INTRUSION TREATMENT IN COMPLETED TUNNELS

METROPOLITAN ATLANTA RAPID TRANSIT AUTHORITY (MARTA) ATLANTA, GA.

Type of Water Problem	Method of Water Control	Advantages	Disadvantages	Comments
Intensive water inflow through tunnel walls and ceiling due to cracks in concrete lining	Galvanized steel plates for intercepting and collecting the water and channeling it away to the pumps	Emergency measure which provides immediate control of water intrusion	Deteriorates architectural appearance of subway stations	Reserved for remedial measures
	Regular grouting with chemical grouts: -5600 (foam)	Good for cracks filling	Admixture needed to cope with groundwater flows	Forms a flexible gasket or plug
	Grouting	Good for patching and sealing in concrete structures		Semi-flexible epoxy gel
	Grouting	Stops water seepage, seal tunnel segment joints		
	Envelope grouting			

TABLE 3.2 SUMMARY OF GROUNDWATER CONTROL METHODS AND WATER INTRUSION TREATMENT IN COMPLETED TUNNELS (CONT.)

METROPOLITAN ATLANTA RAPID TRANSIT AUTHORITY (MARTA), ATLANTA, GA. (continued)

Type of Water Problem	Method of Water Control	Advantages	Disadvantages	Comments
Water leaks emerging from the base of the emergency catwalk	"Toe-bench cutting" (cutting a small trough running to the drainage chase)	Simplicity in maintenance	Labor intensive and requires temporary stops of tunnel operation	
Tunnel ceiling leaks	Sealing leaks with a fast set high strength hydraulic cement and with a flexible epoxy gel applied over a cement surface combined with grouting	Effective if good reliability with the three year warranty		Work done by the contracted service

TABLE 3.2 SUMMARY OF GROUNDWATER CONTROL METHODS AND WATER INTRUSION TREATMENT IN COMPLETED TUNNELS (CONT.)

MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA), BOSTON, MA.

Type of Water Problem	Method of Water Control	Advantages	Disadvantages	Comments
Water pouring intensively through the tunnel walls and ceilings due to: 1) cracks in construction joints sealing 2) shrinkage cracks in concrete lining 3) crack openings in concrete caused by the erosion of concrete	1) Intercepting and collecting the water by means of steel pans or iron plates and channeling it away to the pumps	Effective remedial measures for control of water intruding in large quantities without stopping an operation in tunnel	1) Concrete deterioration 2) Pans can fall	
	2) Sealing cracks with waterproofing materials	Temporary as well as permanent waterproof	Lack of structural strength to resist high water pressure	
	3) Chemical grouting	Least expensive with a large variety of materials available	Some components may be toxic	
Water emerging from the base of track bed; Ballast washed away	"Toe-bench cutting" and channeling the water to the pumps Replacing the ballast	Protects rail structure from intensive corrosion	Labor intensive and requires stopping of tunnel operation	Emergency remedial measures

TABLE 3.2 SUMMARY OF GROUNDWATER CONTROL METHODS AND WATER INTRUSION TREATMENT IN COMPLETED TUNNELS (CONT.)

MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA), BOSTON, MA. (continued)

Type of Water Problem	Method of Water Control	Advantages	Disadvantages	Comments
Hidden leaks in concrete lining behind the wall finish which cause wetness and dampness of walls and toe-benches	1) Chemical grouting 2) Sealing the leaks with waterproofing materials	There is no practical alternative	Lack of structural strength to resist high water pressure	Conventional proven method
A deterioration of wall paint due to calcification of the surface of walls and ceilings	Extensive repair work and replacing the wall finish			

TABLE 3.2 SUMMARY OF GROUNDWATER CONTROL METHODS AND WATER INTRUSION TREATMENT IN COMPLETED TUNNELS (CONT.)

WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA), WASHINGTON, D.C.

Type of Water Problem	Method of Water Control	Advantages	Disadvantages	Comments
Intensive water leaks through the shrinkage cracks in concrete lining	Conventional grouting			
	Improving a quality of concrete lining by partial invert reconstruction	Significantly reduces the number of leaks		Better construction technique, inspection and design resulted in 80% less leaks at Bethesda Station
Large areas of calcification and precipitation around the leaks	Removing the wall finish and placing the new one		Requires temporary stopping of tunnel operation	
Leaks through the construction joints in concrete lining	Conventional grouting			Effective in combination with the concrete
	Collecting the dripping water into the drain and carrying it away to the pump shafts, then pumping it to the surface			

TABLE 3.2 SUMMARY OF GROUNDWATER CONTROL METHODS AND WATER INTRUSION TREATMENT IN COMPLETED TUNNEL (CONT.)

NEW YORK CITY TRANSIT AUTHORITY (NYCTA), NEW YORK, N.Y.

Type of Water Problem	Method of Water Control	Advantages	Disadvantages	Comments
Water leaks through the concrete lining due to concrete shrinkage cracks Leaks through the concrete lining structural joints, not sealed sufficiently Leaks along ventilation system and sewer lines Substantial water deposit caused by a condensation from the humid air	Pumping	Effective in a case of high water deposit	Must be used constantly	These types of water problems represent 95% of all leaks in the NYCTA System; 75% of them, described as minor or moderate, are being controlled by the NYCTA's divisions; 20% of them described as quite intensive are treated by outside contractors
	Channeling by means of steel pipes	Inavoidable when leaks occur from the arches over passenger sidewalks and platforms	Not always a good measure in the presence of 3rd rail	
	Sealing grout		Not efficient in a case of very intensive water inflow	
	Grouting with TACSS	TACSS has a low viscosity which allows to limit injection time. TACSS can be efficient for stopping a water seepage as well as for ground stabilization		
Sunken tubes of tunnels under the Hudson River (high water pressure)	Prefabricated structures done under thorough control of pouring and curing processes and quality of concrete	Have almost no leaks		Location - an extension of the "East 63rd Street" Station

TABLE 3.2 SUMMARY OF GROUNDWATER CONTROL METHODS AND WATER INTRUSION TREATMENT IN COMPLETED TUNNELS (CONT.)

NEW YORK CITY TRANSIT AUTHORITY (NYCTA), NEW YORK, N.Y. (continued)

Type of Water Problem	Method of Water Control	Advantages	Disadvantages	Comments
Infiltration through partially destroyed tunnel concrete walls and floors	Rehabilitation work such as rebuilding of the invert and repairing tunnel structures, which consists of: -removal of architectural cover of walls -diverting of heavy inflow and then sealing all points of water entry -patching all deteriorated or spoiled concrete -installation of waterproof 'Volklay Panels' on the inside face of walls and on the top of a floor slab -filling of ventilator bays with concrete up to 6 feet above the ground water table -occasional drilling of holes in walls to locate waterleaks -constant pumping	Only permanent reconstruction measures can prevent a possible structural failure	The rehabilitation work requires the subway line be closed to passengers on nights and weekends	An estimated cost of the invert reconstruction projects is $25 million. The estimated time required to complete work: -29 months

4. GROUTING FOR GROUND WATER CONTROL IN COMPLETED RAPID TRANSIT TUNNELS

4.1 INTRODUCTION

Final tunnel linings are constructed either of cast-in-place concrete or segmented structural elements made of steel, cast iron, or concrete. Nearly all tunnel linings installed below groundwater levels leak to some extent through cracks in the concrete or through joints between structural elements. Leakage through linings constructed of structural elements frequently can be controlled by tightening connecting bolts and fasteners, or by caulking techniques. Grouting is sometimes used for control of leakage between structural elements, and it is the most commonly used method for control of leakage through cast-in-place linings.

For control of leakage through tunnel linings, grouting is typically done through the lining as opposed to injection through a borehole drilled from the outside of the tunnel. Grout is introduced through pre-installed ports or pipes through the lining or through drilled openings. The discussion of grouting which follows assumes grout injection from within the tunnel in most instances. Grouting outside of the tunnel or in advance of tunneling is usually done as an aid to construction, that is, ground stabilization or reduction of construction dewatering, rather than for control of leakage into the completed tunnel.

Three other possible methods for control of leakage through completed tunnel linings include:

1. Diversion of water by drainage pans, pipes, and channels;
2. Filling of cracks with hydraulic fast-setting cement, epoxies, or crystallization compound;
3. Surface treatment with many different possible materials, using trowel or brush application.

Of the above three alternate methods, diversion is probably the most positive if it is architecturally acceptable. Crack and surface treatments can be effective, but it is difficult to achieve reliable water control by these methods, especially if there is any significant water head outside of the lining.

The grouts used are either cement-based or one of several available chemical materials. Selection of the most appropriate grouting material is a function of ground conditions, structure type, and cost considerations. Cement-based grouts are typically the least expensive, but they do have limitations with regard to their application, primarly due to restrictions on set time and injectability. Chemical grouts, while more expensive, can typically be designed for much faster setting times, and also can typically be injected into finer soil for rock and concrete fissures. While there are many available chemical grouts on the market, the most commonly used types at this time for transportation tunnels include silicates, acrylamides and water-reactive polyurethanes. A more complete discussion of cement and chemical grouts follows.

4.2 CEMENT-BASED GROUTS

Cement-based grouts have been used for many years, and represent the oldest known grouting material. Cement-based grouts, while simple in concept, require much skill and meticulous attention to detail to be used successfully. Quoting Adam Cleave Houlsby (1982), "Grouting, more than most engineering processes, requires an intuitive perception of just what the liquid grout does as it flows through the open joints and cracks hidden underground."

4.2.1 Fillers and Admixtures

A typical grout mix consists of finely ground cement and water mixed in varying proportions. However, these mixes are often modified by the introduction of fillers and a variety of admixtures to affect the grout properties. The main purpose of fillers is to reduce the cost of the grout without greatly affecting its physical properties. Commonly used fillers include clays such as sodium bentonite, montmorillonite, kaolinite, and illite. The clays have a capacity to absorb water and to form gel structures at low concentrations, which stabilizes the cement and prevents bleeding. Pozzolans will react with free lime cement in the presence of water to form a cementitious compound, but they are not themselves cementitious. Naturally occurring pozzolans such as finely ground shale, pumicite and diatomite, as well as artifical pozzolans such as fly ash and ground blast furnace slag, serve as cheap bulk fillers in low strength grouts used for filling relatively large cavities. Fine sand can be added to water cement grouts to create greater volume at relatively low cost. Admixtures can be added in small quantities to affect grouts in many ways, such as acceleration or retarding of set, fluidifying the grout to improve pumpability, expanding the grout to reduce shrinkage and prevent bleeding.

4.2.2 Design and Application Principles

Cement grouts should be designed to be sufficiently fluid to allow efficient pumping and injection, and sufficiently stable to resist displacement and erosion by moving water after injection. The design will also be influenced by the size of fissures to be filled by the grout. The principle variable affecting the properties of water cement grouts is the water-cement ratio. Insufficient water will result in a nonpumpable grout, while excess water can cause bleeding, low strength, increased shrinkage, and poor durability. Water cement ratios by weight typically vary between 0.3 to 0.6.

Successful use of cement-based grouts requires careful attention to detail, confirmation of final designs, constant field monitoring, and adaption of field design as necessary. To obtain successful results requires:

1. Obtaining quality materials from reliable sources;
2. Storage of cementitious materials under dry and constant conditions;
3. Accurate monitoring of moisture content of fillers;
4. Use of fresh cement;
5. Weight batching of materials;
6. Control of water cement ratios;
7. Control of mixing rate in time;
8. Rigid supervision of all operations by experienced staff.

The basic equipment used in a cement grouting operation includes a mixer, agitator, continuous speed pump, circulation line to allow discharge of unused grout back to the agitator, and control fittings, such that volumes and pressures can be regulated.

Cement grout is used on most tunnel projects, and is probably the predominant grouting material used in the tunneling industry for control of groundwater today. An excellent example of extensive cement grouting for control of leakage is described in the case history for the Buffalo, New York, Subway System.

4.3 CHEMICAL GROUTS

There are a large number of chemical grouts available for use in today's tunnel industry. Chemical grouts were first introduced 30 to 40 years ago, and over the last 10 years many new materials have been introduced. The first chemical grouts introduced were the sodium silicate materials, which have been used primarily for stabilization of granular soils. Other available grout types include acrylamides, lignosulphonates, phenoplasts, aminoplasts, and typically water-reactive variations of these generic types. As mentioned previously, the most commonly used chemical grouts in transportation tunnels today are the silicates, acrylamides, and water-reactive polyurethanes. Taken together, these have accounted for more than 83 percent of the chemical grout materials sold since 1970. The most commonly used grouts are the silicates, followed by acrylamides and polyurethane.

4.3.1 Silicates

Silicate grouts, which are free of harmful organics, are nontoxic and noncorrosive. Because of these and other characteristics, silicate-based grouts satisfy many of the geotechnical, hydrological, and environnental requirements of a project. They are, however, more commonly used during construction than for control of leakage.

The Joosten process has been largely replaced by several different single-shot injection schemes that produce high-strength grouts. Organic compounds can be used which react with a water-silicate mixture to form acids or acid salt. Formaldehyde became another popular reactant, but environmental studies have reported it to be a possible carcinogen; therefore its use has decreased.

4.3.2 Acrylamides

Next to silicate grouts, the most commonly used chemical grouts are acrylamides, which were first introduced in 1953. Acrylamides come closest, in terms of performance, to meeting the specifications of an ideal grout. The silicate grouts have low viscosity in the ungelled state. Its gel time can be controlled, and adequate strength can be provided for most applications. These grouts are more costly than silicates, and are neurotoxic.

From 1953 to 1978 acrylamides were available in the United States under the designation AM-9. Due to the neuro-toxicity of AM-9, its manufacture in this country was stopped in 1978. Very shortly after the discontinuance of manufacture by the United States, Japanese and French manufacturers introduced acrylamide-based products to the American market in 1979, and their use continues today.

Acrylamide-based grouts consist of a mixture of acrylamides, constituting about 95 percent of the mixture, which polarize into long molecular chains; and 5 percent of cross-linking agents which bind the acrylamide chains together. The material which forms is a gel which can be varied from a sticky transparent gel of low strength to a hard stiff opaque white gel. Gel times can be varied from nearly instantaneous to many hours. The gels formed are considered permanent. There are examples of field applications which have been in place for more than 20 years without deterioration of strength. The gels will, however, deteriorate mechanically when exposed to alternating, drying, and/or freezing cycles.

Acrylamide in solution or powder form is toxic; however, the gel is nontoxic. Where acrylamides are used, consistent and disciplined safety procedures must be followed.

Acrylamides have been used in varying degrees on most major rapid transit construction projects in recent years. Cases where their use has been documented by this study include Boston, Buffalo, Washington, D.C., and Atlanta.

4.3.3 Water Reactive Polyurethanes

Several naterials are available which gel upon contact with water, and provide obvious possibilities for use in sealing leakage in completed tunnel linings. There are several possible materials which react with water; among these, polyurethane has the best mechanical properties and the widest range of conditions for gel formation. Polyurethane gels of relatively high viscosities are not suited for treatment of fine-grained soils. Polyurethane has been widely used for sealing of sewers, and is applied internally through a packer from within the tunnel. It has been used extensively in Atlanta for sealing shrinkage crack leaks. Its use has also been demonstrated in the New York City Subway System as well.

The polyurethane grout in its unreacted form is a liquid having a viscosity slightly heavier than water. When it mixes with water, a closed cell foam forms which acts as a mechanical seal. Gel time can be varied from nearly instantaneous to many hours.

A common method for sealing cracks in concrete is to drill small holes (i.e., 1/2 inch diameter) at angles into the crack and then to pump grout into the crack through a nipple packer. The process has the advantage that it can be utilized using light, easily transportable hand drills and pumps.

In its unreacted form, the grout is toxic and care must be exercised for protection of workmen. In its reacted foam state, the material is chemically inert.

4.3.4 Lignosulphonates

Lignosulphonate grouts are produced as a waste liquor by-product of the wood processing industry. These grouts are typically used for stabilization of soils in that they have relatively high strengths when gelled. They are relatively inexpensive but the catalyst used is highly toxic. There is also the possibility that the gels will reach toxic materials in the surrounding environment. In general, lignosulfate grouts have not been used on recent rapid transit construction in the United States.

4.3.5 Phenoplasts

Phenoplast grouts are polycondensates resulting from the reaction of phenol and aldehyde. These grouts provide high strength for stabilization of soils, and are considered permanent materials. As with several of the other chemical grouts, however, there are health hazards associated with their use, and they are also potential environmental pollutants. They have not been widely used in rapid transit tunnel construction.

4.3.6 Aminoplasts

Aminoplasts are grouts which consist of urea and formaldehyde, which form a resin. Initially, these grouts were used in the oil industry. They generally require an acid environment for reaction, as do the phenoplasts and the aminoplasts. They are also caustic and present a health hazard. In general, these grouts should be used only when the groundwater is known to be acid, such as for application in coal mines. They have generally not been used for rapid transit tunnel construction.

4.3.7 New Products

Several new products have been recently introduced to the market, such as an acrylate-based product, which is similar to acrylamide, but it is not neurotoxic, and the manufacturer claims its general level of toxicity is about 1 percent of that of the acrylamides. A second product was commercially introduced in 1981 and is similar to the acrylamides, but has eliminated the toxicity problem through increased viscosity and is, therefore, a somewhat less generally suited grout.

4.4 CEMENT/CHEMICAL MIXTURES

Very finely ground cement, known by the term "microfine cement", has been introduced to grouting technology as an alternative to the more toxic chemical grouts. The product was developed in Japan and first used in the United States on the Helms Pumped Storage Project near Fresno, California. Microfine cement can be used to permeate soils down to fine sand.

Set times for microfine cement and water mixes are measured in hours, and for many applications this is acceptable. For set times of 1 to 3 minutes a mixture of microfine cement and sodium silicate is required. Faster set times are necessary for underground water control. The cement and sodium silicate components are introduced together at the point of injection.

CHAPTER 5.

Case Study No.1: Light Rail Rapid Transit System (LRRT)
Location: Buffalo, NY
Owner: Niagara Frontier Transportation Authority (NFTA)

5.1 INTRODUCTION

The LRRT system is being constructed by the Niagara Frontier Transportation Authority (NFTA) under a Federal Grant by UMTA and sponsored by the State of New York. As work progressed, the extensive dewatering system that had been in use during most of the construction was deactivated. As a result of the geological and groundwater conditions, water inflow in excess of that allowed by the design specifications occurred in sections of the tunnels where the dewatering system has been shut down. Remedial actions were taken at that time to control the inflow. Those efforts are providing the unique opportunity to study a major ongoing program of corrective tunnel waterproofing.

During the visit in Buffalo, the group had meetings at the NFTA office with the Facility Director, and the Construction Manager for Hatch Associates Consultants, Inc. (a designer of the LRRT system), and at Goldberg, Zoino and Associates (GZA), Buffalo, NY, office with key persons in the grouting program at LRRT, and with the Project Engineer and Vice President from Hatch. At these meetings the various aspects of waterproofing measures at LRRT were discussed.

Site visits were conducted at Devalan Station and Humboldt Station and the connecting tunnel between them. These stations are located in the rock section of the LRRT system.

5.2 GEOLOGICAL AND GROUNDWATER CONDITIONS

The geological conditions of the construction were obtained through an extensive site exploration and a regional literature search.

According to the site exploration, general ground conditions were indicated as follows:

- Mostly massive to thinly bedded dolostone and dolomitic limestone of Bertie formation with small sections of Camillus Shale, nearly flat lying;
- Extensive zones and pockets of severely weathered and solutioned rock within this formation that can yield large quantities of water. Because of very poor rock quality, the zone became known as the "fractured rock zone."

The Bertie formation is generally relatively permeable with K=0.6 to 14 ft/day. Heavy flows were expected from fractured zones near the base of the formation (up to 800 ft/day). Later exploration work revealed also the presence of an artesian aquifer approximately 20 ft. thick located immediately below the invert of proposed rock tunnel over a distance of about 2 miles. The water table was defined as 6 ft. below to 14 ft. above the crown. The large scale pumping tests resulted in discharge rate of up to 0.014 cu.m/sec (2700 gal/min).

5.3 IMPACT OF GROUNDWATER CONDITIONS ON DESIGN

The presence of the fractured rock zone under approximately two miles of the proposed alignment resulted in a redesign at a higher elevation so that the tunnel would clear the fractured rock zone. Amherst Station, which was originally conceived as a tunnel opening, was redesigned as a cut-and-cover station because of inadequate rock cover that resulted from the raised alignment (the depth from the street surface to the top of fractured rock at Amherst Station is approximately 40 ft.). The station was designed as high as possible, the top of the structure coming within 5 ft. of the street surface. At this elevation the slab invert minimally penetrates the fractured rock zone.

At several other locations the tunnel alignment was also forced very close to the fractured rock because of thin rock cover. The distance from the tunnel invert to the top of the fractured rock was designed to be about 5 ft., which resulted in approximately 10 ft. between the tunnel crown and the underside of the bridge abutments (at this location, the tunnels had to pass beneath a railroad cut and the abutments to a roadway bridge over the railroad).

To ensure a minimum degree of adequate groundwater control prior to tunnel excavation, a deep well dewatering system was designed and made a part of the tunnel and station contracts. This system was designed for an estimated maximum discharge from wells and tunnel sumps of 10,000 gal/min (0.84 m3/sec).

5.4 TUNNEL ENVIRONMENTAL AND STRUCTURAL DESCRIPTION

The current first phase of an expandable system or LRRT system consists of 3 parts:

1. A one mile (1.6 km) pedestrian mall on the surface through the downtown business district;
2. Concrete double-box tunnels with a single central platform, constructed by cut-and-cover methods for a length of 1.7 mile (2.74 km) at a depth of 30-35 ft. (9.1 - 10.7 m) and subsequently drops into bedrock at a depth of 60 to 90 ft.;
3. A 3.5 mile (5.63 km) rock tunnel of 16 ft. nominal finished diameter (this part includes 5 stations). That was the TBM-driven line.

A cast-in-place concrete lining was used for the rock tunnels. The thickness of the unreinforced concrete liner was a minimum of 12 in. (305 mm) to insure a reasonable watertightness of the tunnels and to provide an adequate cover of 6 in. over the steel ribs (where those ribs were used as a primary support). The concrete for the lining was delivered to the site by concrete trucks and was pumped through "slick" lines. The maximum length of pours was set to be 150 ft. The temperature at the time of pouring was a tunnel average temperature of 53 degrees F. The concrete workability was defined as with slumps of 5 1/2 in. to 6 in., with a slump test taken from every third truck. Steel forms were used for concrete liner placement. External and internal vibration was used for placing concrete. The pouring process was supervised by the field engineer and by the constructor's superintendant. The time of the concrete setting was not less than 24 hours.

5.5 WATER INTRUSION PROBLEMS - CONSTRUCTION DEWATERING

In cut-and-cover sections of the tunnels there were no special water control measures except where waterstops were used for the tunnel roof, and regular joint waterproofing. In the rock part of the tunneling, however, the construction dewatering was done by the subcontractor, Moretrench American, Inc.

The dewatering system as constructed included five principal wells plus five supplemental wells. The system adequately controlled groundwater, except in one 300-ft. section where an unexpected aquifer was encountered that necessitated the installation of two additional deep wells.

The requirement for a treatment plant to eliminate hydrogen sulphide and to increase dissolved oxygen levels prior to discharge into surface waters was an additional innovative design feature of this project. The plant has operated continuously, and all environmental requirements were met.

The installed dewatering system provided water discharge for five stations of the ongoing project. However, two special water problems occurred during the construction, which required additional water control measures.[1]

A. Power failure

A major thunderstorm caused a city-wide electrical failure that resulted in flooding of one of the tunnels, thus the standby electrical system could not be started to maintain power to the pumps. The system was inoperative for about a day and half, which resulted in more than a 20 ft. rise in water level, which flooded the tunnels with 8 ft. of water. Two TBMs and a bucket conveyor muck-handling system were damaged. During this time, locally heavy tunnel inflows unrelated to the deep well failure further complicated the problem. It took approximately a week to dewater the tunnels after the deep well system had been restarted (supplemented by high-capacity sump pumps).

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[1] "Effect of Artesian Aquifer on Feasibility of Buffalo LRRT Project" Guertin, Flanagan, pp. 124, 125.

B. Localized heavy groundwater inflow

In early August 1980, a local heavy groundwater inflow was encountered in the inbound tunnel at station 210+00 (±). The initial rate of flow was about 4.3 gal/sec from a 300 ft. section of tunnel. The flows impeded tunnel excavation to the extent that it took approximately one month to drive the tunnel through this zone which was some three or four times longer than was typical for this project. The outbound tunnel, located 60 ft. away, which had been excavated several months earlier, was dry. Several borings were drilled and a previously undetected zone of fractured rock immediately at and just below the invert was identified.

Some fractured rock was found in the invert, but water was observed to be flowing primarily through the vertical joints that intersected an open horizontal seam. The quality of the intruding water was different from the groundwater that was being pumped from the production wells. Specifically, no hydrogen sulphide was observed, but an appreciable amount of dissolved oxygen was detected that was similar to water after a purification process. Further studies strongly suggested that the inflow may have been caused by recharge from the nearby bedrock creek bed located approximately 200 m from the localized heavy inflows. The dewatering system discharged flows into the creek.

Additional piezometers installed in the vicinity of these inflows indicated that the water levels were 0.3 - 1.0 ft. above the invert. Several options were considered for control of the inflow prior to concrete placement, including exclusion by grouting and removal by the addition of pumping capacity. Grouting was judged to be a very uncertain solution because of the unknown extent of the fractured rock zone, and a decision was therefore made to install one additional deep well. A specific capacity of about 4.3 gal/sec was used, but after several months of pumping, the well (DW-7) still failed to control all of the inflow.

Therefore, a second additional well (DW-8) was drilled and pump-tested prior to final installation. The specific capacity and transmissibility of this new well was about the same as for DW-7. The addition of well DW-8 resulted in control of the major inflow. During the removal of approximately 1.5 ft. of muck from the invert additional inflows were observed that would have interfered with the placement of concrete for the final lining. During this period the capacity of DW-8 decreased and could not be restored, and it was also observed that water levels fluctuated by about 3 ft. with rainfall. The combined effect of decreased yield of DW-8 and heavy rains resulted in continuously troublesome water inflows. As the concreting operations approached the inflow area, a drain (some 2.5 ft. wide and deep and 300 ft. long) was oonstructed in the invert to remedy the problem quickly. The drain consisted of a stone-filled trench covered with a plastic membrane. A 6.0 ft. square by 6 ft. deep sump was excavated at one end of the drain, and a pump was installed and covered with stone and a steel plate. The entire invert drainage system was then protected by a lean concrete mud mat. The drain and sump pit effectively controlled the water, and the monolithically poured liner was placed successfully and without difficulty. After completion of the lining, the drain and sump were later backfilled with a cement grout pumped under low pressure.

The following sequence of events at LRRT can be mentioned:

1. Tunnels were lined with concrete.
2. Pumps were turned off.
3. Water table rose.
4. Tunnel leaked beyond specifications.
5. Some wells were turned back on.

To reduce or eliminate the leakage, NFTA started a large grouting program. The following sections describe the grouting material and techniques employed.

5.6 GROUTING FOR WATER CONTROL

The grouting consisted of drilling a hole 1-7/8 in. in diameter through the concrete liner and subsequently injecting either a water-cement mixture or a chemical, acrylic polymer compound which on set up seals off inflows through cracks.

The grouting operations began in December 1982. Grouting records were made for every grout hole and include:

1. Volume of grout,
2. Grout type,
3. Location of hole,

4. Grout pumping rate and pressure,
5. General comments such as water inflow before and after grouting, downtime, mapping of leaking cracks, observations by the drillers with respect to drilling resistance, etc.

5.7 CHEMICAL GROUTING

Technical Grouting Services (TGS) of Hyattsville, MD, with support crews supplied by Stimm-Fitzpatrick Constructors of Buffalo, NY, was retained by NFTA to do remedial chemical grouting for water tightness in the 1C0011 Section of the rock tunnels. At the time of grouting, the concrete tunnel liner was in-place and water inflows approximately 2 to 3 orders of magnitude over specifications were experienced. It was decided by NFTA to proceed initially with chemical grouting because of the urgent need to complete this first section of the tunnel in order to permit the track-laying crew to have access.

5.8 GROUT TYPE

The only crack areas in the tunnel liner that showed any leakage have been grouted. An acrylamide chemical grout was used to control the water inflows through the shrinkage cracks in the concrete tunnel liner because it easily penetrated the shrinkage crack (having a viscosity essentially the same as water), maintained a constant viscosity during injection until immediately before setting up and had good gel time control. Once in place, the gelled grout was also considered permanent as long as the grout remained damp or in a humid environment.

This grout consists of a specialized system of two catalysts and water. The grout is a powder mixture of two organic monomers consisting of 95 percent acrylamide which will polymerize into long molecular chains, and 5 percent of a cross-linking agent which binds the acrylamide chains together. The specialized system of catalysts is used to form the gel from the monomer solution. This system consisted of triethanolamine (T) called the activator and ammonium persulfate (AP) called the initiator, which triggers the reaction. The gel time is dependent on the concentrations of AP and T used in the mixture. Varying these concentrations, gel times ranging from approximately 10 seconds to 2 minutes were used.

5.9 CHEMICAL GROUTING TECHNIQUES

Chemical grouting of the cracks was done from behind the concrete tunnel liner. Holes were drilled through the liner across and/or adjacent to the cracks depending on the amount of water flowing from the cracks. The number of holes drilled along a crack and the amount of grout pumped into each hole varied depending upon whether the leakage from the crack was stopped. Each crack was grouted starting at the highest position of that crack in the tunnel and working down. Grouting at an individual crack was stopped when there was no longer any visable leakage emanating from the crack. A red dye was mixed into the grout prior to pumping so that its travel could be traced.

The grout holes were drilled using 1-7/8 in. diameter drill steel using percussion drills. The length of the grout holes was a few inches greater than the thickness of the concrete liner. Mechanical packers were inserted into each hole for the purpose of injecting the grout behind the liner. The mechanical packer provided a positive leakproof joint between the grout hoses and the grout hole. By rotating the handle on the mechanical packer, the flexible rubber sleeve in the packer was expanded to form a seal against the wall of the grout hole, allowing the grout to be injected.

An equal volume grout pump system was used to inject the grout into the grout hole. The equal volume system consisted of two 15 gallon tanks and two pneumatically driven pumps exactly alike and operated by a common drive. Twenty-five pounds of the monomer powder grout were dissolved in 15 gallons of water in one tank. The activator and initiator were mixed at varying proportions with 15 gallons of water in the second tank. Equal volumes were pumped from both tanks into a separate discharge hose to the mechanical packer where mixing of the grout components took place. These hoses were attached to the packer using a "Y" connection. An equal volume system was used because it eliminated the problems associated with passing catalyzed grout through the pumps and discharge hoses, thus permitting the use of very short gel times and pumping for periods which greatly exceed the gel time.

5.10 CEMENT GROUTING

Cement grouting crews supplied by Stimm-Fitzpatrick Constructors of Buffalo, NY, with the support of GZA, were retained by the NFTA to do the remedial cementitious grouting for water tightness in the remaining portions of the 1C0011 section of the rock tunnels. It was decided by NFTA to see if the leaks in the tunnel liner could be stopped by the much less expensive method of cementitious grouting developed by NFTA's grouting consultant.

Cement grouting was initiated in the outbound tunnel at Sta. 2189+00, during which time the chemical grouting had been proceeding in the inbound tunnel. At the time of cement grouting in the outbound tunnel, water inflows approximately 2 to 3 times over specification were experienced.

A test section of 31 leaking cracks between Sta. 2189+00 and Sta. 2208+00 of the outbound tunnel was chosen to determine the effectiveness of the cement grouting. Flow measurements were made before and after cement grouting of these cracks. Eighty-four percent of the cracks were rendered completely dry, and the remaining 16 percent showed reductions in inflows of 60 to 75 percent after grouting.

It was decided to continue with the cement grouting in the O.B. tunnel approximately to Sta. 2216+00, with a reduced follow up grouting effort using chemical grout within this area.

5.11 CEMENT GROUTING TECHNIQUES

Cement grouting of the cracks is done from behind the concrete tunnel liner. Grout holes are drilled using 1-7/8 in. diameter drill using percussion drills and are within approximately 6 in. of a crack. The length of the grout holes is approximately 1 or 2 ft. into rock, depending on the thickness of the concrete tunnel liner. Mechanical packers are inserted into each hole for the purpose of injecting the cement grout behind the liner.

Prior to grouting, all holes are given a quick hydraulic pressure test to determine which holes will take grout. This is accomplished by injecting water through the packer for approximately 3 minutes and monitoring the amount of water and the pressure at which it is being injected.

Cement grouting is accomplished using a pneumatically driven grout plant consisting of two 70 gallon mixing tanks. A return line and a pressure gage are monitored to the packer. Grout pressures are monitored using the criteria of 1 pound per square inch (psi) per foot of cover over the tunnel. The return line is used to keep the grout from setting up in the lines, as well as to help control the grouting pressure.

The grouting of each hole is begun with a relatively thin mix, 6 parts water to 1 part cement by volume, but thickened to as much as 1.5 to 1 if the rate of grout injection is great. Type II portland cement is used because of the presence of sulfates in the ground water.

The number of holes drilled along a crack depends on whether leakage from the crack was stopped after grouting. If the cement grout is injected at a rapid rate into the grout hole, the grouting pressure is reduced and the grout mix thickened. The amount of grout pumped into each grout hole is arbitrarily limited to 50 bags in an effort to minimize costs. Once the grout is allowed to set up in these holes, grouting is resumed and the holes are usually brought to refusal.

Grouting operations have begun on tunnel Contract 1C0031. However, this tunnel contract presently does not have inflows because of the lowered water table at the LaSalle Station construction. Nevertheless, grouting of the cracks is being done using the procedures and experience gained by grouting in Contract 1C0011. Cracks are grouted where they show staining (from previous inflows) and where drill holes took appreciable quantities of water when pressure tested.

5.12 GROUTING RESULTS

Inflow measurements were done at given locations by using a weir and calibrated bucket. The measurements were repeated until successive trials, at the same location, indicated nearly identical flows.

Table 5.1 presents, for Contract 1C0011, measured inflows before and after grouting. Inflows on the northern portion of the contract have not been measured after grouting due to the temporarily lowered water table for the construction of the LaSalle Station, therefore making any measurements taken prior to recovery of water table elevation unrepresentative of the ultimate

TABLE 5.1 TUNNEL INFLOW MEASUREMENTS AT LRRT SYSTEM CONSTRUCTION

STATION	SECTION LENGTH (FT)	INFLOWS (GALLONS/MIN) BEFORE GROUTING	INFLOWS (GALLONS/MIN) AFTER GROUTING	ALLOWABLE INFLOW (GALLONS/MIN)	% REDUCTION OF WATER INFLOW DUE TO GROUTING (April 1984)	MEETS WATER TIGHTNESS SPECIFICATION
2195 + 23 to 2216 + 65 Inbound	2142	129.0	0.268	0.37	99.8	YES
2221 + 50 to 2235 + 00 Inbound	1343	48.6	0.09	0.23	99.8	YES
2195 + 23 to 2216 + 65 Outbound	2142	77.7	0.24	0.37	99.7	YES
*2221 + 60 to 2234 + 00 Outbound	1240	11.3	0.684	0.22	93.9	NO

* Inflow over spec is thought to be due to the flow of construction water coming from the north.

Note: The allowable inflow as stated in Section 03300, Paragraph 3.12 water tightness is 0.005 gallons/day/ft^2 of tunnel lines over a 3000 ft. length of tunnel.

inflow conditions. When the LaSalle Station construction deep well system is deactivated, GZA will complete the inflow measurements in this area.

Table 5.1 generally indicates that in Contract 1C0011 grouting has reduced seepage flows by more than 99 percent, and inflow specifications have been achieved. One section remains slightly over the allowable limit, i.e., less than 0.5 gallons per minute over a 1200 ft. section of tunnel. However, an important and possibly major contributor to this inflow, roughly equivalent to a flow of only 2 quarts over a quarter of a mile, is the invert flushing associated with the current construction of the adjacent station. On completion of the flushing discharge, now easily accomodated by the permanent sumps, inflows will be remeasured for conformance to specifications.

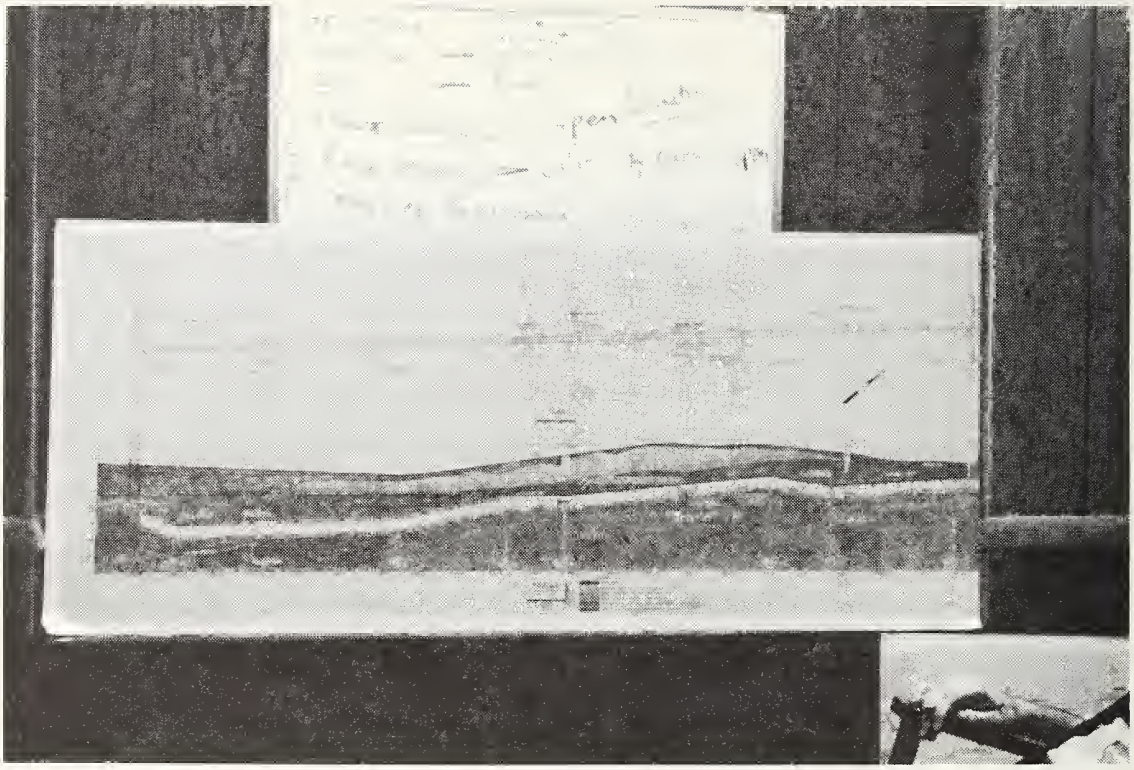


FIGURE 5.1 LRRT LINE PROFILE

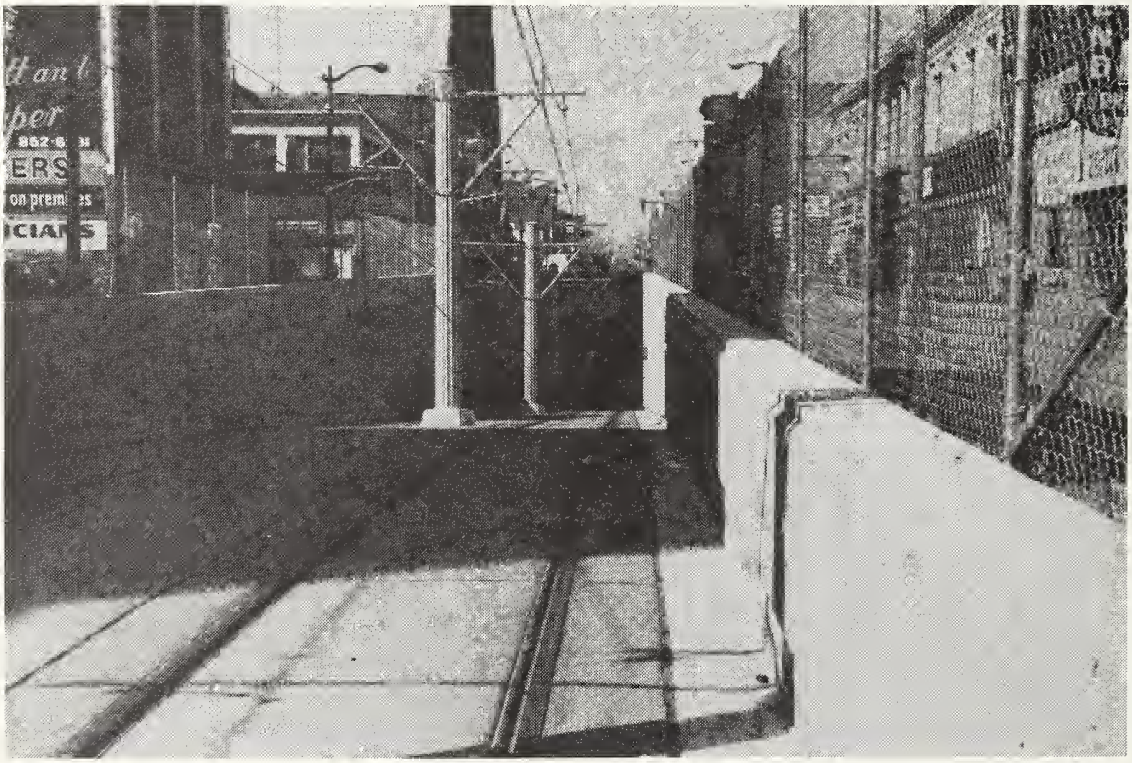


FIGURE 5.2 PORTAL OF LRRT LINE

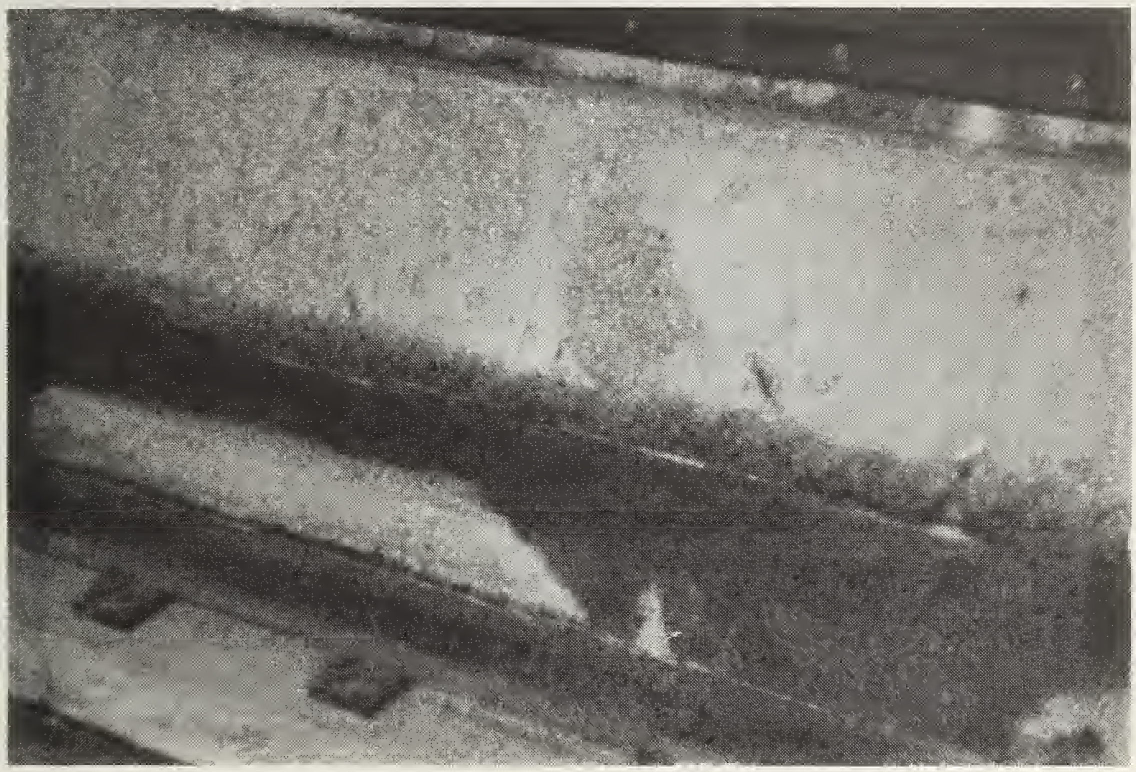


FIGURE 5.3 LEAKS ONTO TRACKBED

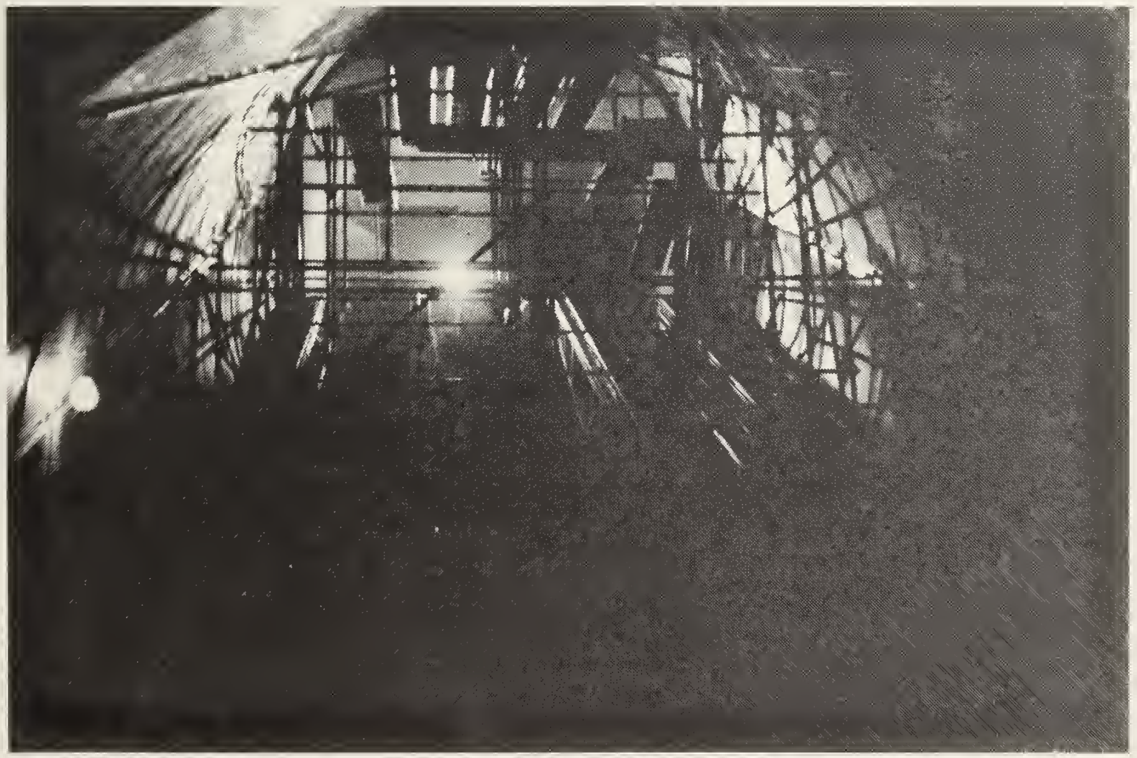


FIGURE 5.4 CONSTRUCTION VIEW IN HUMBOLT STATION

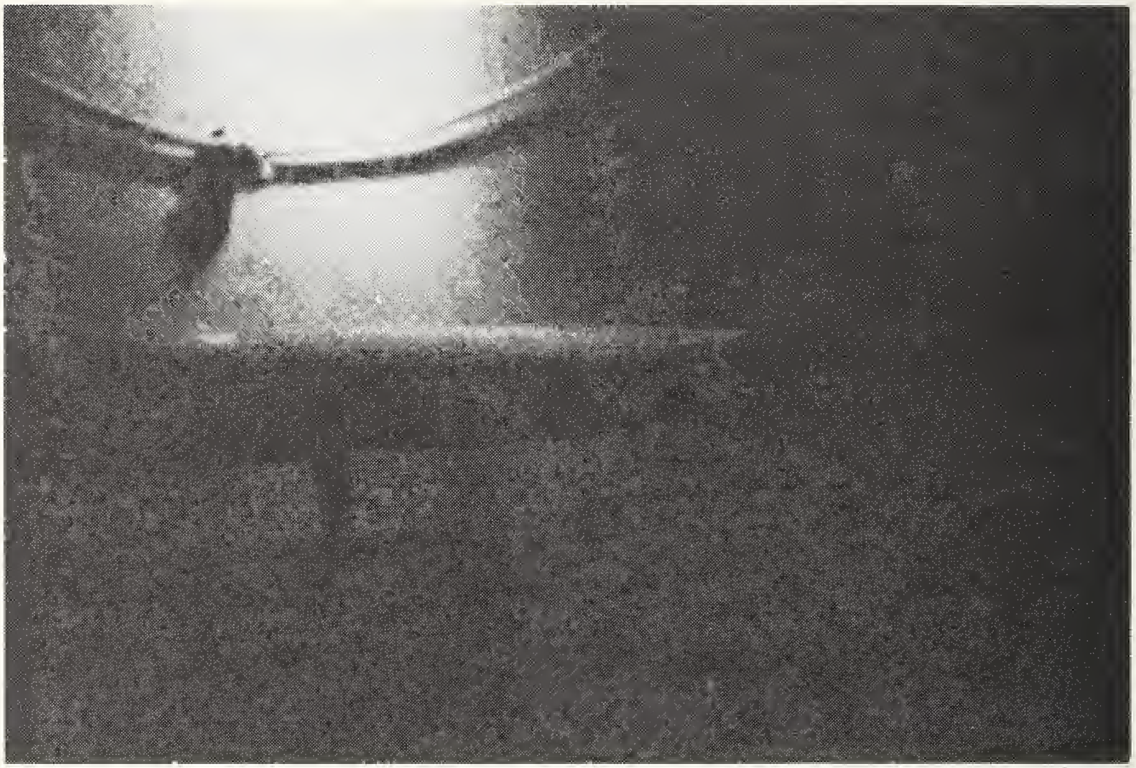


FIGURE 5.5 WATER PUMPING IN THE TUNNEL OF HUMBOLT STATION

CHAPTER 6.

Case Study No. 2: Metropolitan Atlanta Rapid Transit Authority (MARTA)
Location: Atlanta, GA
Owner: MARTA

6.1 INTRODUCTION

Case Study No.2 investigated water intrusion problems in the Rapid Transit Subway System in Atlanta, GA, which is owned and operated by the Metropolitan Atlanta Rapid Transit Authority (MARTA).

A site-visit team collected information that was obtained through meetings with the system's representatives and through technical visits to tunnel construction sites and operating subway stations.

Information collected related to:

1. Basic design for groundwater control;
2. Construction dewatering (grouting, pumping);
3. Construction waterproofing (joint sealing);
4. The concrete pouring and curing processes;
5. Major leaks and remedial measures applied.

A tour on the MARTA Subway System, including the construction site of the North Line extension, showed the basic remedial measures applied for stopping water inflow. Tunnel lining construction, joint sealing, as well as concrete pouring and curing processes were of particular interest. It is believed that these processes contributed tremendously to the structural quality observed in the tunnels.

6.2 GENERAL INFORMATION

The MARTA Subway System consists of two major lines, the South-North Line and the West-East Line (see Figure 6.1).

The first stations were opened in 1979, and almost immediately the subway system began having water leaks. Although most tunnels operate with limited quantities of water inflow, there is a system for collecting and removing the intruding water. In spite of the system, the amount of water intrusion on the MARTA Subway System exceeds the allowable level. To correct the situation, MARTA has a contract for repairing approximately 3000 ft. of leaks in various existing tunnels and stations.

6.3 TUNNEL ENVIRONMENTAL AND STRUCTURAL DESCRIPTION

6.3.1 Geological and Groundwater Conditions

General geological conditions are characterized by fill and residual soils to about a 60-foot depth underlaid by excellent quality gneissic rocks. Tunnel types include soft ground, mixed-face and rock.

Ground water was expected along soil-rock transition, and well-point dewatering was recommended for shallow tunnel sections. Tunnel sections over 20 ft. below rock surface were expected to experience minimal amounts of water intrusion.

6.3.2 Structural Description

A. Types of underground structures and methods of excavation

MARTA has used circular, box and horseshoe shapes in tunnel design. The most recent design utilized a horseshoe shape in areas where tunneling was done, and a box shape where cut-and-cover construction methods were used.

Tables 6.1 and 6.2 contain a description of tunnel and station structures. The cut-and-cover sections of tunnels as well as vents, shafts and entrance ways were excluded.

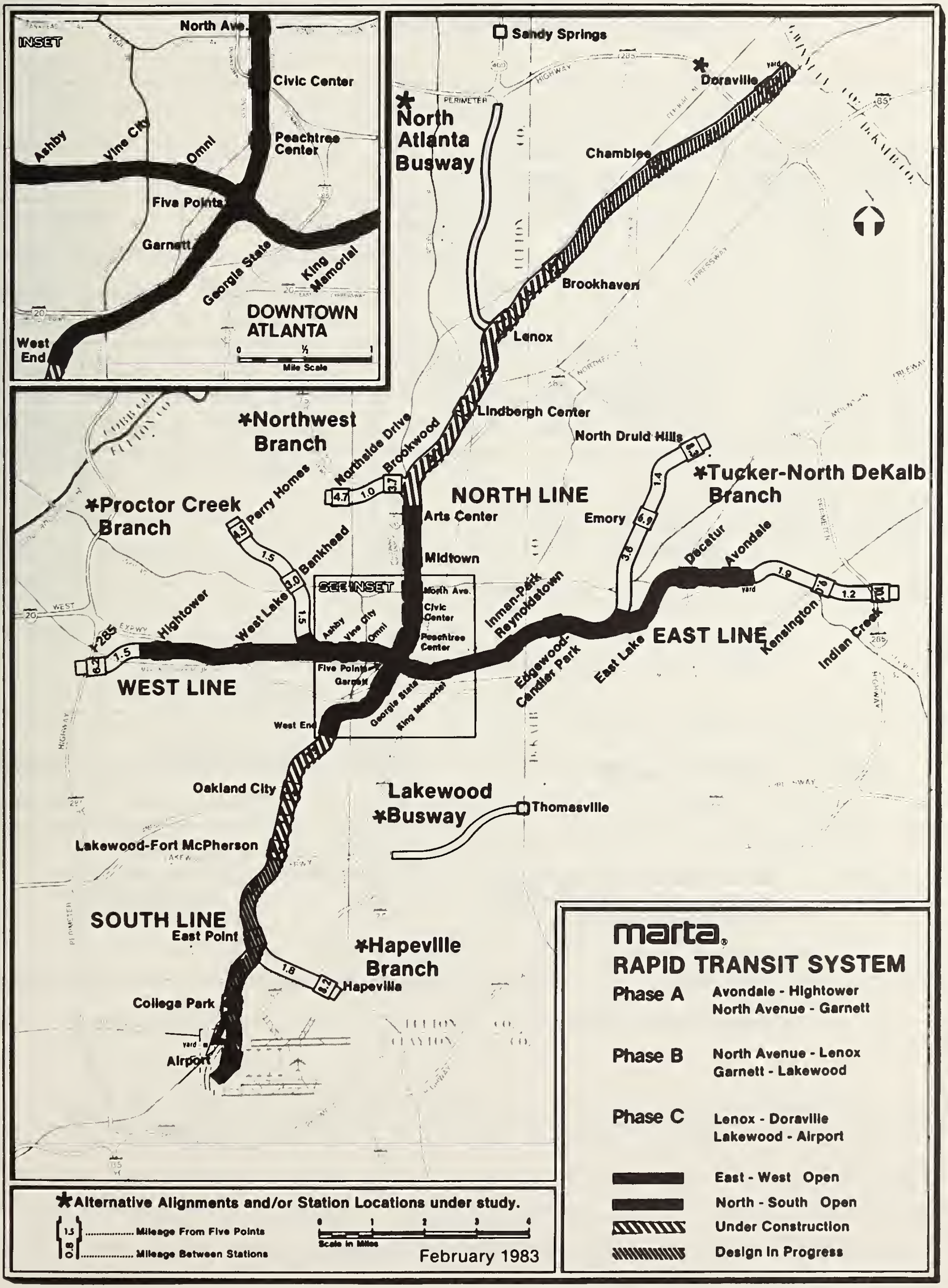


FIGURE 6.1 MARTA RAPID TRANSIT SYSTEM

TABLE 6.1 TUNNEL PROFILES - PHYSICAL SIZE

Type of Ground	Method of Excavation	Shape	Face Area Sq.Ft.	Size				
				Length	Height		Width	
					Type A	Type B	Type A	Type B
Rock	Drill and Blast	Circular	314	2490'	20'0"	20'6"	20'0"	20'6"
		horseshoe	356		17'3"	18'9"	17.3"	18'9"
		station	2450	770'	42'0"	43'6"	60'0"	61'6"
Soft & mixed face	Shield driven	Circular	626					
		horseshoe	1291					
		station						

TABLE 6.2 TUNNEL PROFILES - TYPES OF FINAL SUPPORT

Types	Methods of Excavation	Types of Final Support	
		A, C	B, D
A, C	Both tubes excavated as one double arch chamber with RCIP concrete pillar	RCIP Concrete	Rock bolts and shotcrete
B, C	Excavated as twin tubes		

B. Lining Structures

The MARTA subway structures (tunnels and stations) were built in rock, soft soils and mixed-face grounds. No uniform lining design method has been universally accepted because of variable tunnel sizes and ground conditions. Lining thickness has also varied with construction technique. Recent tunnels which have cast-in-place (CIP) concrete lining generally have a one-foot thick wall and ceiling section, while shotcrete-lined tunnels have a minimum lining thickness of four inches. Cut-and-cover structure wall thickness varied from 2 ft. 0 in. to 3 ft. 6 in., while ceiling thickness varied from 3 ft. 0 in. to 5 ft. 0 in. The distance from top of rail to bottom of underlying slab varied from 4 ft. 5 in. to 5 ft. 2 in. Thickness of cut-and cover sections varies with depth of cover.

Table 6.3 represents all types of primary support and final lining in rock, soft and mixed-face tunnels and station covers at MARTA Subway System.

In the latest tunnel contract, the MARTA used cast-in-place and shotcrete as tunnel liner materials, although steel has been used in the past.

C. Concrete Properties

Cast-in-place concrete lining placed against rock surfaces in mined excavation and cut-and-cover construction concrete were both Class 4000 psi portland cement concrete with 1-1/2 in. maximum size aggregate. Slump of concrete was 5 in. and was tested in accordance with American Society for Testing Materials (ASTM) C143. Air entraining agents as specified in ASTM C260 and accelerators specified in ASTM C494 were allowed. Admixtures containing chloride were prohibited. Coarse aggregate was granite having a specific gravity of not less than 2.7 and conforming to Georgia Department of Transportation (GA DOT) Section 800, Group I Class A. Fine aggregate was natural sand conforming to GA DOT article 801.02.

Shotcrete used to line tunnel walls was a portland cement concrete, containing aggregate up to one inch in size, with an approved accelerator, if required, applied from a spray nozzle by means of compressed air. The maximum accelerator allowed was 2 percent by weight of cement. The shotcrete mix was designed to develop minimum compressive strength progressively as follows:

TABLE 6.3 TUNNEL PROFILES - TYPES OF LINING STRUCTURES

Type of Ground	Type of Support	Types of Lining Structures	
		Tunnels	Station Caverns
Rock	Primary	Rock bolts 10' to 20' long at 5' x 5' pattern (most common) or as required	Rock bolts 10' to 20' long at 5' x 5' pattern (most common) or as required
	Final	4" of shortcrete in majority or rock tunnels or 12" RCIP concrete	4" of shotcrete in portion of station walls or 2'11" to 3'6" RCIP concrete in arch walls; with exposed rock; 4" shotcrete or 9" RCIP concrete
Soft and mixed-face	Primary	No primary support other than shield	RCIP concrete
	Final	Liner plates installed with shield advance - for tunnels with circular shapes	RCIP concrete

1. In 8 hours - 800 psi;
2. In 72 hours - 2000 psi;
3. In 28 days - 4000 psi.

Aggregates and accelerating admixtures were the same as defined for cast-in-place concrete. Actual mix design was developed by the contractor and approved by the engineer. This design was adjusted as field conditions required.

Concrete was pumped through slick tubes directly from the concrete truck mixers that arrived at the site in 15 minute intervals. It was pumped continuously in level layers of a thickness that could be properly consolidated. The length of pour of cast-in-place sections varied with an average of 50 ft. The temperature at the time of pouring ranged from 40 degrees F. to 85 degrees F. The pouring process was supervised by MARTA general engineering consultants - Parsons, Brinckerhoff, Quade and Douglas, Inc., and Tudor Engineering Company. During curing, concrete was covered with a double thickness burlap sheet, laid directly on the concrete and kept wet at all times. Temperature and moisture were controlled for not less than seven days. Forms for cast-in-place tunnel were removed when concrete reached 25 percent of the indicated 28 day compressive strength, but not sooner than 24 hours after placement.

To insure quality control, the concrete plant was approved by MARTA. The concrete supervisor must have a minimum of five years experience in placing, consolidating and curing portland cement concrete in structures similar to those under construction, with two years in responsible charge of such work. The concrete pumping plant conformed to the recommendations of the American Concrete Institute (ACI). Before cast-in-place concrete was placed, all surfaces were prepared for concrete, and framework and reinforcement were inspected. During the concrete pour, samples of ingredients and mixed concrete were taken and tested. Mixed concrete was tested for air content, slump and compression.

For each 150 cubic yards the contractor furnished three molds conforming to ASTM C470 for casting test specimens in accordance with ASTM C39 and ASTM C94, Section 16.

6.4 TUNNEL CONSTRUCTION METHODS RELATED TO WATER CONTROL

No unusual steps were taken during construction to prevent future water problems. The usual inspections of waterproofing techniques were done. A hydrostatic pressure relief system consisting of wall drains and weep holes in specified patterns was installed in the tunnels. Nevertheless, during the construction of tunnels and stations and later, during their operation, numerous water leaks were discovered. The new stations began having structural leaks through concrete floors, walls and ceilings almost from the day they were opened in 1979.

6.5 MAJOR LEAK LOCATIONS AND THEIR DETRIMENTAL EFFECTS IN TUNNELS AND STATIONS

The site visit team explored the tunnel leak locations during the time of its visit in May 1984.

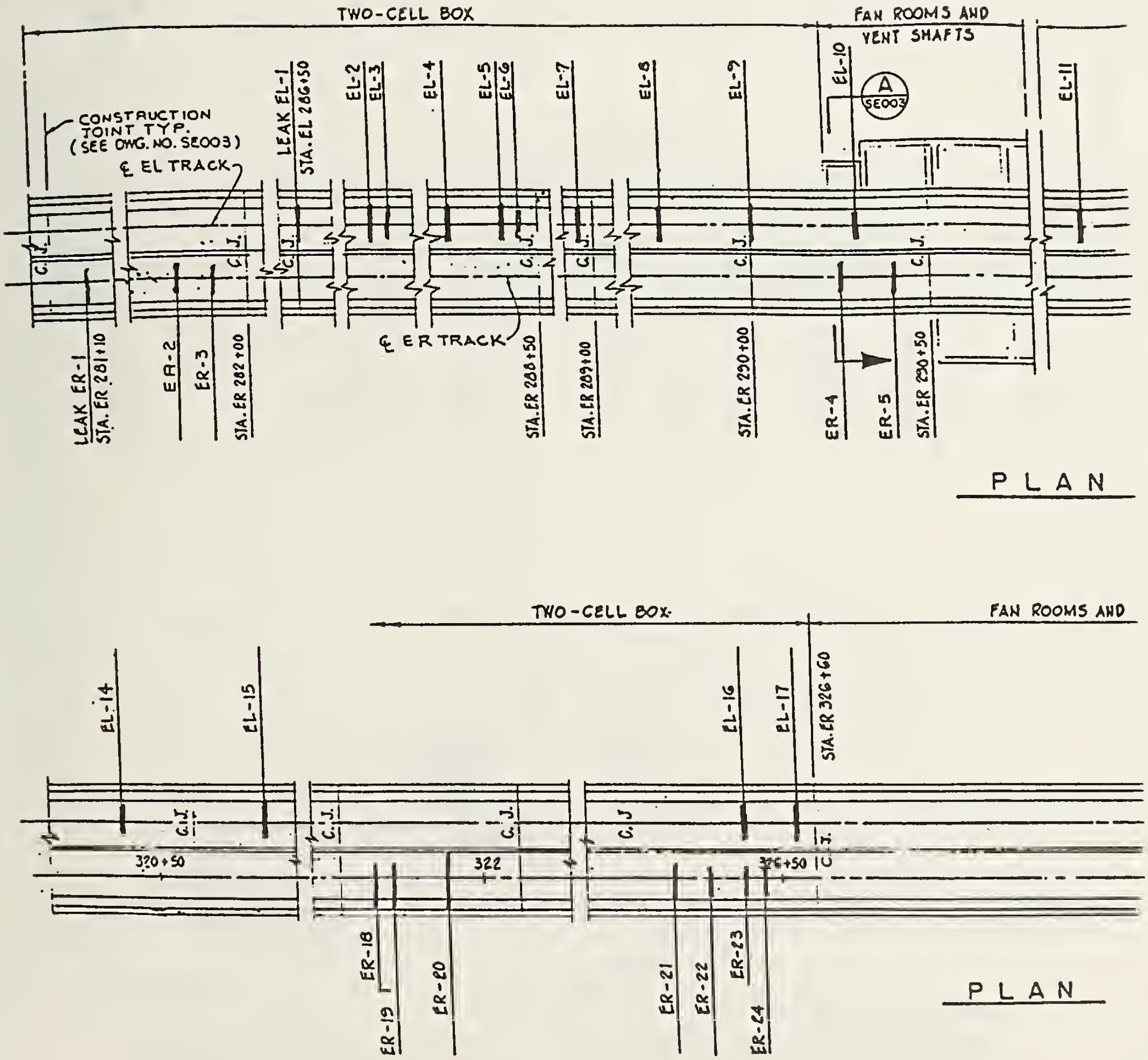
It was stated that the leakage paths occurred in radial directions only. There were no longitudinal leaks. The majority of leaks have taken place through concrete lining and not through the construction joints. This would indicate that the longitudinal shrinkage of concrete is a major factor which contributed to the appearance of numerous radial cracks in tunnel lining.

Figures 6.2 and 6.3 show the number of leak locations. As can be seen, the frequency of leaks at some tunnel segments reaches a magnitude of 15-20 leaks per 100 ft.

Figure 6.4 shows typical water leaks. The leakage problems exist for both shotcrete and CIP concrete walls.

Figure 6.5 demonstrates typical leaks through the station roof. This type of leakage results in significant deterioration of both structural and architectural elements of the stations. It also has a deteriorative effect on functional components of a subway system. For example, the stray currents seek the path of water or dampness, thereby concentrating electrochemical attacks on rails, which results in severe corrosion of rail structures.

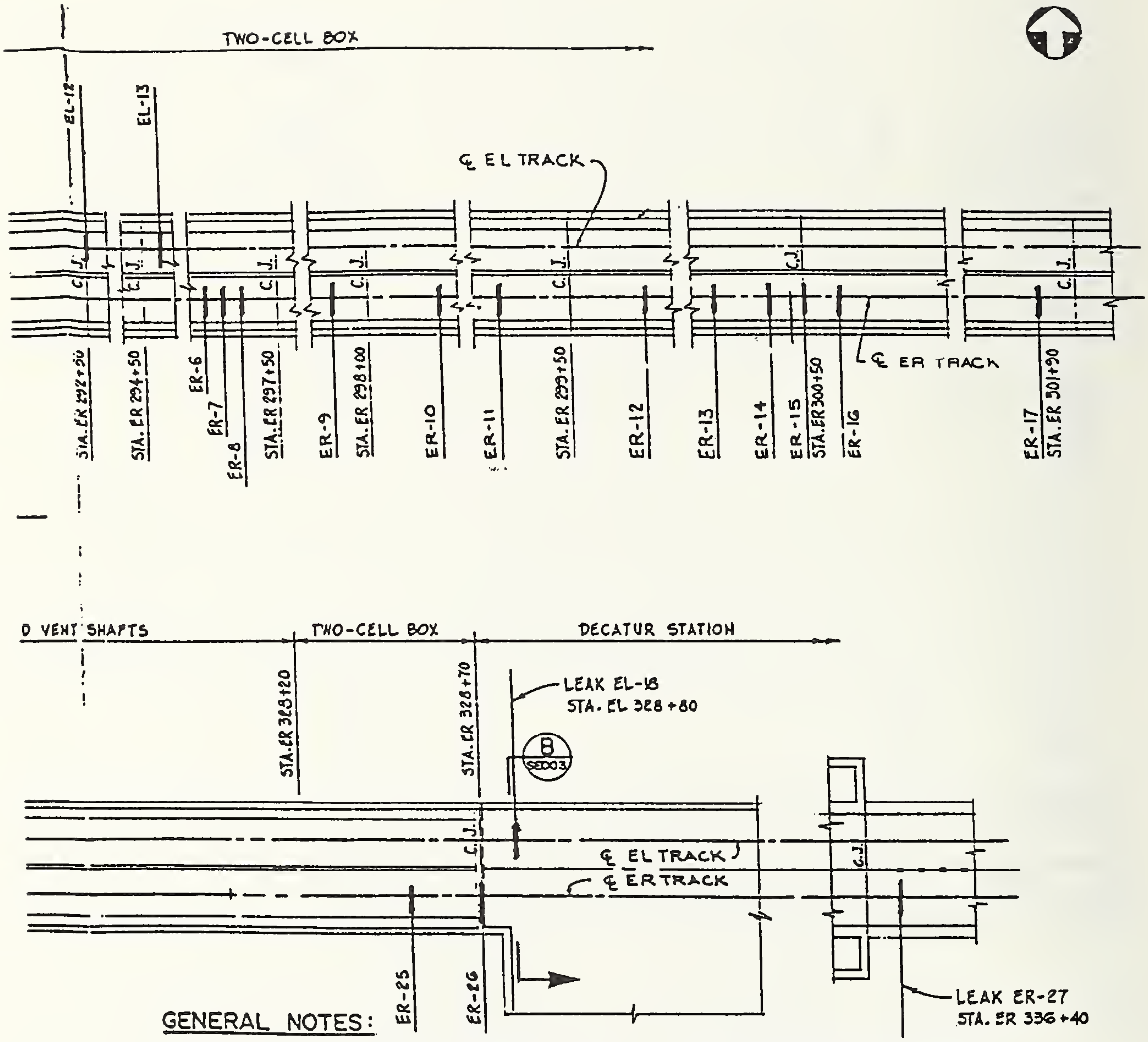
The steel inserts which are embedded in the concrete second pour, and which hold the direct fixation fasteners (DFF) in place, were rusting badly. These inserts would be almost impossible to replace.



NOTES:

1. FOR TWO-CELL BOX SEE DWG. NO SE003.
2. SEE TABLE I & II DWG. SE004 FOR LEAK LENGTHS.
3. UNLESS NOTED OTHERWISE ALL LEAK LENGHTS ARE TO BE TAKEN AS SYMMETRICAL ABOUT CENTER LINE OF TRACK.

FIGURE 6.2 EAST LINE SUBWAY STRUCTURE - LEAK LOCATIONS



GENERAL NOTES:

1. LEAK LOCATION STATIONING FOR SUBWAY ROOFS AS SHOWN ON THESE PLANS IS APPROXIMATE AND FOR INFORMATION ONLY. ACTUAL LOCATION OF LEAKS AND LENGTH OF LEAKS TO BE FIXED HAS BEEN MARKED WITH YELLOW MARKING PAINT ON THE WALLS ADJACENT TO THE LEAKS IN THE ROOF. CONTRACTOR WILL VERIFY THESE LEAKS IN THE FIELD WITH THE ENGINEER BEFORE STARTING WORK ON THEM.

2. LEAK LOCATION STATIONING FOR WALLS OF INTERLINE CONNECTOR ARE APPROXIMATE AND ARE NOT MARKED IN THE FIELD. CONTRACTOR WILL VERIFY THE LEAKS IN THE FIELD, MARK THEM APPROXIMATELY AND COORDINATE THEM WITH THE ENGINEER FOR APPROVAL OF LOCATIONS BEFORE STARTING WORK ON THEM.

3. RAILS AND COVERBOARD FOR THE 3RD RAIL WILL BE PROPERLY PROTECTED FROM ANY SPILLAGE AS A RESULT OF LEAK REPAIRS.

4. DRAINS AND CATCH BASINS WILL BE FULLY PROTECTED AGAINST ANY POSSIBLE CLOGGING DUE TO CONSTRUCTION OPERATIONS

◊1

FIGURE 6.2 EAST LINE SUBWAY STRUCTURE - LEAK LOCATIONS (CONT.)

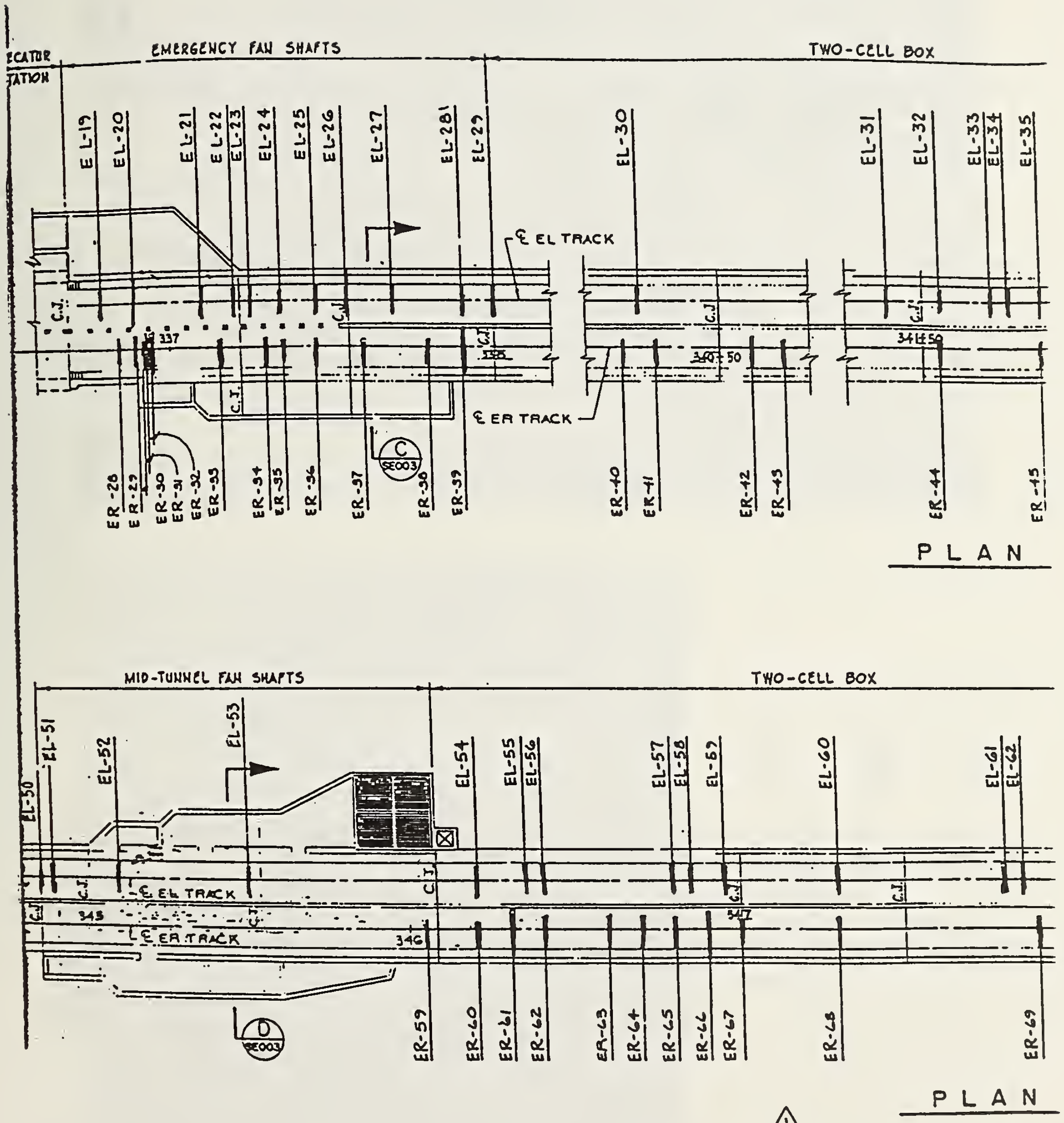
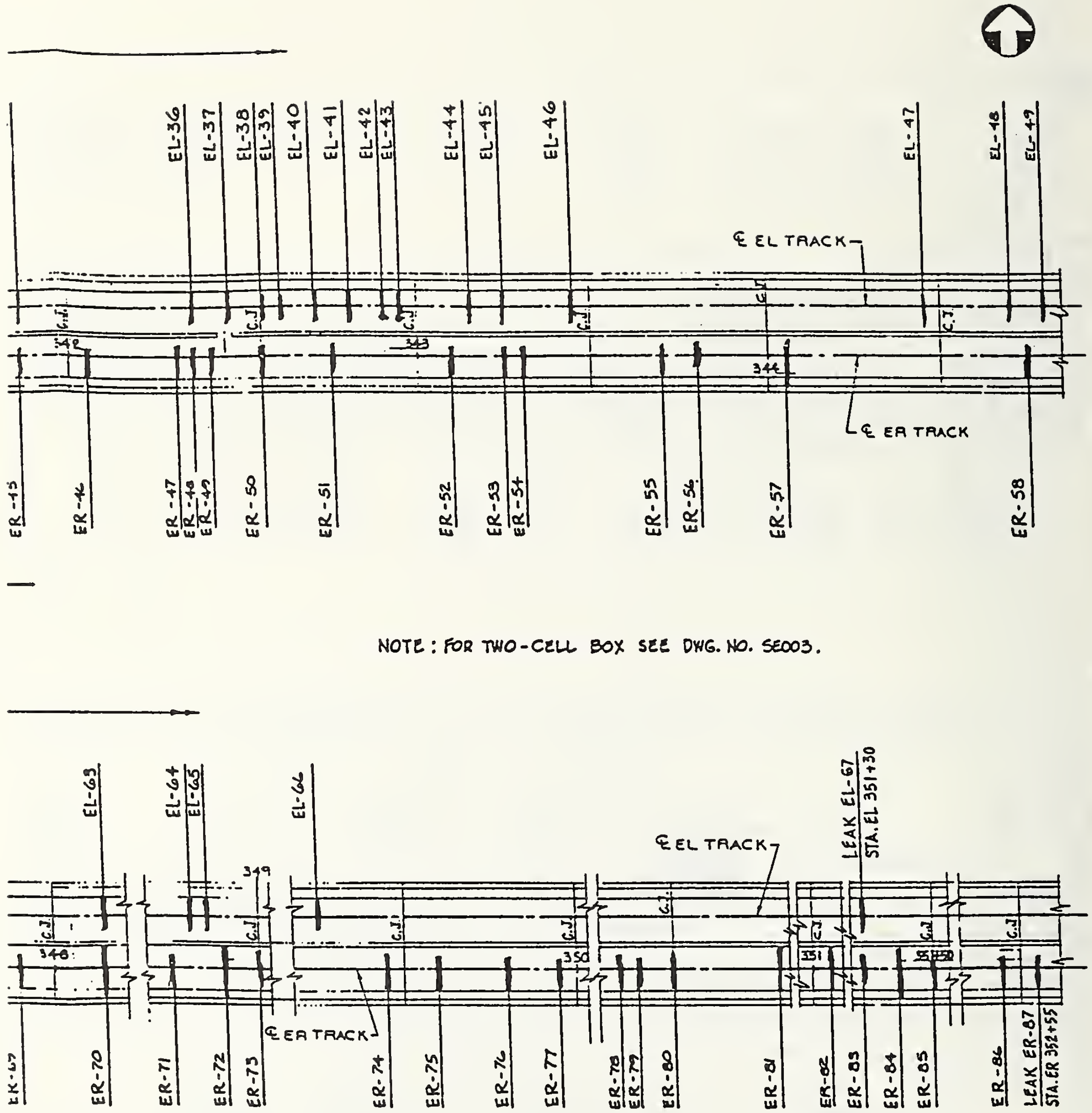


FIGURE 6.3 EAST LINE SUBWAY STRUCTURE - LEAK LOCATIONS



NOTE: FOR TWO-CELL BOX SEE DWG. NO. SE003.

FIGURE 6.3 EAST LINE SUBWAY STRUCTURE - LEAK LOCATIONS (CONT.)

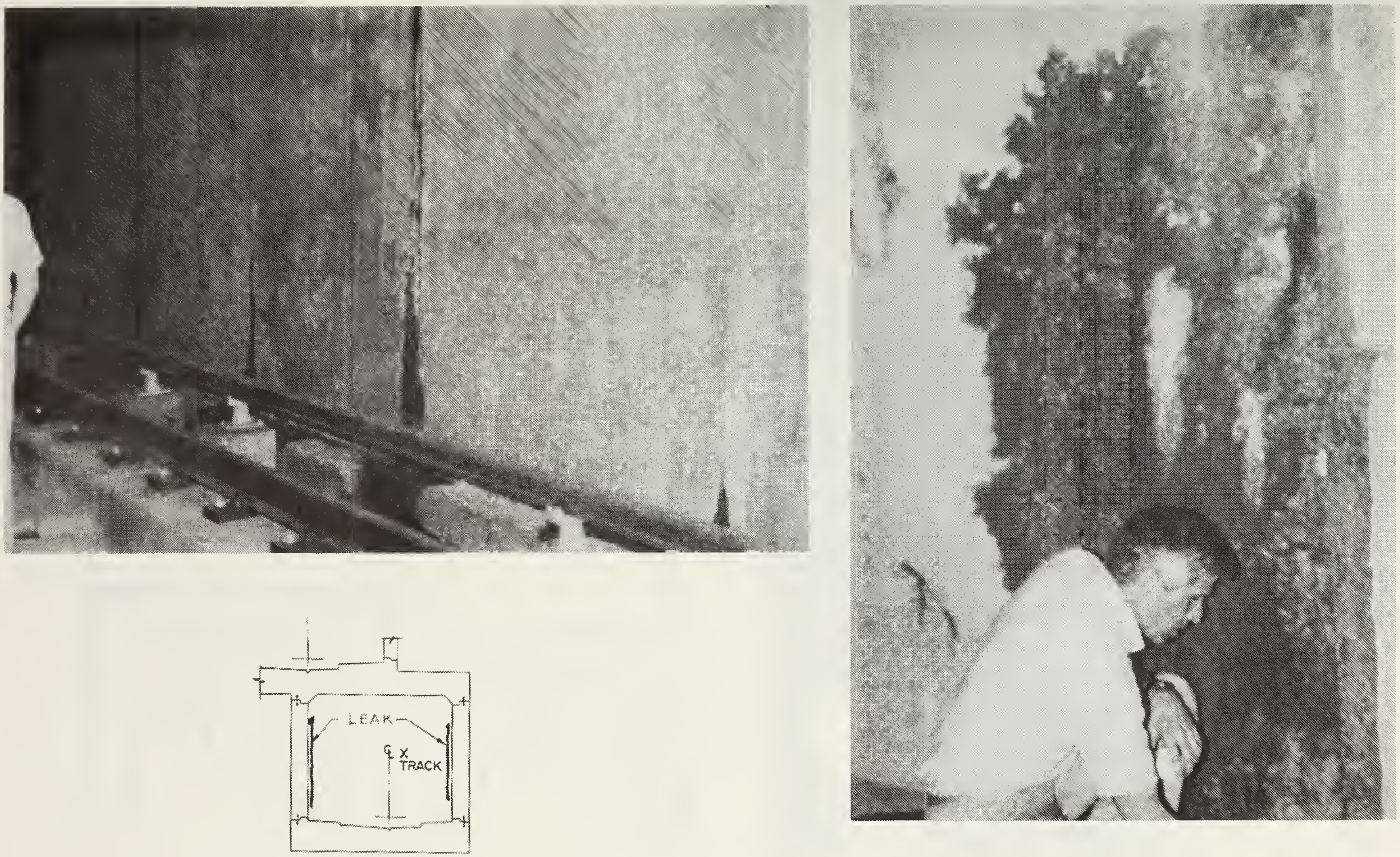


FIGURE 6.4 WATER INFILTRATION THROUGH THE WALLS

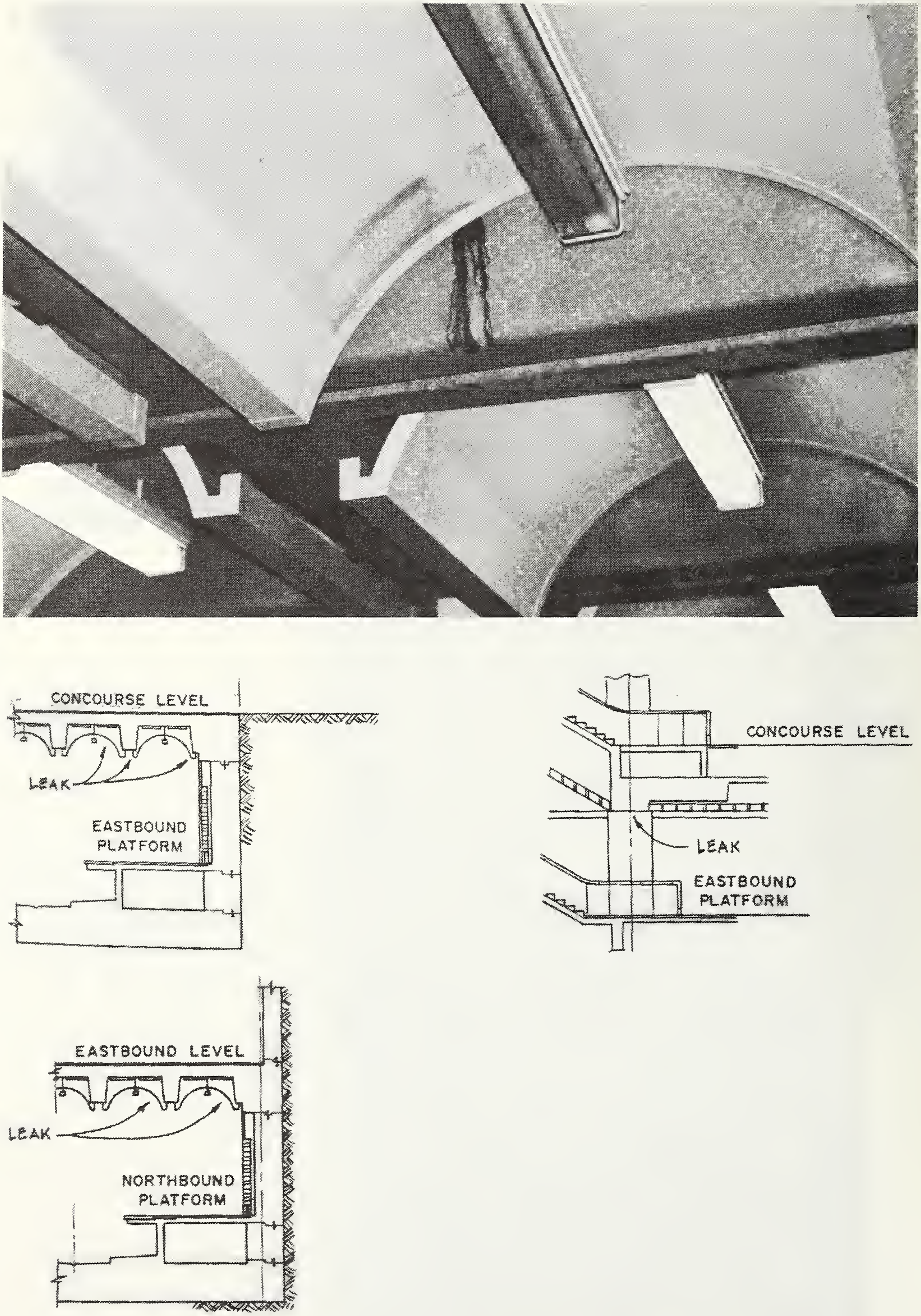


FIGURE 6.5 WATER INFILTRATION THROUGH THE STATION ROOF

The fasteners themselves were also rusting badly along with their bolts and rail clips. The rails were rusting prematurely. At some locations, the intruded water had a high sulphate content (determined in a subsequent water analysis of that location) which caused the deterioration of the concrete.

Another problem associated with leakage is the unsafe condition of pedestrian walkways.

In some locations water was dripping through the station roof, and temporary emergency measures had to be taken to alleviate the problem (Figure 6.6).

Figures 6.7 and 6.8 demonstrate various types of leaks and their locations in the MARTA Subway System. Figure 6.7 shows numerous leaks through the concrete ceiling of "Five Point" Station. Figure 6.8 shows numerous leaks in West Line tunnels where locations of leaks were mainly through the concrete walls and ceilings in different cross-sections of tunnels.

6.6 REMEDIAL MEASURES FOR WATER CONTROL

6.6.1 In-House Remedial Measures

The major in-house remedial measures for water control and waterproofing at the MARTA Subway System depended on locations of leaks and their intensity, or the amount of water intrusion.

The following measures were applied:

- Intercepting and collecting the water flow and channeling it to the pumps by means of galvanized steel plates installed directly against water leaks, thereby diverting wall and ceiling water leaks from rail structures;
- Installation of steel lining consisting of concrete arches with steel pans, for diverting the water (this measure was taken at construction time as well as during post-construction maintenance);
- For many leaks that were emerging from the base of the emergency cat walk, "toe bench cutting" was used. This procedure entails cutting a small trough adjacent to all second pours that were lower than the

FIGURE 6.6 SAFETY HAZARD DUE TO WATER INTRUSION THROUGH STATION CEILING

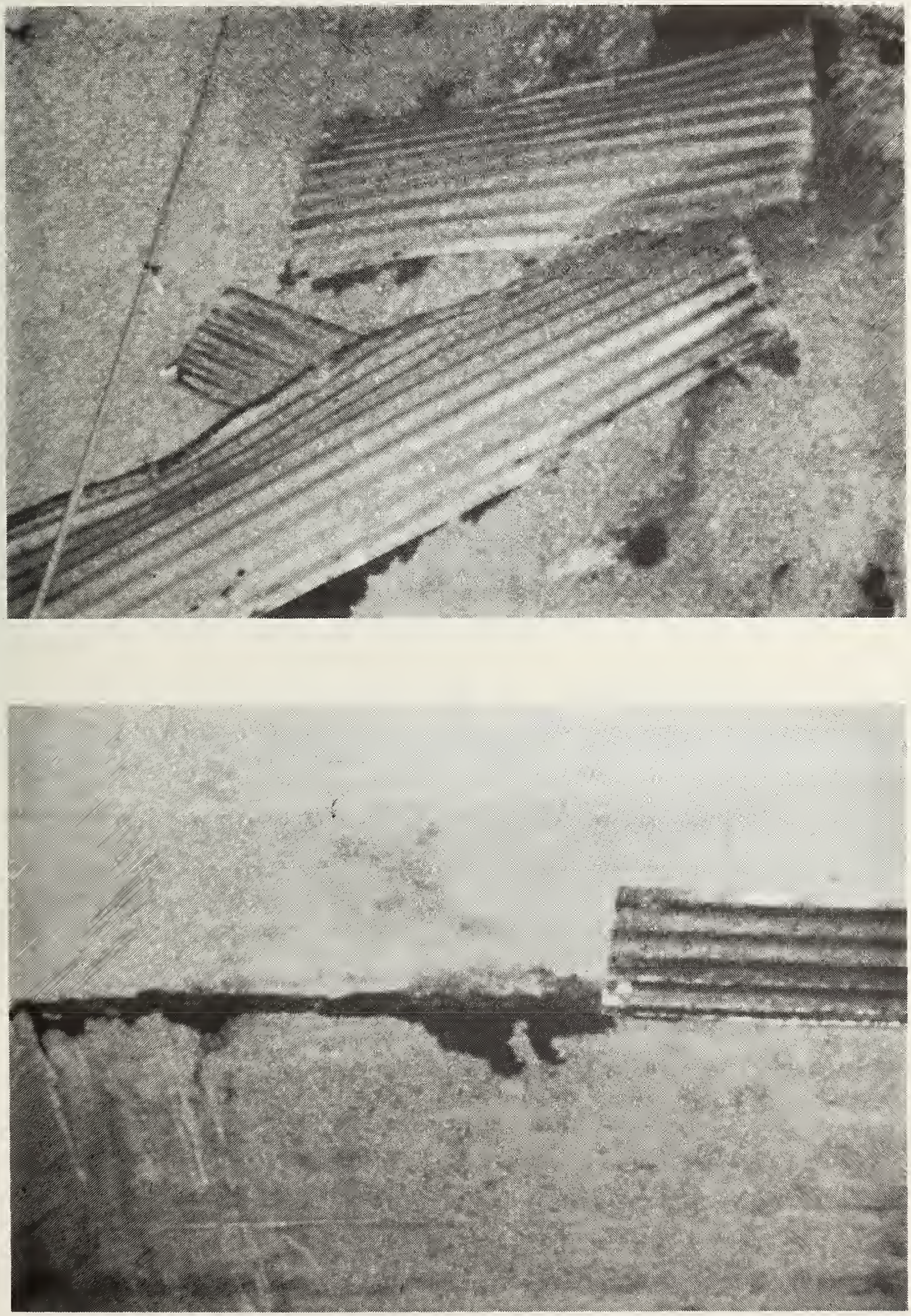


FIGURE 6.7 LEAKS AT FIVE POINT STATION

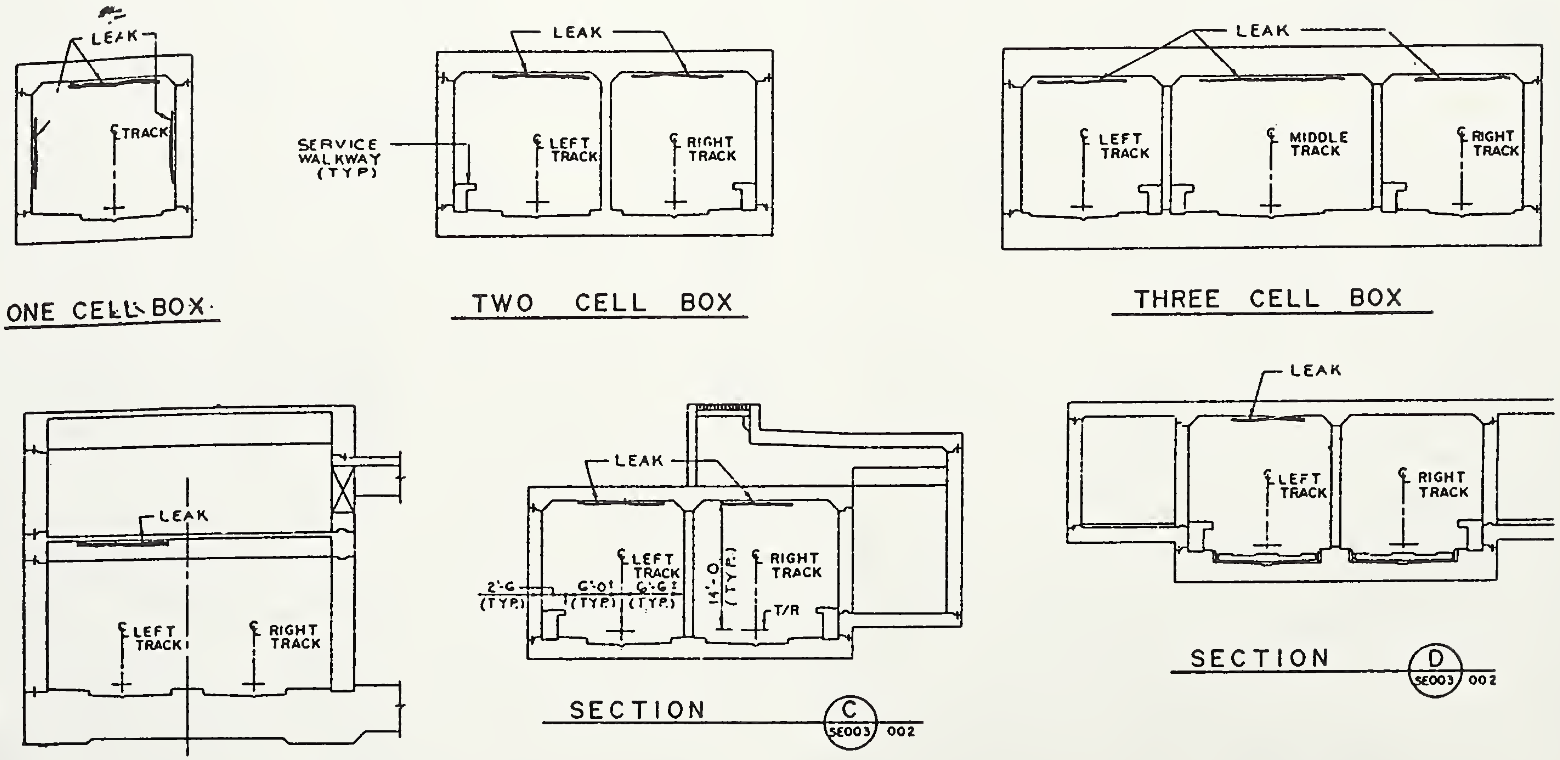


FIGURE 6.8 LEAKS AT SUBWAY STRUCTURES IN WEST LINE

adjacent "toe benches". The trough was cut about 2 in. wide and 1-1/2 in. deep and run to the nearest drainage chase between second pours. The leaking water would then go into an undertrack drain.

6.6.2 Tunnel Ceiling Leak Repairs by Contracted Service

All of the in-house remedial measures were not sufficient to control the water inflow. In some cases the water intrusion exceeded 600 gallons of water per day. To correct the situation a contract was executed to seal leaks in three stations and in 2,733 ft. of tunnel.

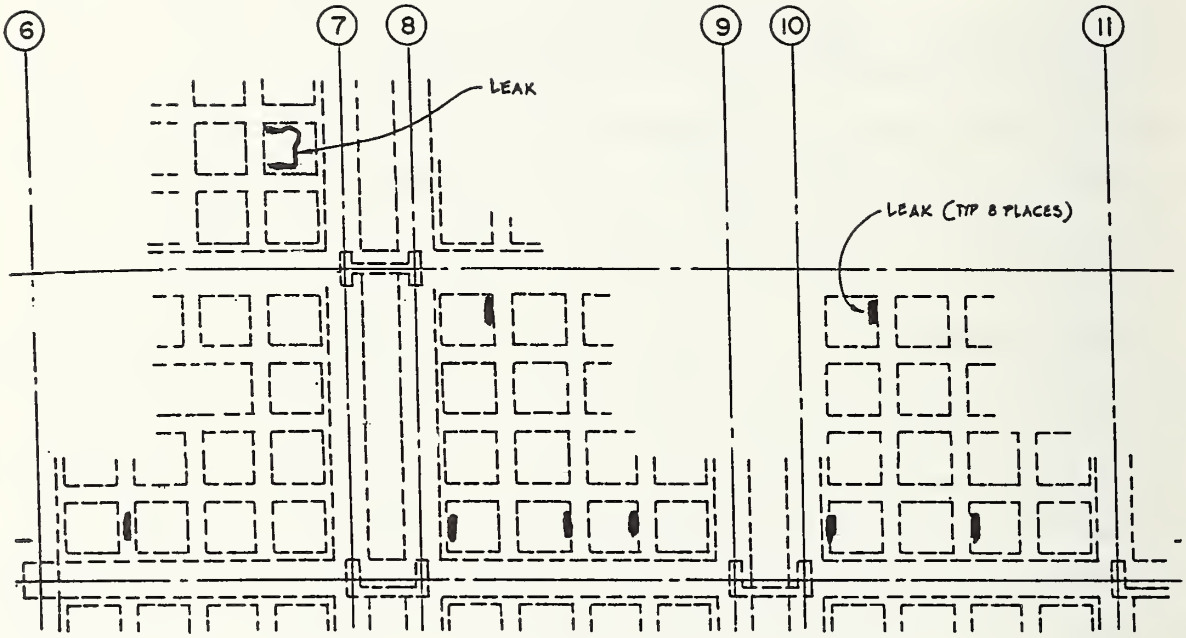
Under the contract, the major leak locations were traced and registered for future treatment first. The results were then represented in a set of drawings, "Major Leakage Locations on MARTA Subway Lines and Their Repair," with a corresponding manual (see Figure 6.9). The manual and the drawings were used as a basic guideline for water intrusion treatment at MARTA subway lines. The contractor was required to make the recommendations for the products and methods to be used, subject to MARTA's approval and with the warranty for three years of work performed.

The contractor started repair work on the tunnel ceiling leak in 1982. It was decided not to seal the entire crack length across the ceilings and walls but rather to seal only a 10 ft. width of crack over the track. The area over the catwalk and the third rail cover board was to be protected, but the containment (rather than diversion) of the water caused leaks to occur at a heretofore nonleaking crack. At the same time, the containment cost would be reduced. The price for similar sealing in stations was approximately $30.00 per foot. A summary of contractual considerations is as follows:

A. Quantities and Costs

1. East Line - 1,582' at $43.66/LF = $69,070.12
2. West Line - 436' at $46.2/LF = $20,160.64
3. South Line/Connector -
   715' at $42.66/LF = $30,501.90

$119,732.66



PLAN

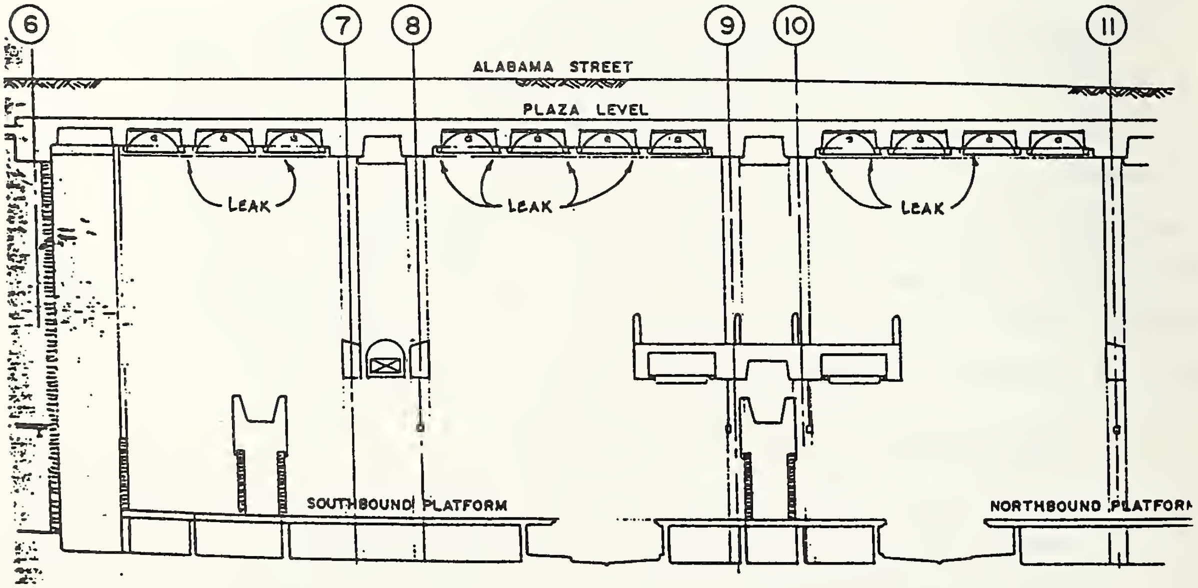


FIGURE 6.9 INTERCEPTING OF LEAKAGE (REMEDIAL MEASURES)

The disparities are due to the following:

1. The East Line had a more tightly bunched set of cracks, as well as a higher total quantity; therefore, set up and travel time was reduced.
2. The Interline Connector was not used during the day, therefore overtime rates were not applicable.
3. The West Line cracks were farther apart and the quantity was smaller.

It is interesting to note that the time of year of the surveys impacted the number of leaking cracks. The initial survey was done in February 1982, and another was done the following summer. Cracks in the East Line tunnel were significantly fewer during the summer.

The costs per linear foot included overhead, labor, supervision, tools, equipment, and supplies furnished by the contractor. The price per foot also included all subsequent warranty repairs as well as "before and after" photographs of each crack.

The cost did not include the labor costs of the management staff of MARTA, or the flagman who was provided for each day's work. Nor did it include any cost of inconvenience to the track gang since their work was subordinated to that of the contractor.

B. Track Time

The contractor was allowed under his contract to enter the East, West, and South Lines four out of seven consecutive days between 11:20 P.M. and 3:40 A.M. He was also contractually allowed to work in the Interline Connector from 10:00 A.M. to 3:00 P.M. any day of the week, although he had to be prepared to clear the area if Central Control needed to move trains between lines. In addition, he was occassionally allowed to work some 12-hour shifts during the day on Sundays.

C. Sealing Procedure

The contractor's sequence of operations was as follows:

1. Cracks or joints to be repaired were identified and marked by a MARTA representative prior to any contractor activity.

2. 5/8 in. diameter portholes were drilled adjacent to and along the plane of the crack or joint at 45 degree angles to approximately 1/2 the thickness of the structure.
3. Drilling debris was washed from the portholes.
4. Mechanical injectors with a ball check device were then inserted and secured.
5. Cracks were then flushed with clean water. The purpose of this procedure was to:
    a. Clean dust and debris from the crack system;
    b. Flood the system with water for the grouting compound to react with (if water-activated grout is used);
    c. Allow the injection technician to observe how each crack was likely to behave during the injection procedure and determine if a surface sealer was required to contain the grouting compound.
6. Surface seal was applied. Seal was a fast set, high strength hydraulic cement (used occasionally for wide cracks).
7. Once preparation was completed, the technician started pumping at low pressure, and increased pressure until flow of material was achieved. Injection continued until crack or joint was filled and water flow stopped. Full penetration was determined by resin "bleeding" through adjacent injectors or at points along surface of structure. Grouting compound quantities were recorded for future reference.
8. Resin was allowed to cure.
9. Injectors were removed and holes filled with a high-strength hydraulic grout.
10. Surface of cracks or joints were then ground, and all debris was removed, leaving a sound, clean surface.
11. A flexible epoxy gel (paste) was applied over a surface approximately 2 ft. wide. This insured total sealing.

12. All trash and debris were removed from tunnel and disposed of.

D. Products

Believing that the tunnels are "capable of extreme movement and leakage due to thermal expansion and contraction," the contractors recommended using:

1. A flexible, water activated grouting compound for the injection material. Note that this material has a 700-800 percent elongation when the ratio of water to grout is 1:1. Originally, this material was developed for joint sealing sanitary and storm sewers.
2. A semi-flexible epoxy gel used as a surface sealer. The flexible grout injection method differs from the epoxy injection method because the grout has no structural value.

E. Contractor Personnel

The contractor provided one superintendent who was required to have a minimum of five years experience in this method of sealing leaks. The contractor also provided two technicians and one laborer.

F. Production Rates

The contractor estimates that he was able to complete about 30 ft. per night, including all the steps of the procedure.

G. Warranty

The contractor had to warranty that "the sealed joints and cracks will be absolutely watertight from date of project acceptance until three years after the date of acceptance."

H. Work Accomplished

On May 8, 1983, the contractor requested that the tunnel work be discontinued since he felt that he could no longer warrant the work. At that time he had completed over half the East Line section. His request was granted and he was given a time extension.

On December 1, 1983, he resumed work in the Interline Connector. He has completed that work and the East Line.

6.7 CONCLUSIONS

The major factors which contribute to water intrusion at the MARTA Subway System are cracks in concrete lining structures caused by concrete shrinkage. All the cracks occurred in a radial direction, due to a longitudinal shrinkage of concrete. There were no longitudinal cracks.

The water leaks have taken place through such cracks in tunnel walls, floors and ceilings. There are also a few water leaks through construction joints.

For water problems that already existed, the following remedial measures proved to be satisfactory:

- The galvanized steel plates were used to intercept and collect the waterflow and channel it away from electrical installations, pedestrian walkways, cables, etc. Steel lining consisting of concrete arches with steel pans for dripping off the water were installed during the construction period and later.
- At some locations a regular grouting technique was used. Although grouting is labor intensive, it has been confirmed to be efficient. An envelope grouting can be used after installation of lining, but only after appearance of signs indicating that the lining has started to leak (see Chapter 4).

Water intrusion can also be controlled or significantly reduced by some preventive measures, such as improving the quality of concrete lining structures and reducing the shrinking of concrete. For that purpose, an improved pouring and curing process may help. The number of radial cracks can be diminished by reducing the length of concrete pours (the average length of pours during the construction of some tunnels in the MARTA Subway System was about 50 ft.). The concrete cracks can also be reduced if various special admixtures in concrete preparation are used. It is believed that a higher quality of concrete is the best way to make a tunnel sufficiently watertight.

CHAPTER 7.

Case Study No.3: Massachusetts Bay Transportation Authority
Location: Boston, MA
Owner: MBTA

7.1 INTRODUCTION

Case Study No. 3 is the study of water intrusion problems in the Boston Subway System, owned and operated by the Massachusetts Bay Transportation Authority (MBTA). The study includes:

1. Meetings with the system representatives, during which various aspects of water intrusion problems experienced by the MBTA Subway System were discussed.
2. Site visits to system tunnels and stations severely affected by water intrusion.
3. Data collection concerning water leak locations; an intensive study of water leakage and its detrimental effects on system structures, maintenance and operation; and of remedial and preventive measures of water control used at the MBTA Subway System.
4. Analysis of collected data, evaluation of the effectiveness of water control measures used to prevent, control or correct water intrusion problems, and development of possible recommendations.

The site-visit team has visited the MBTA Subway System twice. The first visit took place on June 4, 1984, and the second on September 13, 1984.

During the second visit, the team visited various tunnels and stations of the operating lines. Another meeting also took place with system representatives.

The following subjects were closely scrutinized during the visits to the MBTA Subway System:

1. Various tunnel environments and types of tunnel structures.
2. Geological and groundwater conditions along each subway line.

3. Water infiltration during the time of construction in relation to the methods of excavation (cut-and-cover and underground excavations);
4. Various methods of preventing water intrusion (grouting technique, quality of concrete, etc.);
5. Remedial measures to control or to stop the water intrusion (water collection, pumping or grouting, etc.);
6. Stability of the building foundations and city sewer system along the construction of new tunnels;
7. Effectiveness of excavation machinery and technology;
8. Quality control of materials and structures.

7.2 GENERAL INFORMATION AND HISTORY OF THE PROBLEMS

The nation's first underwater mass transit tunnel, the East Boston tunnel under Boston Harbor, was opened in December 1904. Other major subway tunnels in downtown Boston were also constructed mainly in the first two decades of this century.

The existing subway system, as shown in Figure 7.1, consists of four lines which are officially designated and distinguished in all plans and documentation by their different colors: Green, Orange, Red and Blue.

The age of most of Boston's underground subway structures predetermined many water intrusion problems which are inherent to the MBTA tunnels. The following sections describe the various types of leaks experienced by MBTA tunnels and the remedial measures used for ground water control. The four different lines are considered separately.

7.3 MAJOR LEAK LOCATIONS AND THEIR DETRIMENTAL EFFECT IN TUNNELS AND STATIONS

7.3.1 Red Line (North Extension)

A. General Information and Structural Description

The new extension of the MBTA Red Line has now been completed. The project, designed by Bechtel Engineering Corporation, consists of 3.2 miles of

1 - GREEN LINE	3 - RED LINE
2 - ORANGE LINE	4 - BLUE LINE

FIGURE 7.1 MBTA RAPID TRANSIT SYSTEM

tunnels and stations, from Harvard Square to Somerville. Tunnels are mostly double tube or circular in shape. The tubes are approximately 18 ft. in diameter, and are spaced by about 40 ft. The average depth of tunnel is approximately 40 ft. to 60 ft. under the surface. There was also a cut-and-cover section of tunnel construction.

B. Geological Conditions

Geological conditions range from rock to soft soil and mixed face, with quite a significant amount of ground water.

The tunnel shield was used for excavation in the soft and mixed face ground. There were two types of shields being used: round buckets and square buckets.

C. Ground Water Problems

Water infiltration was observed in both cut-and-cover and underground excavation sections. There were two major categories of water leaks: those through the structural joints, and those through the numerous cracks in the tunnel walls, caused by the shrinkage of concrete.

7.3.2 Red Line (South Extension)

The Red Line South Extension, an old part of the subway system, has been experiencing various water intrusion problems. The site-visit team observed extensive leaks, such as:

1. Water pouring extensively through the tunnel walls and ceilings;
2. Pools of water standing in track bed area;
3. Numerous small streams of water emerging from the base of the track bed;
4. Large wet areas on the walls and toe benches.

Leakage such as water streams emerging from the base of the track bed creates a specific problem by washing ballast away, as can be noted in Figures 7.2 and 7.3, where large segments of the washed-out ballast are shown.

FIGURE 7.2 BALLAST WASHED OUT BY STREAMS OF RUNNING WATER (RED LINE, SOUTH STATION)

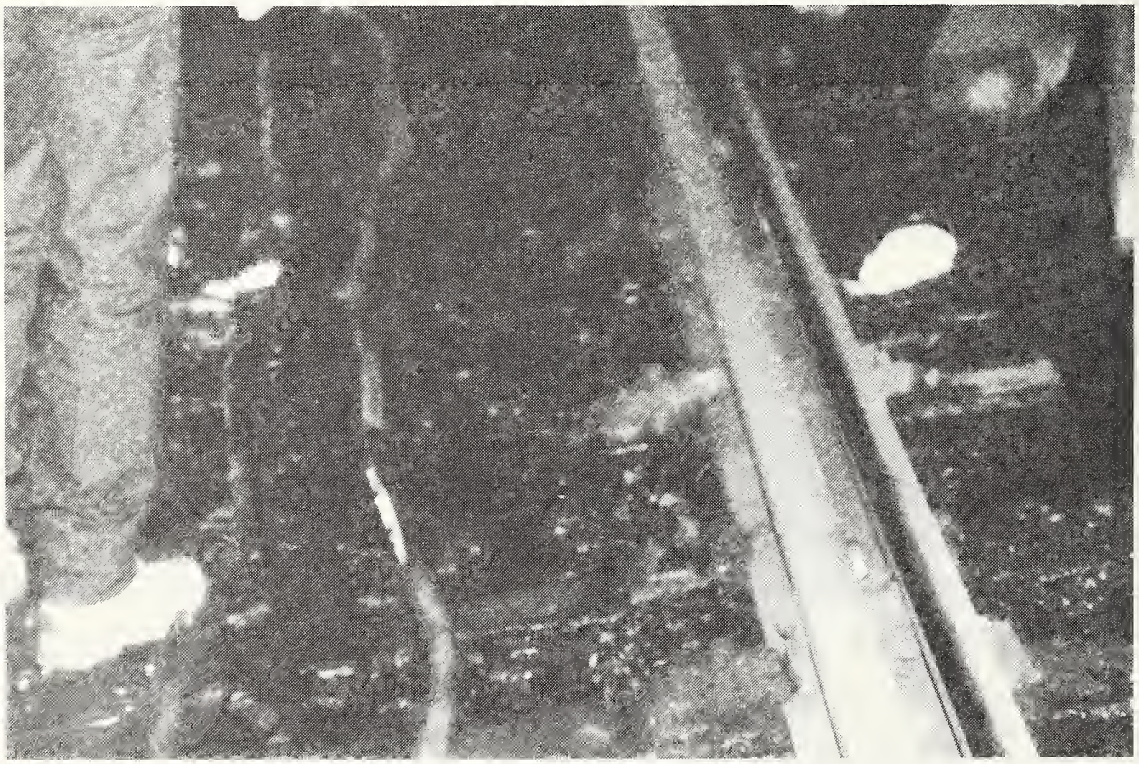


FIGURE 7.3 STANDING WATER IN THE TRACKBED (RED LINE, SOUTH STATION)

Figure 7.4 shows a wide area of calcification around shrinkage cracks in concrete. The calcification was caused by water leaks which also resulted in standing pools of water in the track area.

Figure 7.5 shows a channeling of water which runs through the tunnel ceiling. The water leaks also created large zones of calcification around shrinkage cracks in the ceiling.

7.3.3 Blue Line - Aquarium Station

Aquarium Station (formerly Atlantic Station) of the Blue Line was visited by the site-visit team on September 13, 1984. Although this station was completely modernized in 1968, it is still experiencing various water intrusion problems. These range from water leaks across the entire tunnel lining to numerous wet spots on the toe bench. There are also some pools of standing water in an area under the third rail and in a track bed. Water leaking through tunnel walls and ceilings has deteriorated the architectural finish of the Aquarium Station (Figure 7.6). Figure 7.7 shows stalactites growing on tunnel ceilings as a result of water leakage through the shrinkage cracks in the tunnel concrete lining.

The surface of some structural concrete elements such as ceiling beams remains permanently wet due to hidden water leaks behind the finish of walls and ceilings, as shown in Figure 7.8.

Figure 7.9 depicts a ceiling finish section removed to allow access to the concrete roof structure behind the finish for an investigation of a cluster of leaks.

Figure 7.10 shows a large area of calcification on the wall finish caused by the water infiltrating through the walls and ceiling of the concrete lining. Such structural and architectural deterioration requires extensive repair work.

It should be pointed out that the Aquarium Station is located approximately 60 ft. below sea level and is positioned very close to the Boston Harbor floor. Such a location creates a very intensive ground water pressure acting upon station underground structures.

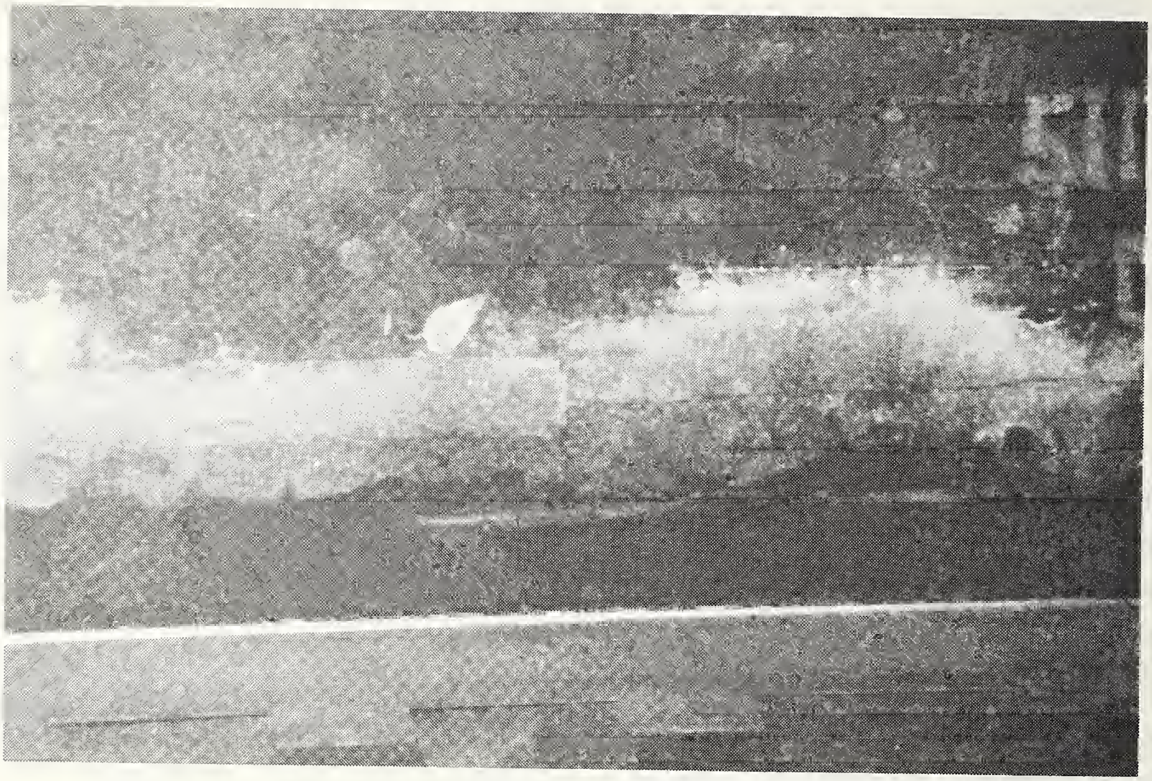


FIGURE 7.4 CALCIFICATION AROUND A SHRINKAGE CRACK (RED LINE, SOUTH STATION)

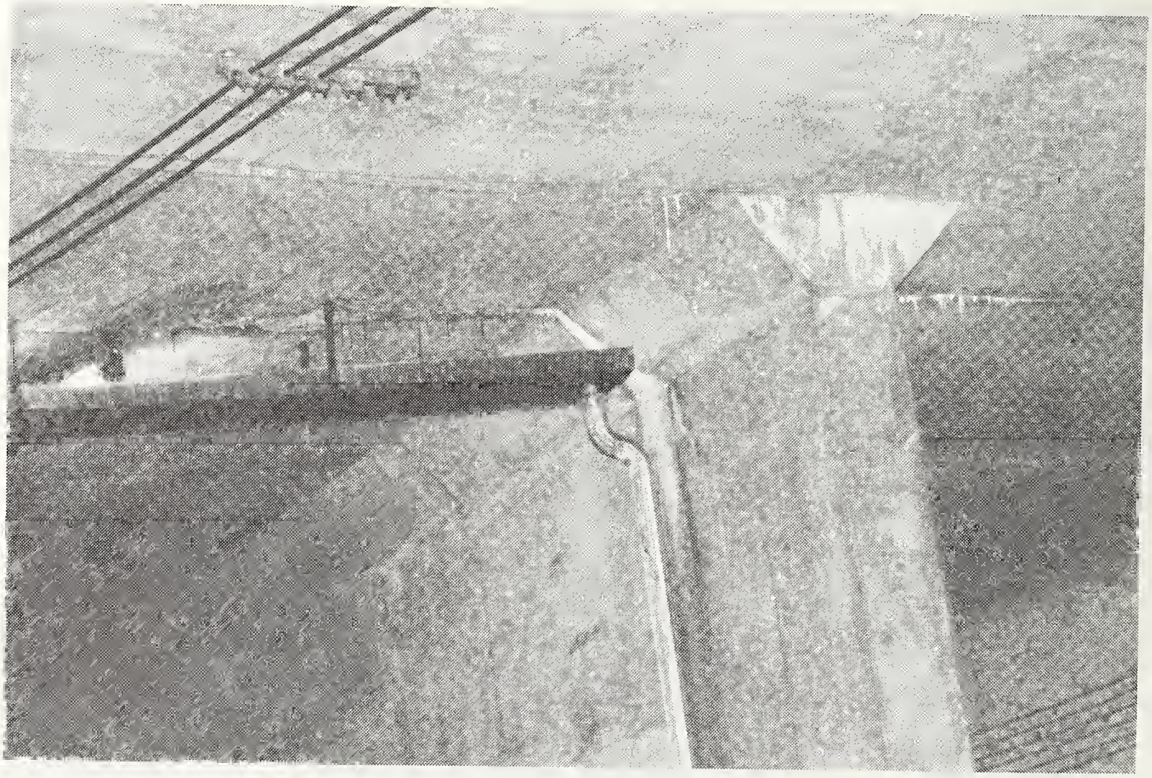


FIGURE 7.5 CHANNELING OF THE WATER (RED LINE, SOUTH STATION)

FIGURE 7.6 DETERIORATION OF PAINT (BLUE LINE, AQUARIUM STATION)

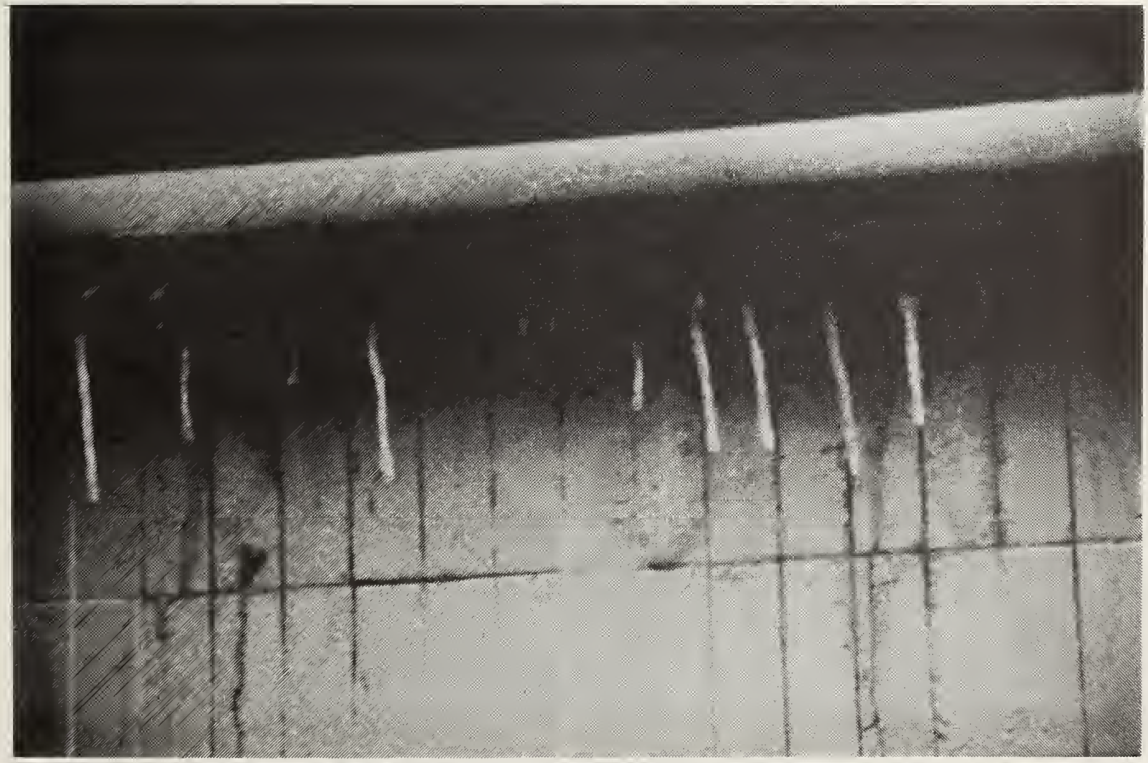


FIGURE 7.7 STALACTITES GROW (BLUE LINE, AQUARIUM STATION)

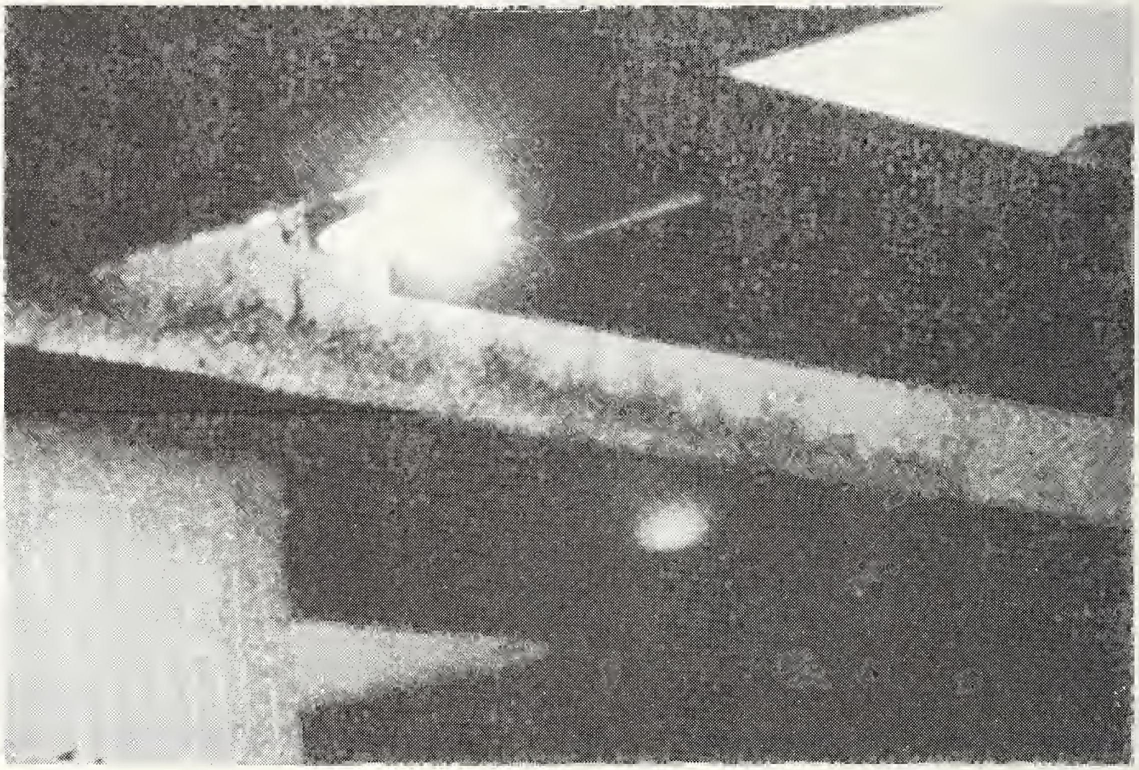


FIGURE 7.8 WET CEILING BEAMS (BLUE LINE, AQUARIUM STATION)

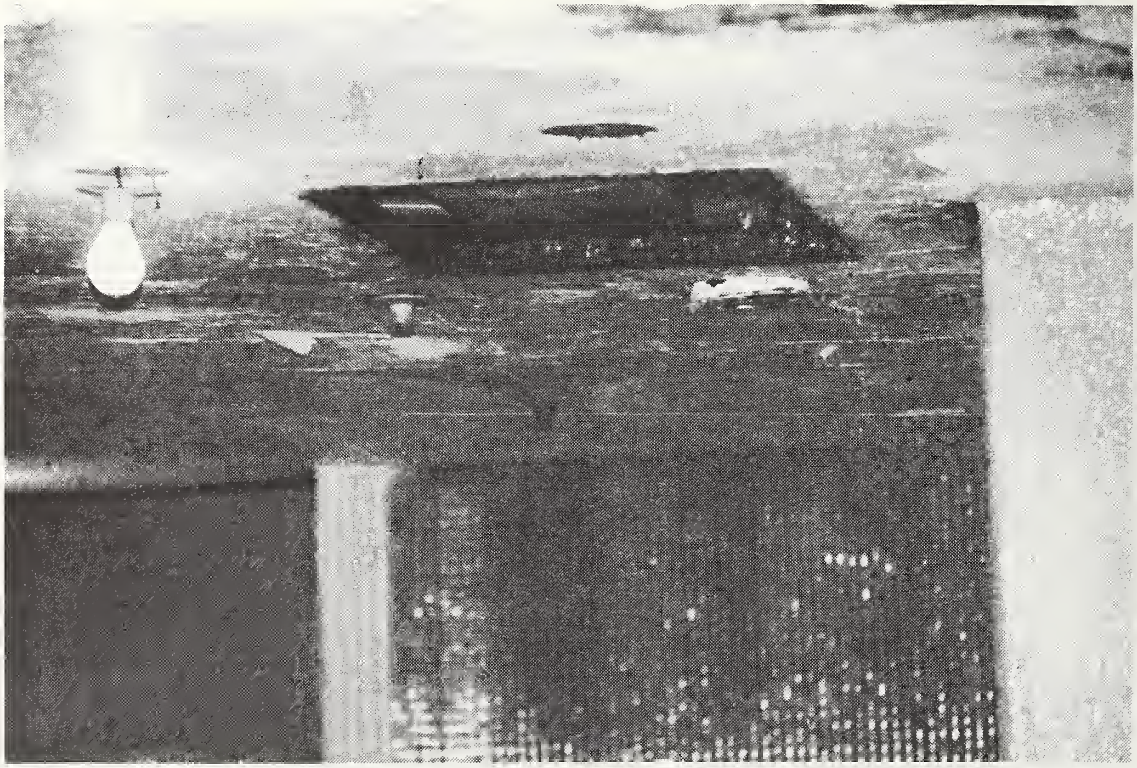


FIGURE 7.9 CEILING SECTION REMOVED FOR INVESTIGATION OF MAIN ROOF LEAKS (BLUE LINE, AQUARIUM STATION)

FIGURE 7.10 CALCIFICATION OF THE WALL FINISH (BLUE LINE, AQUARIUM STATION)

FIGURE 7.11 STANDING POOL OF WATER WITH FLOATING DEBRIS IN TRACKBED AREA (BLUE LINE, AQUARIUM STATION)

Figures 7.11, 7.12, and 7.13 also depict the deteriorative effect of water on the trackbed. There are some zones where ballast has been completely washed out.

7.3.4 Green Line - Tunnel Between Boylston and Arlington Stations

The Green Line is the oldest line in the Boston Subway System. The concrete lining of the tunnel suffers from many different types of cracks (shrinkage cracks, construction joint cracks, etc.) both large and small. Those cracks allow ground water to infiltrate in large quantities. Having persisted over a long period of time, the water intrusion resulted in the formation of heavy precipitation structures which sometimes cover the tunnel concrete lining almost completely.

Figures 7.14 and 7.15 depict such zones of extensive calcification on the walls of the running tunnel between Boylston and Arlington Street Stations. The cross-section of the tunnel is shown in Figure 7.16. The tunnel has the following types of water problems:

1. Leakage through tunnel walls onto the toe bench of the roadbed;
2. Pools of standing water in the trackbed area up to the top of the ties;
3. Wet toe benches.

7.3.5 Orange Line - Essex Station

The Essex Station of the Orange Line was visited by the PPA site-visit team on September 13, 1984. During the visit the team investigated the underground structures of tunnels and the station and discovered that typical water intrusion problems exist as for most Boston subway lines. These included leaks through the shrinkage cracks in the tunnel concrete lining and water accumulated in the track bed area. The Essex Station can be characterized as having the worst track bed conditions. The infiltrated water forms running streams which are seriously affecting the rail tracks.

Figures 7.17 and 7.18 demonstrate the conditions of the station tracks. In Figure 7.17 one can see a heavy precipitation in the area of the third rail. Figure 7.18 shows part of the track bed where the ballast was washed out almost

FIGURE 7.12 WATER STREAM IN TRACKBED (BLUE LINE, AQUARIUM STATION)

FIGURE 7.13 BALLAST WASHED OUT (BLUE LINE, AQUARIUM STATION)

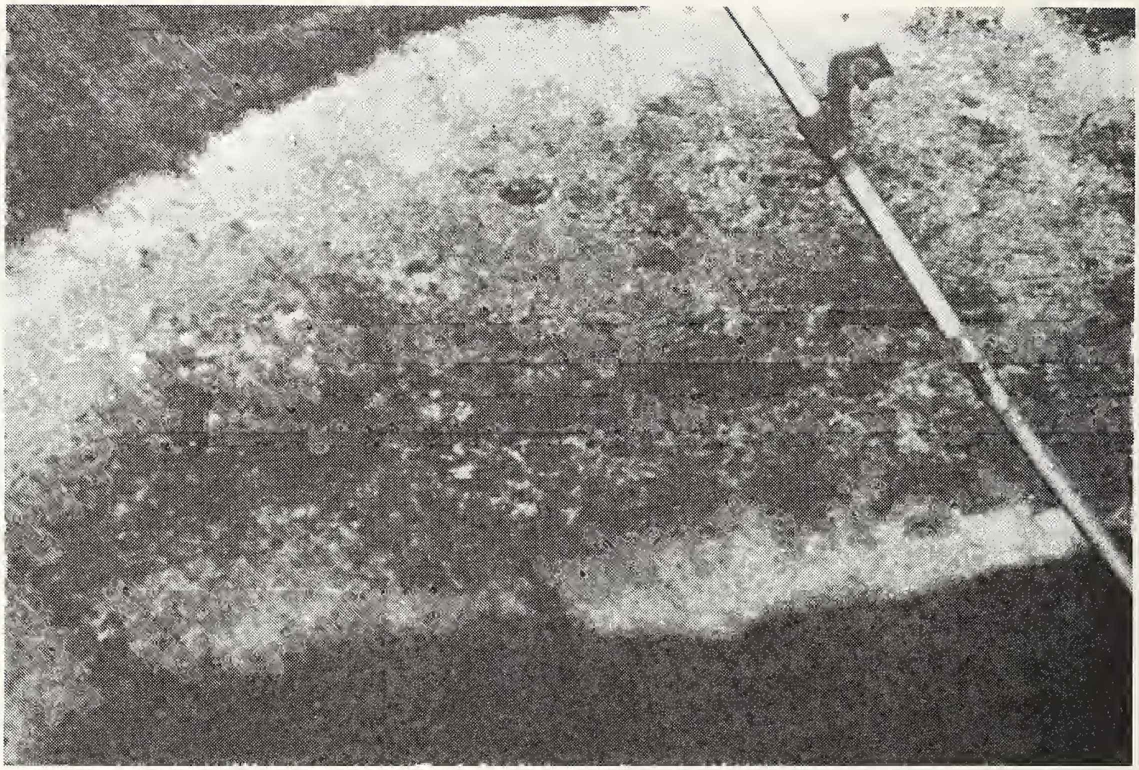


FIGURE 7.14 ZONE OF CALCIFICATION AND STALACTITES AROUND A CRACK (GREEN LINE, BOYLSTON-ARLINGTON TUNNEL)

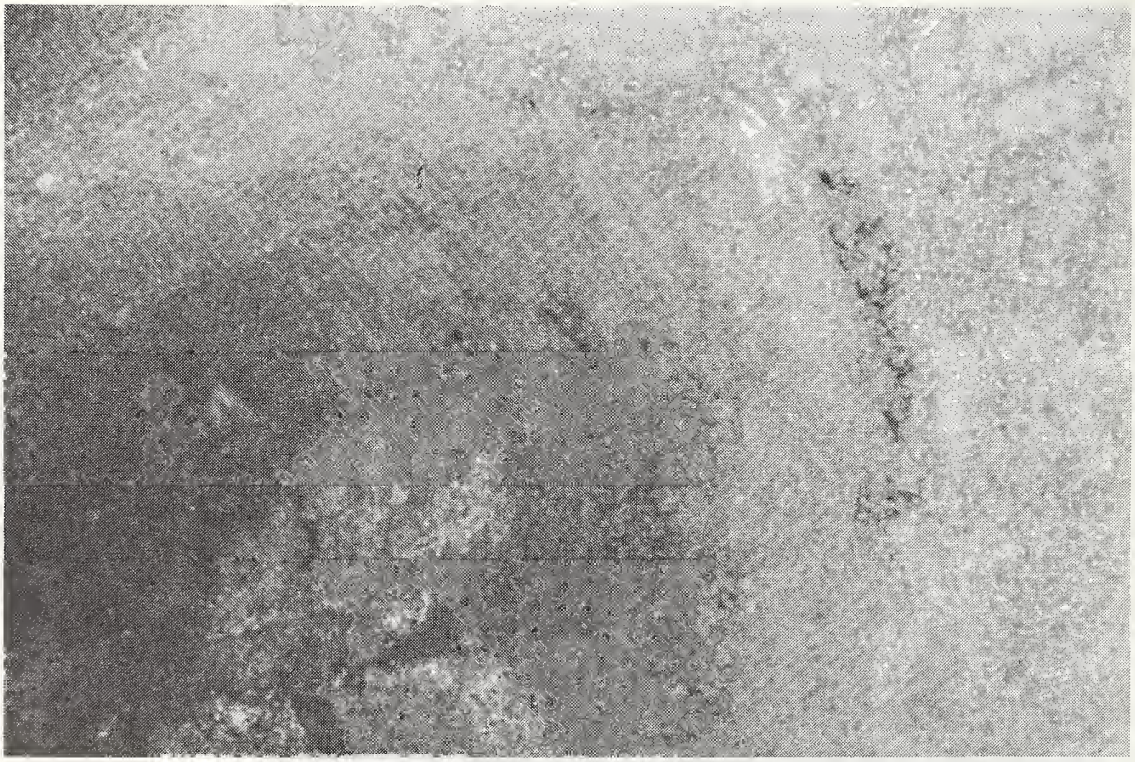


FIGURE 7.15 AREA OF MASSIVE CALCIFICATION (GREEN LINE, BOYLSTON-ARLINGTON TUNNEL)

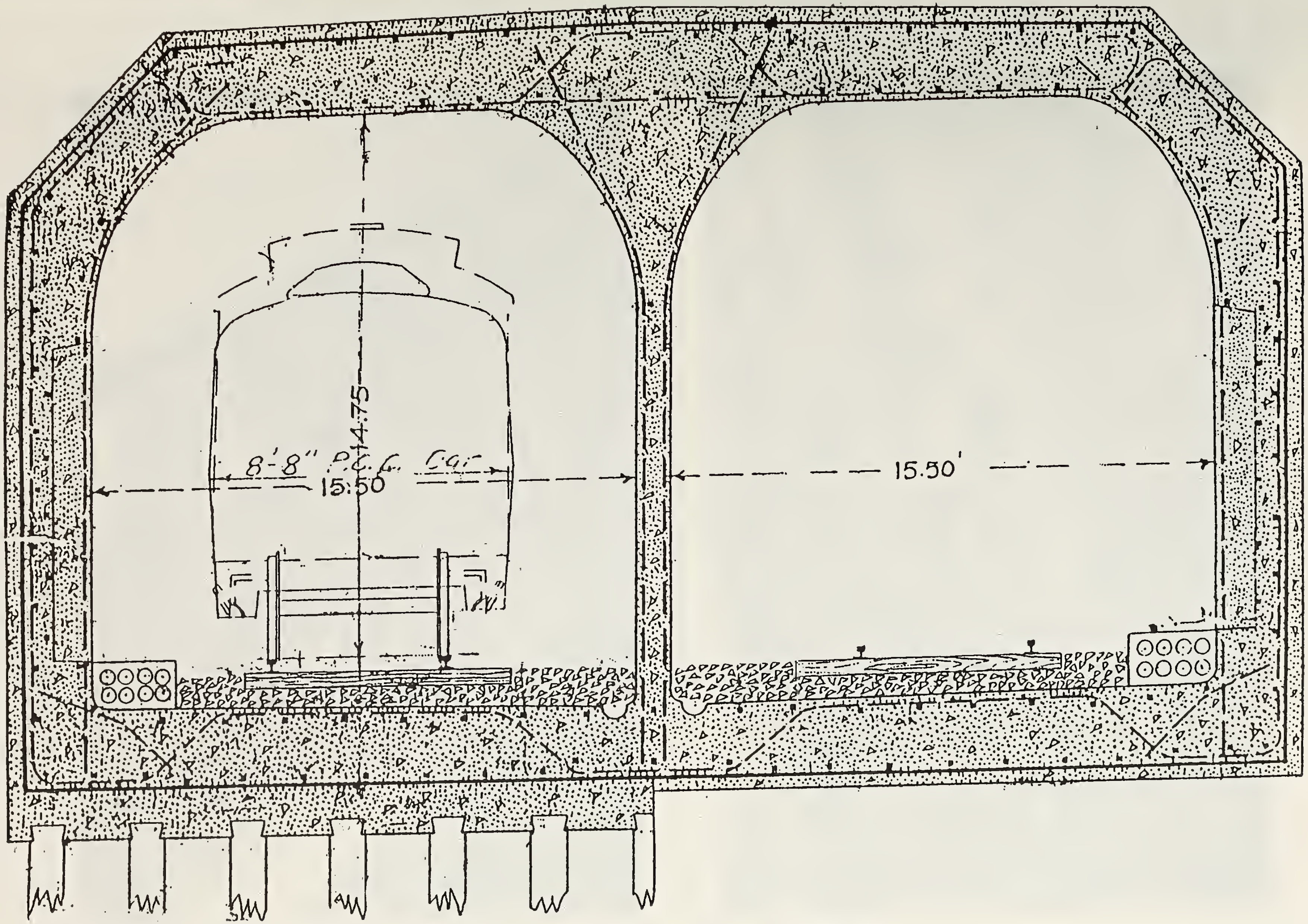


FIGURE 7.16 BOYLSTON STREET SUBWAY

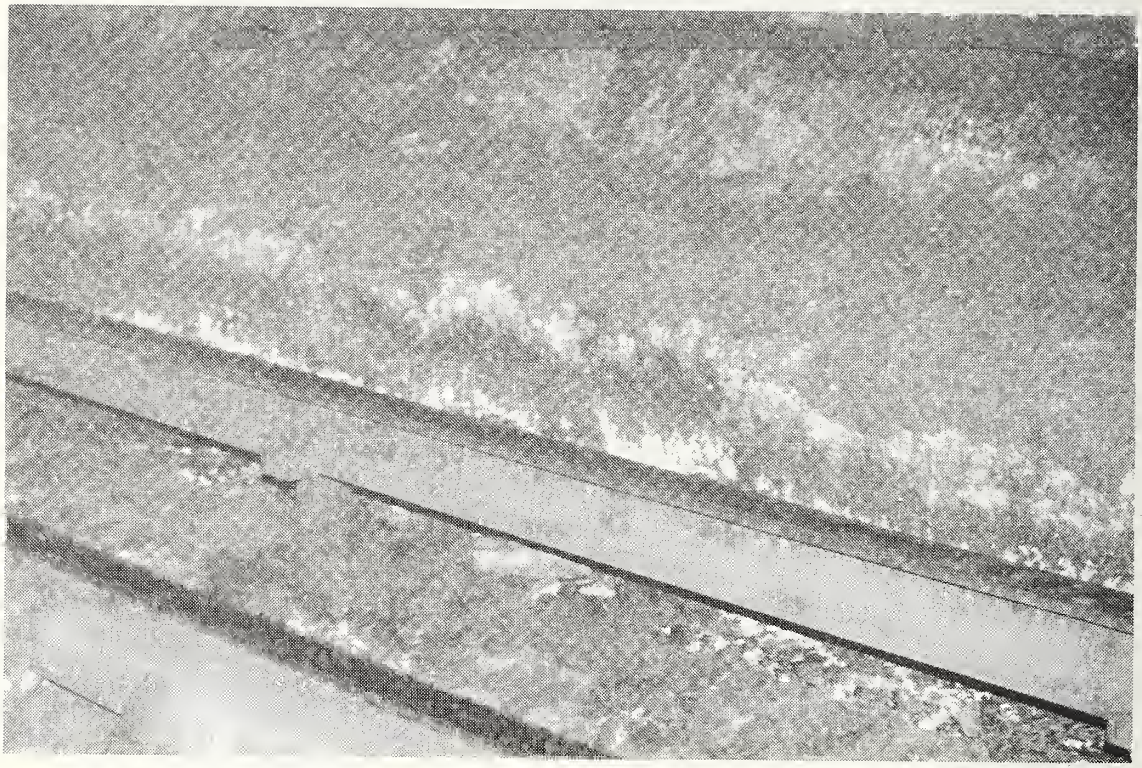


FIGURE 7.17 CALCIFICATION IN AREA OF THIRD RAIL (ORANGE LINE, ESSEX STATION)

FIGURE 7.18 AREA WHERE BALLAST IS WASHED OUT COMPLETELY (ORANGE LINE, ESSEX STATION)

entirely. To prevent disintegration of the rail track due to the absence of ballast, both rails were bolted together with the transverse beam (see Figure 7.18).

7.3.6 Summary of Water Leaks and Their Intensity

The water leaks in the Boston Subway lines can be classified as follows, according to type, location, and intensity.

A. Major Paths of Water Leakage.

1. Through the construction joints of the tunnel oonerete lining;
2. Through the numerous cracks in the concrete lining caused by the shrinkage of concrete;
3. Through the numerous crack openings caused by the erosion of concrete.

B. Intensity of Water Inflow and Its Consequences

1. An intensive infiltration of water which results in substantial streams of water in the track bed area;
2. Relatively moderate infiltration of water which causes small streams of water on tunnel floor;
3. Water dripping from tunnel ceilings onto station sidewalks;
4. Hidden leaks in a concrete lining behind the wall finish, which causes wetness and dampness of walls and toe benches.

7.4 REMEDIAL MEASURES FOR WATER CONTROL

7.4.1 Water Control in Tunneling

In the new North Extension of the Red Line, the types of leaks discovered required serious treatment during the time of construction. Among the various methods of water treatment, a novel approach was used for sealing lining construction joints. This method was first invented and tested by the Dutch "De-Neef" Company. In this method, a reinforced rubber tube is placed between the foundation footing and the wall above. After the concrete wall is built, the tube left inside the wall is injected under high pressure with a chemical filling (Acrylamide or some other chemical). As a result, the filled tube works as an impervious gasket sealing construction joints. Although evaluated as "a good idea", it has not been introduced into practice in the United States.

Another water treatment that proved reliable was chemical grouting, which is considered to be the cheapest and the most effective method to prevent water infiltration through the cracks in the concrete lining. The average price is $5.50 per gallon of grout, while other grouts cost about $55 per gallon.

Cement grouting was not used in Red Line tunnel construction.

For the first time in tunnel practice, serious consideration was given to the shield buckets configuration as they affect water leakage. During the construction, it was noticed that the round shield buckets allow for better excavation and result in better inside tunnel surfaces, which, in turn, allows for better quality of concrete lining.

A good quality of concrete lining substantially reduces the leaking problems. At the same time it has to be noticed that round buckets are more expensive (more than a $2,000 difference in price when compared with square buckets).

7.4.2 Water Control in Tunnel Maintenance

Depending on the intensity of water inflow in running tunnels and the geological environment of tunnels in different subway lines, the MBTA uses the following remedial measures to control or prevent water intrusion:

1. Chemical grouting;
2. Sealing of cracks and leaking construction joints by waterproofing matrials;
3. Intercepting and collecting the water from ceilings and walls and channeling it to pumps.

CHAPTER 8.

Case Study No. 4: Washington Metropolitan Area Transit Authority (WMATA)
Location: Washington, DC
Owner: WMATA

8.1 INTRODUCTION

Case Study No. 4 is an investigation of various aspects of water infiltration in the Washington, DC, Subway System tunnels. The system is owned and operated by the Washington Metropolitan Area Transit Authority (WMATA).

The study contains a detailed description and an analysis of various water leakage problems experienced throughout the WMATA Subway System's tunnels and stations. The information was collected while visiting the WMATA Subway System during June 27-29, 1984, and can be divided into the following categories:

1. Types of leaks;
2. Deterioration effects of water intrusion;
3. Remedial measures and other methods of water control.

The following subjects were discussed during the meeting:

1. Structural and geological characteristics of the WMATA Subway System;
2. Major water problems experienced by the system and remedial measures being used;
3. New Austrian tunneling method for a recently designed tunnel section.

A meeting was held at the Tracks and Structures Maintenance Center of WMATA (6211 Blair Road, N.W.) with Timothy Reed, Maintenance Director. Mr. Reed briefly outlined the major water problems in operating tunnels, then accompanied the group on a technical tour of the subway system.

The amount of water inflow into the tunnels is acceptable and is kept under control by collecting it into the drains and carrying it away to the pump shaft, where it is pumped to the surface.

The investigating team held a meeting in New York at the office of Mueser-Rutledge-Johnston-Desimone, designers of the WMATA Subway System. The major areas of discussion at this meeting were quality of concrete, shrinkage cracks and various types of liner structures.

Information was obtained on a European (Austrian) procedure in lining design and construction, in which multilayered linings consisting of concrete and plastic film were placed between a layer of shotcrete and the concrete lining.

8.2 GENERAL INFORMATION

The Washington, DC, Subway System is one of the largest in North America. It will be about 100 miles long when completed and contains about 60 miles of running tunnels.

Figure 8.1 is a general scheme of the WMATA Subway System. Almost every tunnel in the system is currently experiencing some form of water leakage. Water leaks cause various problems in the system, such as deterioration of structures and track elements, and damage to power equipment like the third rail. Associated with these problems are safety hazards, architectural damage, pumping costs, and others.

8.3 GROUND WATER INTRUSION (HISTORY AND CONDITIONS)

As previously mentioned, there are some leaks in almost all WMATA tunnels. Some of them are quite intensive and have caused damage. Discussions with WMATA representatives and previous reports reveal differing opinions on the cause of water leakage.

Along with the direct water effect on structure and functional elements, there are problems associated with calcification, hydrostatic pressure relief system and acid waters. Continuous leakage has caused chemical reactions resulting in a precipitation of materials, which severely reduces or totally prohibits the ground water from flowing freely and causes pressure on the structure.

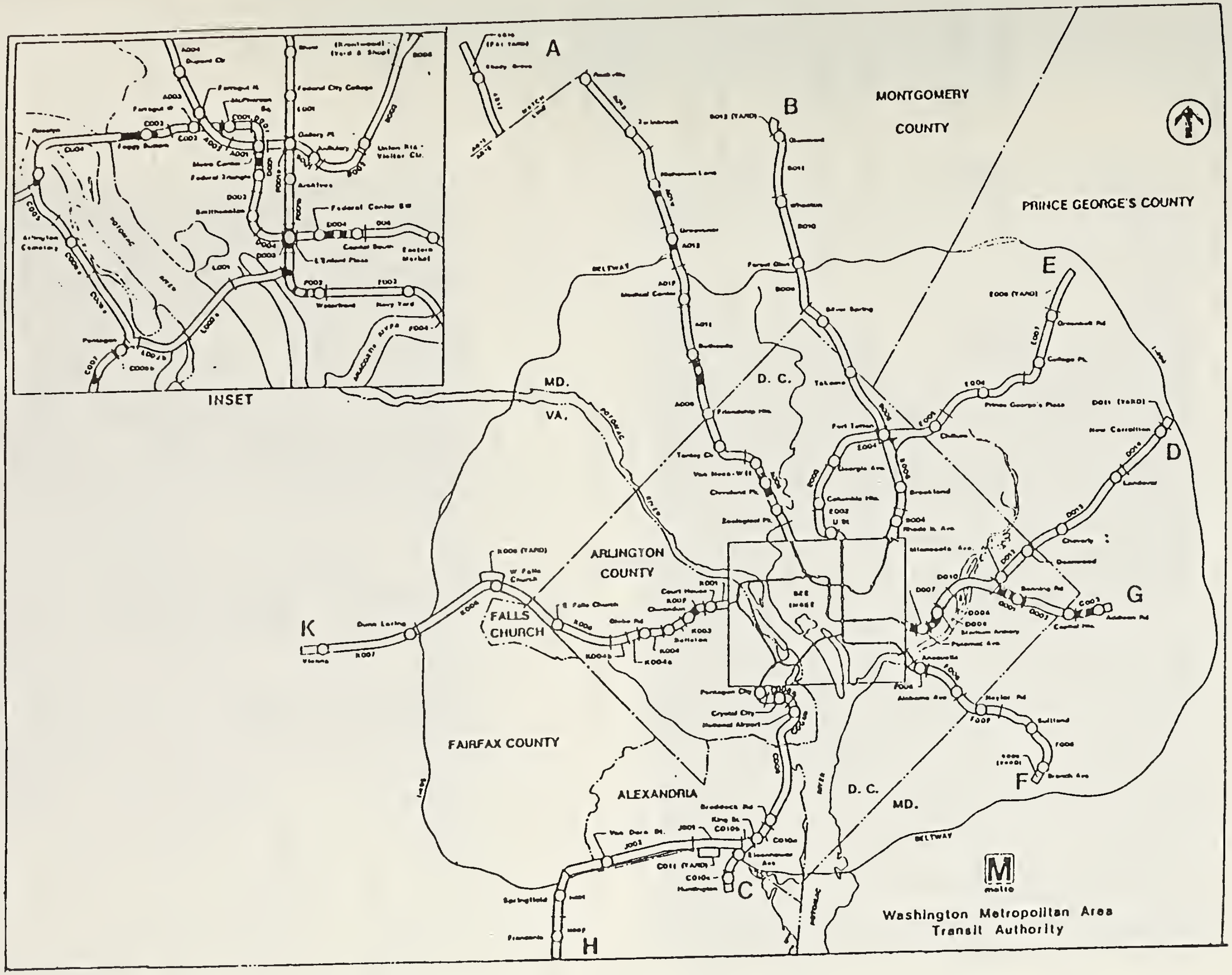


FIGURE 8.1 THE GENERAL MAP OF WMATA SUBWAY SYSTEM - WASHINGTON, DC

This study is primarily concerned with the investigation of water leakage and waterproofing and therefore consists of an analysis of the cause of water leaks and waterproofing methods used. For this reason, the described site visits to the WMATA transit system were devoted mainly to the collection of factual data on leaks through joints, cracks, and natural fissures.

8.4 MAJOR LEAKAGE TYPES AND LOCATIONS

Figures 8.2 to 8.8 demonstrate various aspects of water intrusion problems in the WMATA Subway System. These photographs were taken by the site visit team during its visit to WMATA on June 27 and 28, 1984.

Figure 8.2 shows quite intensive water leaks and their collection at the superstructure of running tunnels. The direct effect of the water on the rail system can be seen.

Figure 8.3 reflects architectural damage of the station wall caused by infiltrated water. Some water spots on the walls can be seen in Figure 8.4.

Figure 8.5 reflects an effect of calcification and precipitation caused by leaks. The upper photo of Figure 8.5 shows stalactites caused by this process.

Photographs of Figures 8.6 and 8.7 show some typical leaks through the shrinking cracks in the walls of the running tunnel.

The final photographs in Figure 8.8 show leaks through the joints and concrete lining. It was pointed out during meetings with WMATA representatives that leakage through joints represents the most consistent cases.

8.5 REMEDIAL MEASURES FOR WATER CONTROL

In-depth discussions of various approaches to the problems of water infiltration and control were held on June 29, 1984, at the meeting with representatives from Mueser-Rutledge-Johnston-Desimone, Inc. (designers of the WMATA Subway System). The method most commonly used in the WMATA tunnels is conventional grouting to reduce water intrusion (see Chapter 4). During the meeting, some other innovative methods of water control were discussed, including techniques such as membrane and porous lining systems for seepage control, which were recently developed in Austria.

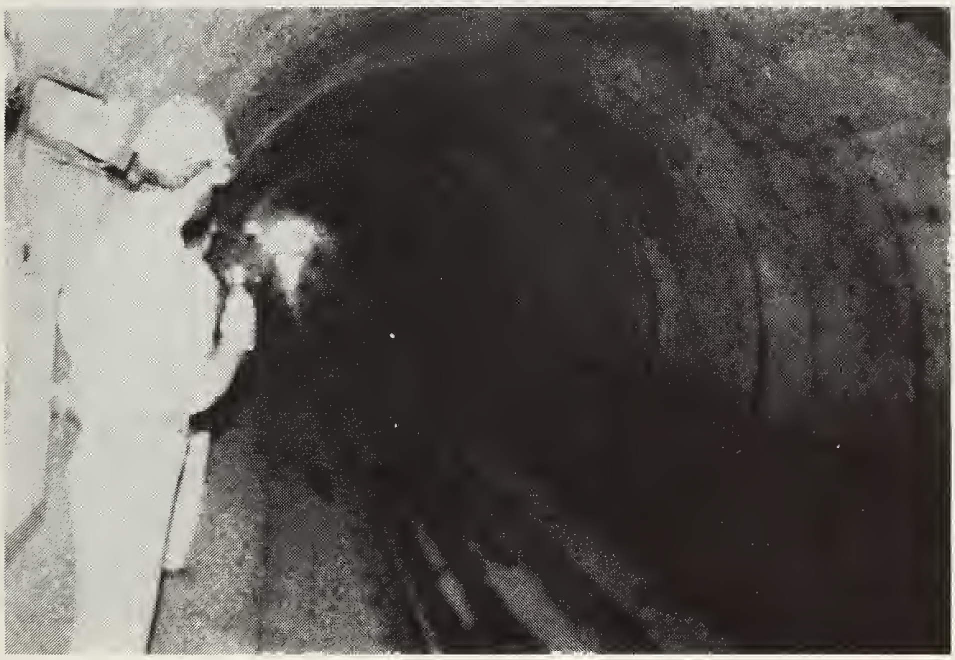


FIGURE 8.2 WATER LEAKS ON RAIL SUPERSTRUCTURE

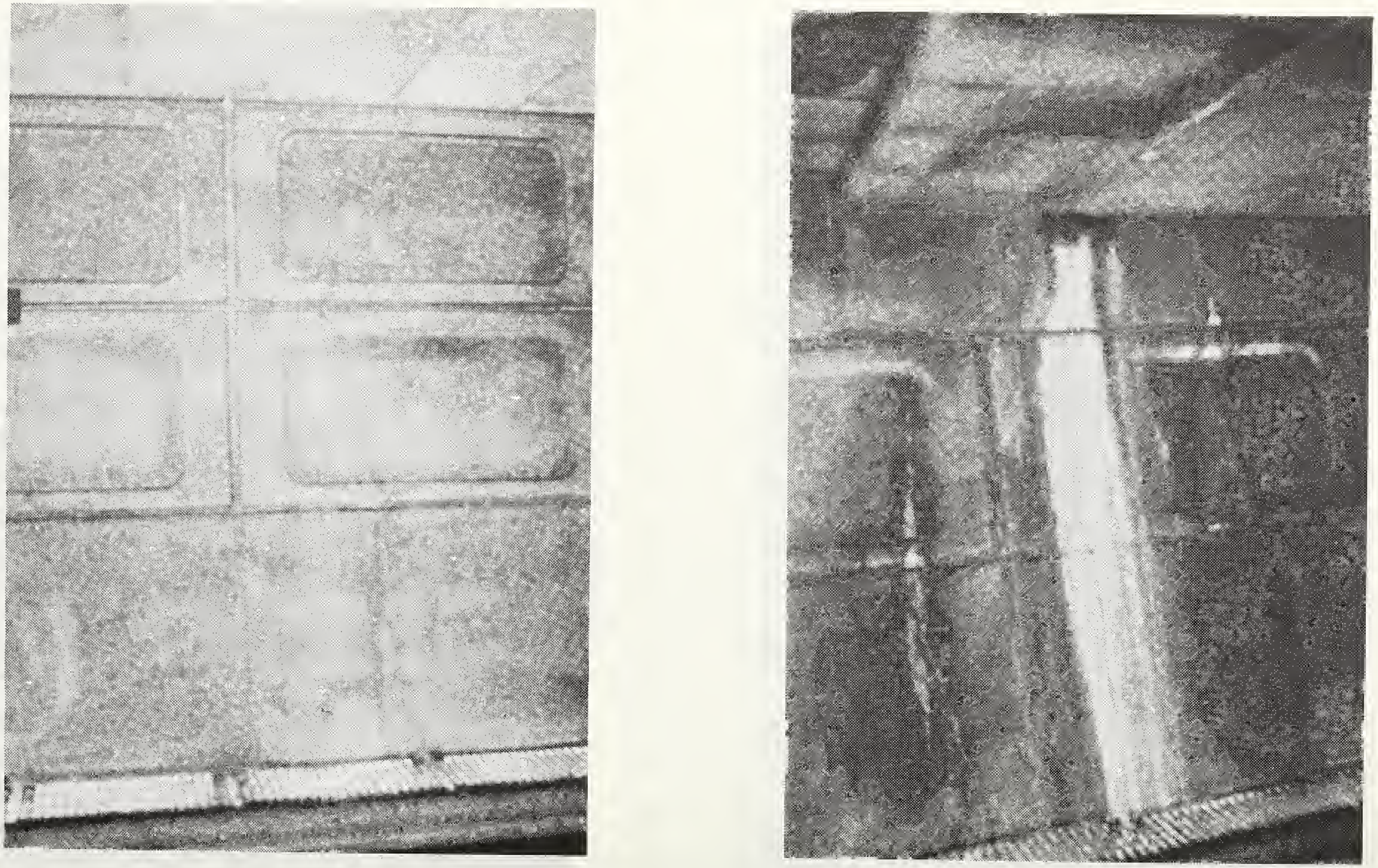


FIGURE 8.3 STONE WALLS DAMAGED BY WATER INTRUSION

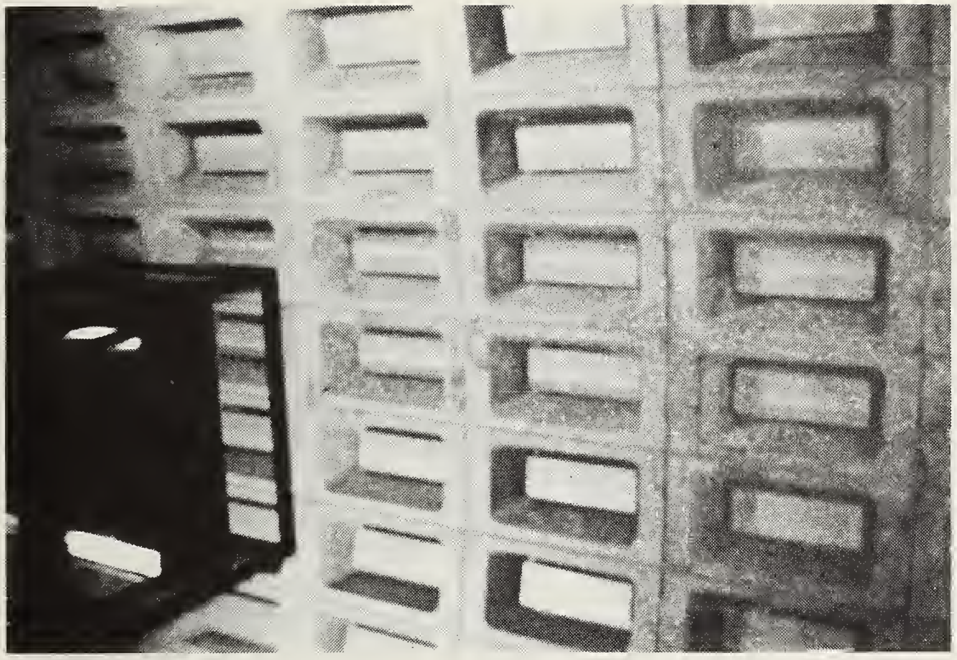


FIGURE 8.4 LEAKS THROUGH PRECAST AND CAST-IN-PLACE CONCRETE WALLS

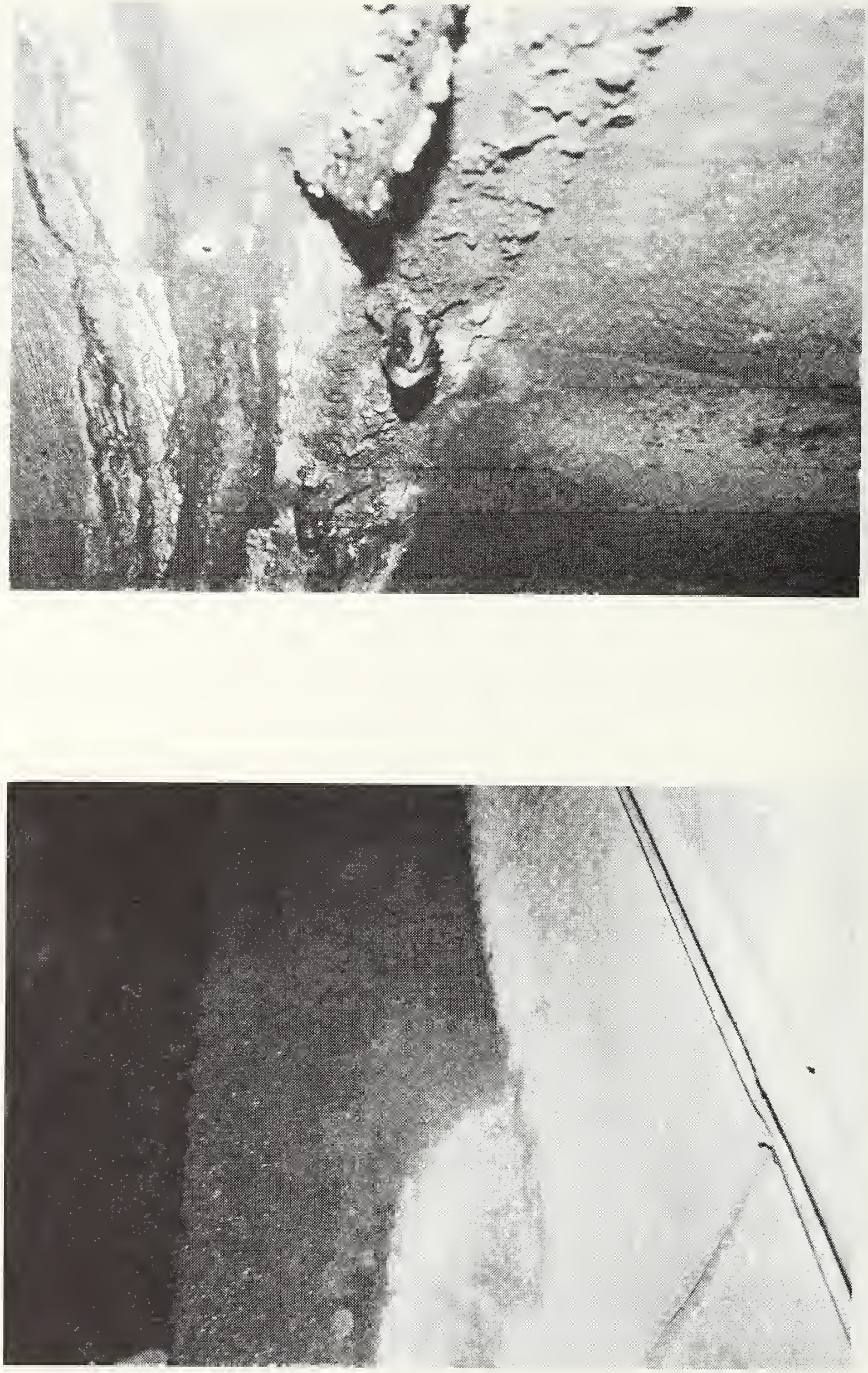


FIGURE 8.5 CALCIFICATION AND PRECIPITATIONS CAUSED BY LEAKING WATER

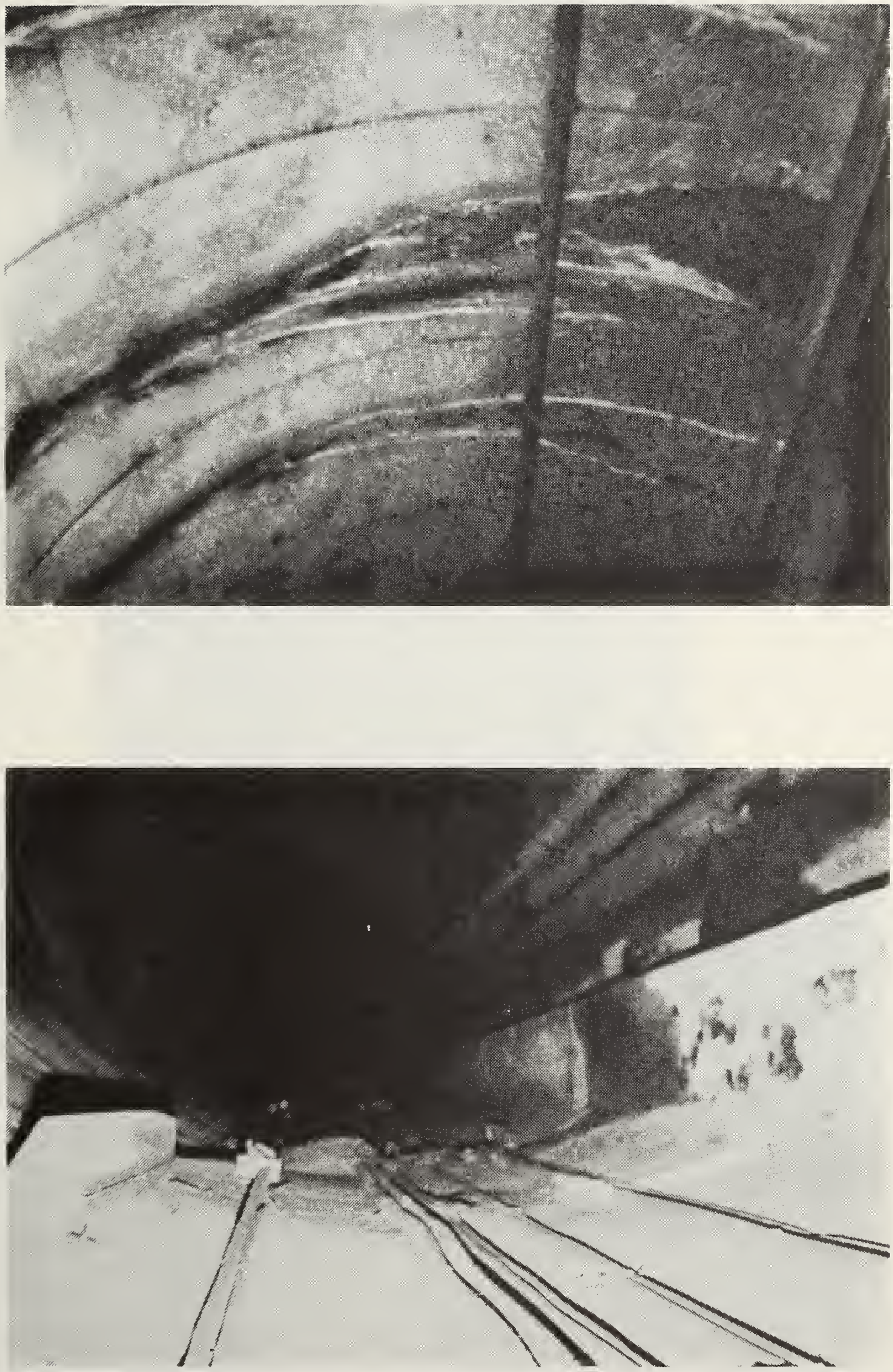


FIGURE 8.6 SHRINKAGE CRACKS IN CONCRETE LINING

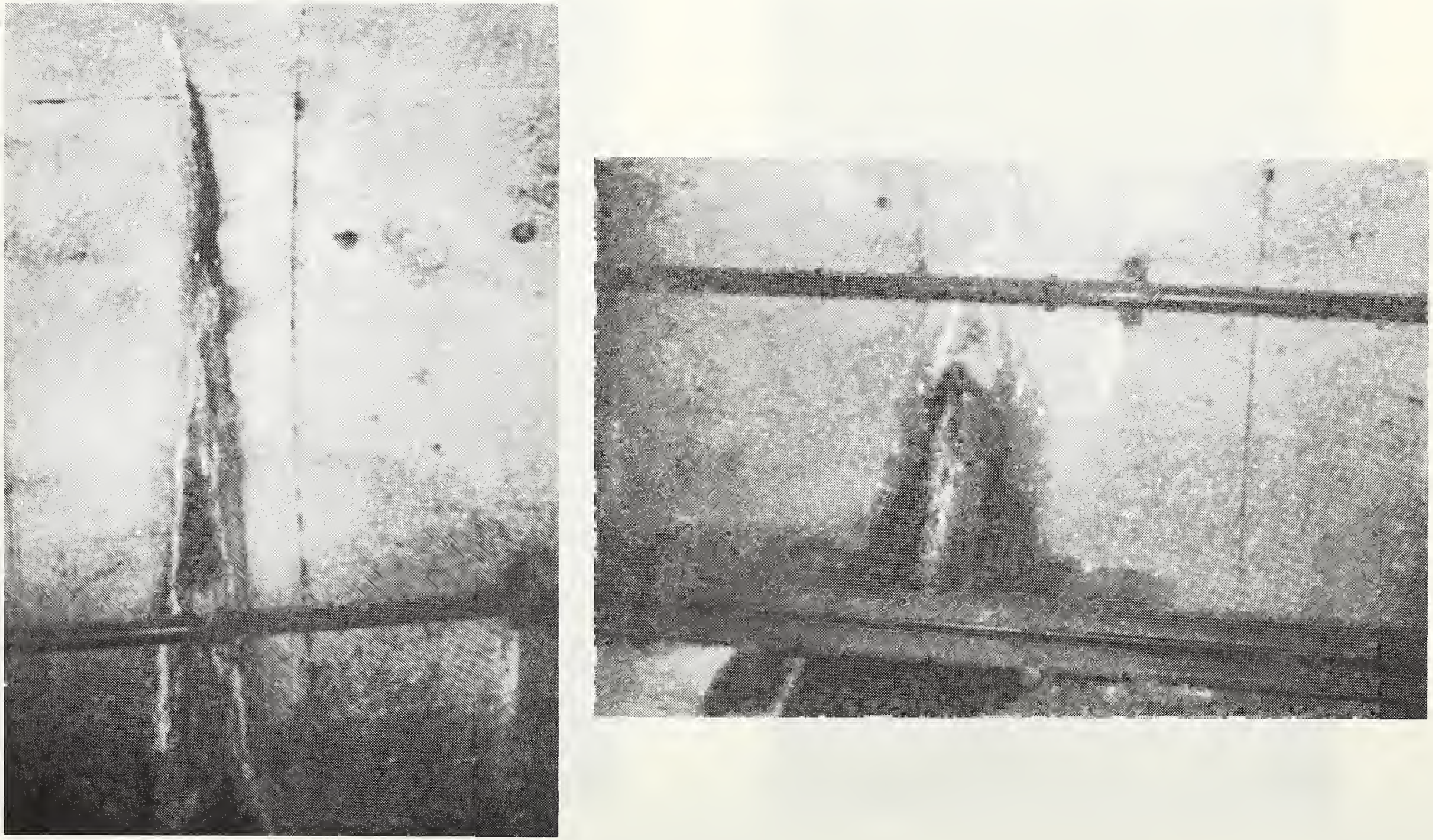


FIGURE 8.7 LEAKS THROUGH THE SHRINKAGE CRACKS IN CONCRETE LINING

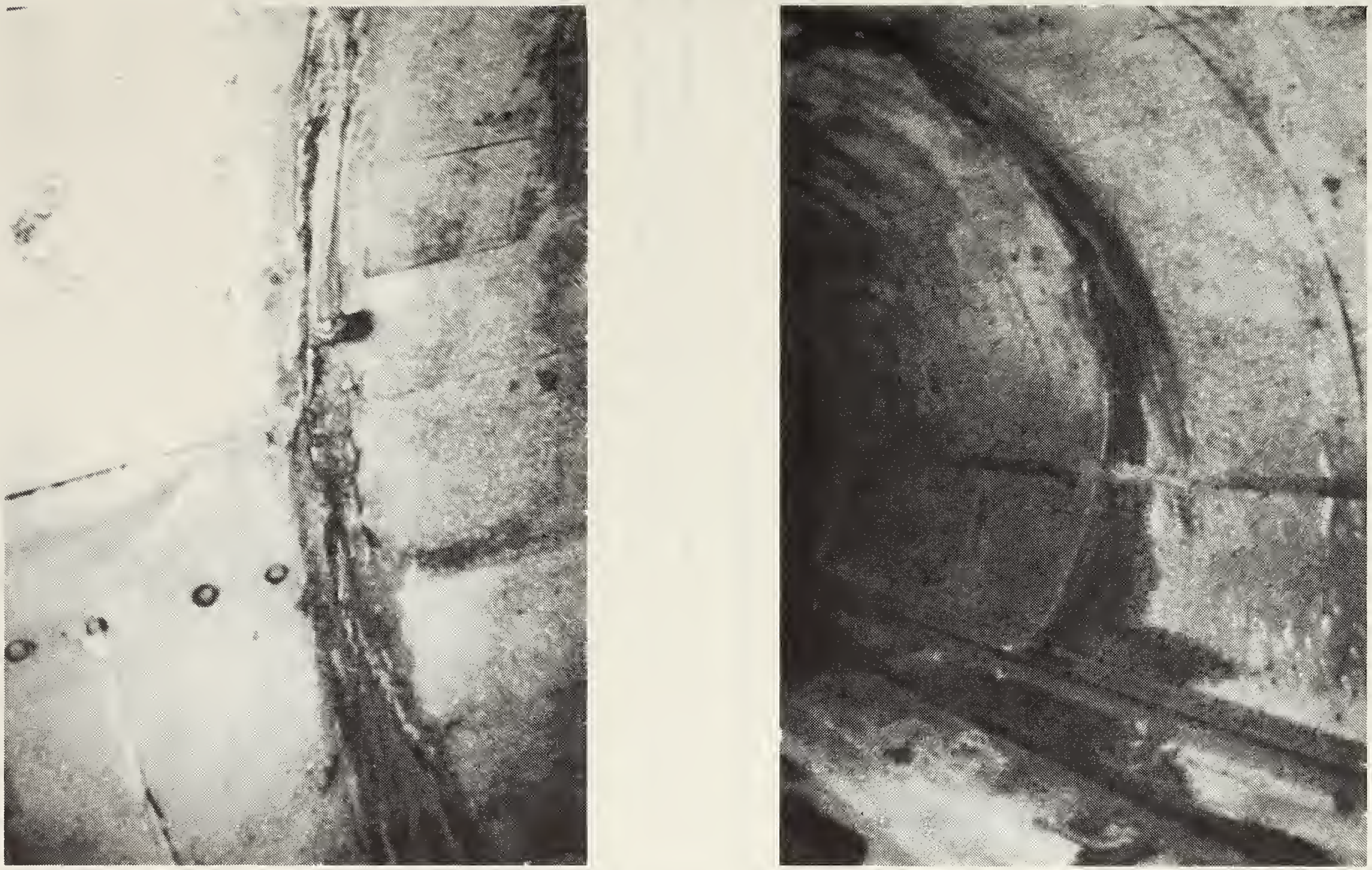


FIGURE 8.8 LEAKS THROUGH THE STRUCTURAL JOINTS IN CONCRETE LINING

Many portions of Austrian and German Federal Railway are located in volcanic rock where almost all tunnels are subject to water leakage. Running water in the tunnels leads to substantial destruction of the railway superstructure, that is, steel, concrete and power equipment.

As an alternative to the traditional water-impervious inner concrete (bituminous waterproofing), a new method was developed and used in Austria and Switzerland in the early 1970s. This method is based on the incorporation of a polymer plastic material known as the HP sealing strip. The strip is applied between the outer shotcrete shelf and inner concrete lining. This method creates a tunnel lining that is practically impervious and, consequently, has been successfully adapted for subway and railway tunnels. All participants at the meeting expressed interest in the Austrian method and agreed that it deserved further study.

Also mentioned was the possibility of utilizing plates welded to anchors on the inner surface of the tunnel lining. Such a system, being welded along the plates' joints, would also be impervious.

At the end of the New York meeting, the common desire was expressed to proceed with a search for the most effective and economical scheme to remedy water leakage problems in WMATA subway tunnels.

8.6 CONCLUSION

As previously mentioned, the major tunnel leaks at WMATA occur through lining joints and shrinkage cracks in concrete. A similar situation was observed in Buffalo, Atlanta and Boston subway tunnels (see Case Studies No. 1, 2, and 3).

Improving the quality of concrete structures along with using the proper grouting will substantially reduce water intrusion, although it still will not make tunnels impervious.

As an alternative, a more in-depth study of the Austrian polymer lining scheme is recommended, keeping in mind the possible application of this method in the United States.

CHAPTER 9.

Case Study No.5 : New York City Transit System
Location: New York, NY
Owner: New York City Transportation Authority (NYCTA)

9.1 INTRODUCTION

Case Study No. 5 was the study of the New York City Transit Subway System, owned and operated by the New York City Transportation Authority (NYCTA).

The study contains a detailed description and analysis of various water leakage problems experienced throughout the New York City Subway tunnels and stations. The information collected during the time of the visit can be divided into the following categories:

1. Types of leaks;
2. Deterioration effects of water intrusion;
3. Remedial measures and other methods of treatment used.

A meeting was held with the NYCTA representatives from the Engineering and Construction Department and from the Department of Maintenance of Way. The main host of the meeting was John Ferrelli, P.E., from the Department of Maintenance of Way. The PPA working group discussed various aspects of existing problems caused by water intrusion, and their detrimental effects on structures of the subway system.

On August 8, 1984, a visit was made to the Bergen Street Station (Prospect Park-Coney Island Line), which is one of the sites most affected by the water intrusion.

August 9, 1984, another meeting was held with NYCTA representatives at the Brooklyn Headquarters, including representatives from the Engineering and Construction Department. The main topic of discussion was the tremendous water leakage in the Lenox Line tunnels and the problems caused by the rising water table.

On August 9, 1984, a site visit was made to the new intersection station "East 63rd Street", where various leakage problems exist.

The photographs Figures 9.1 and 9.2 were taken during the site visits at Bergen Street Station and East 63rd Street Station.

9.2 GENERAL INFORMATION

The New York City Subway System is one of the oldest in the United States. It is also the most overloaded in the country. The following tables provide general information on system characteristics.

TABLE 9.1 TOTAL TRACK MILEAGE OF RAPID TRANSIT LINES

Construction	Manhattan	Bronx	Brooklyn	Queens	Total
Underground	206.55	30.47	134.88	59.05	430.95
Open, not on structure	-	8.76	51.53	19.61	79.90
On elevated structures	9.74	58.99	67.46	52.67	188.86
Total	216.29	98.22	253.87	131.33	699.71

TABLE 9.2 TOTAL ROUTE MILEAGE

Construction	Manhattan	Bronx	Brooklyn	Queens	Total
Underground	65.22	10.96	40.10	16.73	133.01
Open, not on structure	-	3.38	14.03	6.95	24.36
On elevated structures	4.25	18.60	28.90	21.34	73.09
Total	69.47	32.94	83.03	45.02	230.46

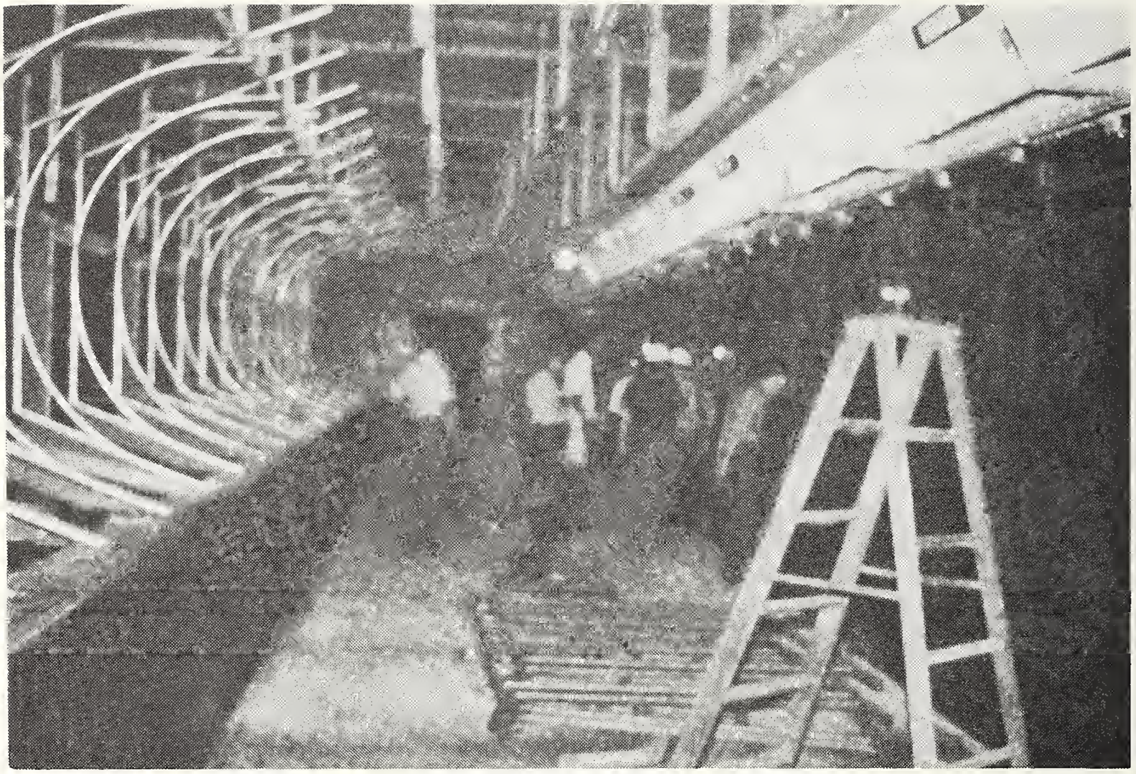


FIGURE 9.1 THE PPA SITE-VISIT TEAM AT THE 63RD STREET STATION

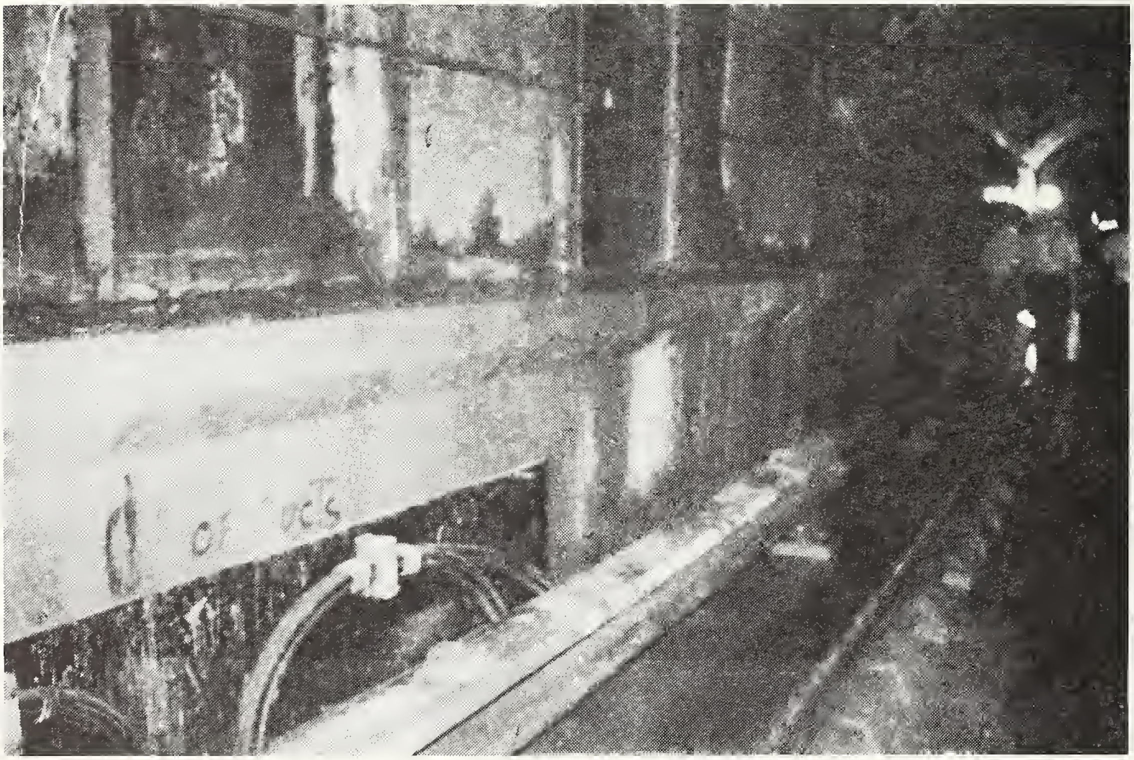


FIGURE 9.2 THE PPA SITE-VISIT TEAM AT THE 63RD STREET STATION

The general scheme of the NYCTA Subway System is shown in Figure 9.3. Figure 9.3 also shows the sites of the most intensive water leaks. Arrows 1, 2, and 3 point to the underground subway site locations that were visited by the site-visit team. Those sites are the most affected and are undermined by the infiltration of ground water.

It should be pointed out that even the oldest tunnels (e.g., Lenox) were not waterproofed when constructed. Ground water levels were below the concrete structures. Over the years the tunnel structure has been deteriorating, and the water table has risen. Now, water carrying soil and oil enters the tunnel at numerous points.

There is one factor which, along with other natural factors, has contributed to the substantial increase of underground water pressure. When New York City almost entirely stopped consuming the underground water from artesian wells for its population needs (this occurred during the 1940s), it resulted in the rise of the underground water table which consequently caused upward pressure on the tunnel structures.

9.3 HISTORY OF WATER INTRUSION PROBLEMS

The water table in New York City has risen as much as 10 ft. over the last 30 years, eroding some subway tunnels so badly that the inverts need to be entirely reconstructed. The Transit Authority is now pumping more than 13 million gallons of water a day, but parts of the roadbed are nevertheless soaking in water.

In the last ten years, the Authority has spent about 50 million dollars strengthening subway floors, installing pumps and building sewer lines to steer water away from the tracks. But when a pump is inoperable, water reaches the third rail and power must be shut off.

Due to extensive water control measures, water has not risen significantly in the last 10 years, but its presence over the years causes difficult problems. For example, stretches of tracks have been weakened, so about 3 percent of NYCTA's underground route miles (7 miles of track) are being carefully monitored and inspected.

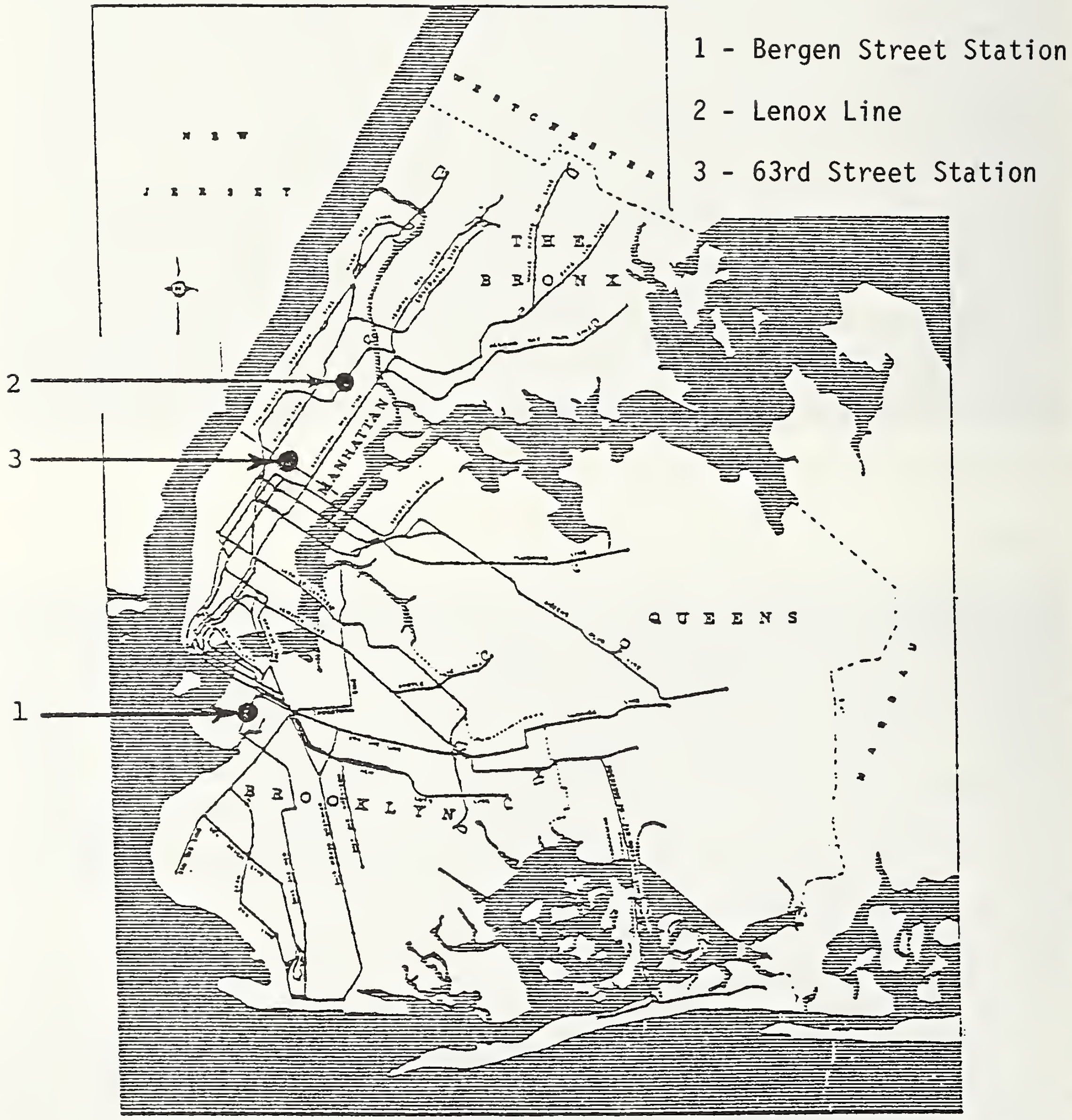


FIGURE 9.3 SITES OF INTENSIVE WATER LEAKS

Other problems relate to the tunnel invert. In most of the subway tunnels, some of them built more than 70 years ago, there is a concrete floor that forms a seal with the sides of the tunnel, creating, in effect, a box. Ideally, the box rests on dirt. But in certain areas where the water has risen, the dirt base has been eroded, and the box is now resting on water. When the trains pass, they put pressure on the floor, but without the solid dirt base the concrete box is no longer properly supported and has a tendency to crack. When the concrete box cracks, water can then get onto the tracks. This leads to the eroding of the ballast which supports the rail ties. Other problems which occur are rotting of the ties, corroding rails and shorting out signal systems.

Figures 9.4 and 9.5 show a tremendous water inflow through the tunnel walls and floor at the Bergen Street Station. The lower level of that station has been closed since 1964.

What follows is the overall review of the water problems in the New York City Subway System as they were described by the NYCTA representatives.

About 5 percent of all leaks look like small rivers. They cannot be stopped without full reconstruction of the main structures, which, in turn, requires an end to tunnel and station operation. Such a situation exists, for example, at Bergen Street Station. About 20 percent of leaks can be described as quite intensive and are treated by outside contractors.

Seventy-five percent of the leaks, described as minor to moderate are being controlled by the Transit Authority's divisions.

In addition to water intrusion there is infiltration of oil and steam from ground transport and working equipment, which complicates overall the problem.

9.4 MAJOR LEAKAGE TYPES AND SITE LOCATIONS

As in the other subway systems (NFTA, MARTA, MBTA, and WMATA) previously studied in this report, the underground structures (tunnels and stations) of the NYCTA Subway System have numerous leaks which occur through the tunnel concrete walls due to concrete shrinkage cracks and structural joints not sealed completely.

FIGURE 9.4 WATER INFILTRATION (BERGEN STREET STATION)

FIGURE 9.5 WATER INFILTRATION (BERGEN STREET STATION)

There are also a number of leaks along the ventilation system and sewer lines. However, the most extensive and dangerous type of leakage in tunnels occurs when the water can infiltrate through partially destroyed tunnel concrete walls and floors, as previously described. Figure 9.6 shows an example of such deteriorated structures.

As can be observed, the central column no longer serves as a structural support, but instead is suspended from the tunnel ceiling. There is a large gap between column pedestal and concrete floor. The concrete floor does not rest on the ground because the ground dirt has been eroded by water. Instead of having a solid base, the floor is supported at several points. Under permanent dynamic loads of trains the concrete floor cracked and split into separate blocks. That created many paths for water to penetrate easily into the tunnel with such intensity that only constant pumping can control the water inflow.

The following is a more detailed description of three subway sites. These sites are shown in Figure 9.3.

9.4.1 Bergen Street Station (No. 1 in Figure 9.3)

The Bergen Street Station is located on the Prospect Park - Coney Island Line (Brooklyn Borough). The station has two levels. The lower level has been closed due to intensive ground water inflow which caused a deterioration of structures and operation systems.

The main water inflow paths are through shrinkage cracks and structural joints and through a ventilation system. The water infiltrates into the station at a very high rate and it has stopped normal operations at the station lower level (see Figures 9.4 and 9.5).

Figures 9.7 and 9.8 depict typical leaks through shrinkage cracks and structural joints on the walls of Bergen Street Station.

A cross section of the station is shown in Figure 9.9. The ground water table is even above the rail base at the top level station. This creates quite a high water pressure on tunnel walls and floor of the lower level station.

Figures 9.10 and 9.11 show a water inflow onto rail tracks and a corrosion of the arch beams.

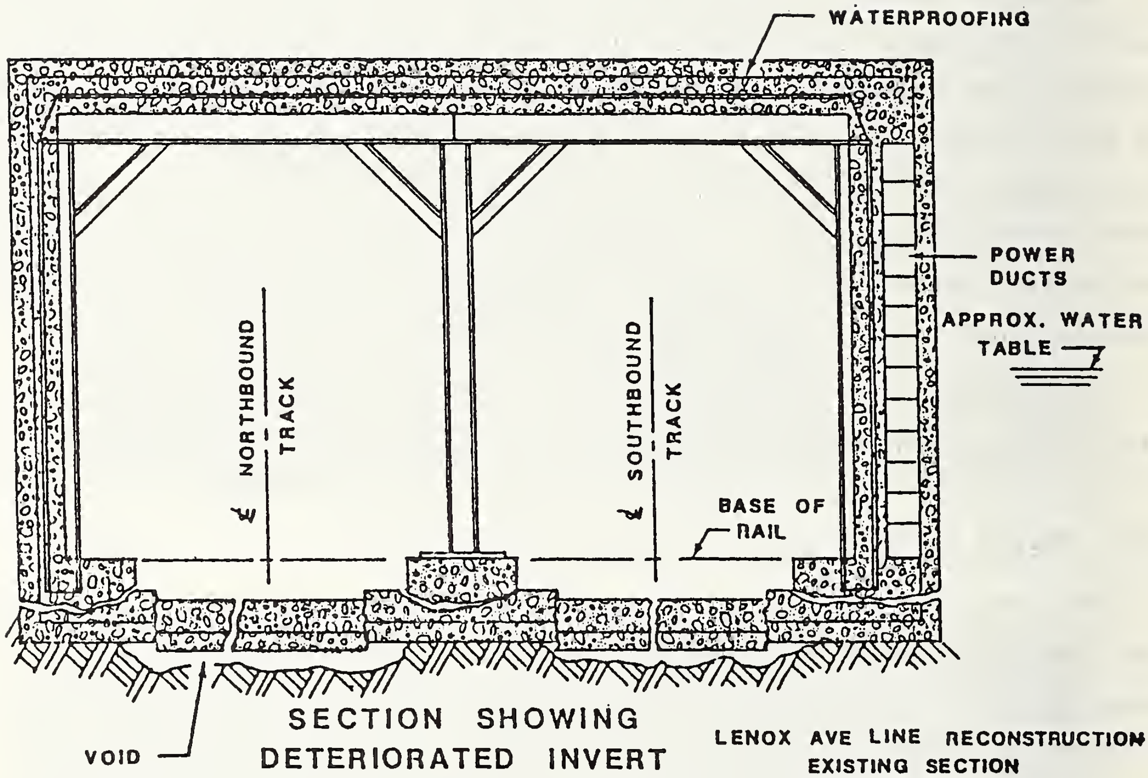


FIGURE 9.6 WATER INFLOW BETWEEN THE BLOCKS OF DESTROYED TUNNEL FLOOR

FIGURE 9.7 LEAKS THROUGH SHRINKAGE CRACKS

FIGURE 9.8 LEAKS THROUGH WALL JOINTS

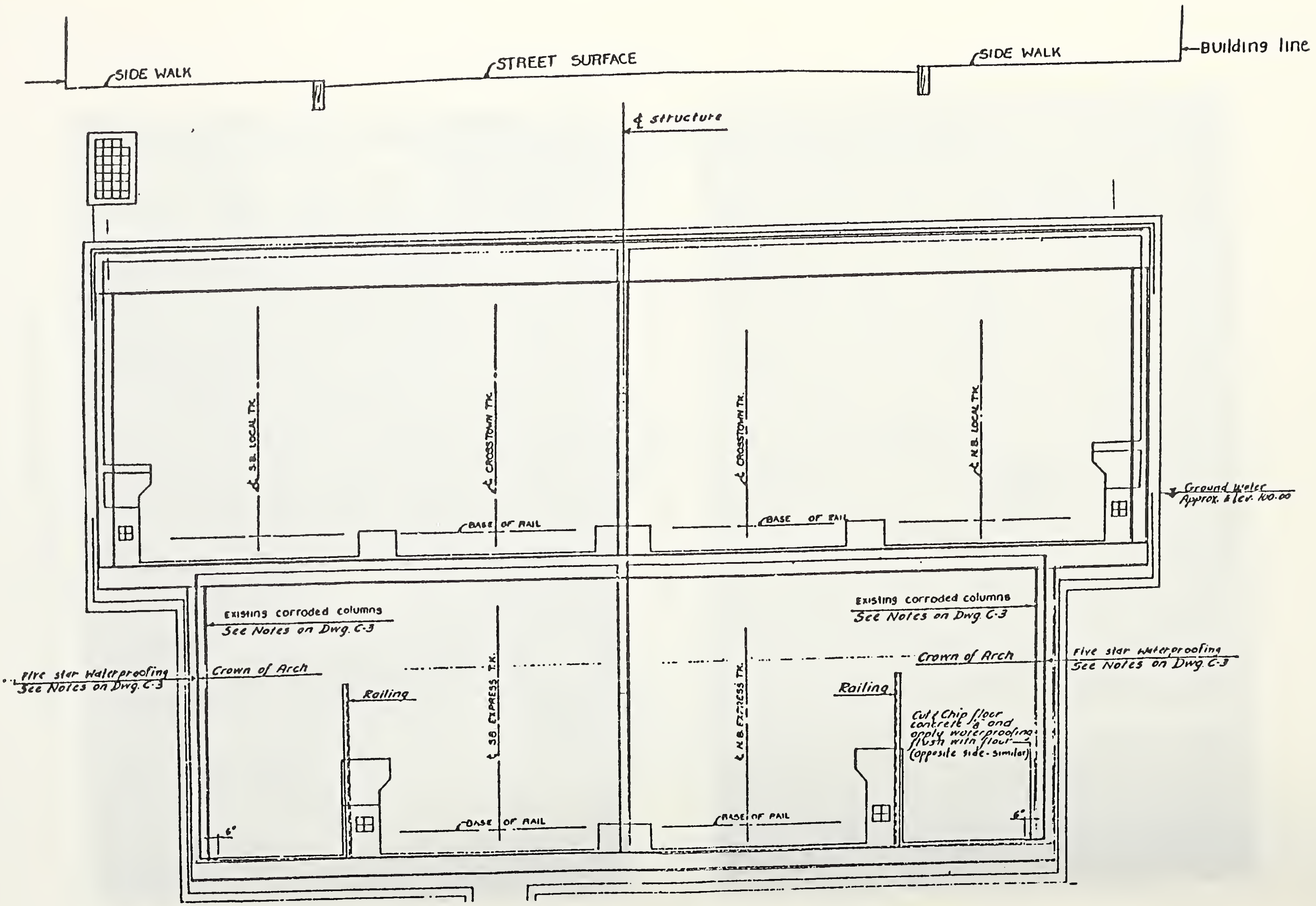


FIGURE 9.9 CROSS SECTION OF BERGEN STREET STATION

FIGURE 9.10 WATER INFLOW ON THE RAIL TRACK (BERGEN STREET STATION)

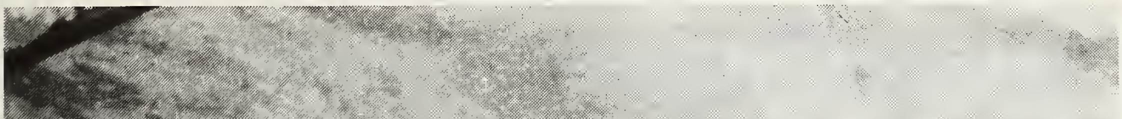


FIGURE 9.11 CORROSION OF ARCH BEAMS (BERGEN STREET STATION)

At the lower level, rehabilitation work is being undertaken. That work includes the following procedures:

1. Removal of architectural cover of walls;
2. Sealing all the cracks with waterproofing materials;
3. Diverting heavy inflow and then sealing all points of water entry;
4. Patching all deteriorated and/or soiled concrete;
5. Installation of waterproof "Volklay Panels" on an inside face of walls and on the top of a floor slab;
6. Filling ventilator bays with concrete up to 6 ft. above the ground water table.

Rehabilitation procedures include drilling holes in walls to locate water leaks. A heavy water inflow, if encountered, shall be channeled away, as is shown in Figures 9.12 and 9.13.

9.4.2 Lenox Avenue Line (No. 2 in Figure 9.3)

This line is one of the oldest in the New York Subway System. It was first opened in 1904 and has been in operation since that time.

Over the years of operation the tunnel structures have seriously deteriorated (see Figure 9.6), allowing a tremendous water inflow. Due to this problem, NYCTA proposes to rebuild the invert and to repair tunnel structures on the Lenox Line between 117th Street and 124th Street. The proposed Lenox Line reconstruction is shown on Figure 9.14.

Groundwater is entering the tunnels and stations at numerous points, and carrying particles of soil. That results in the deterioration of the structures, and may even lead to their collapse. Inflowing water causes corrosion of steel and rotting of ties.

Concrete structures have no steel beams or reinforcing bars. Lack of reinforcement has permitted cracks to grow. This, in turn, has allowed fine soil to enter along with the water and led to breaks in the concrete, which grow at an accelerating rate.

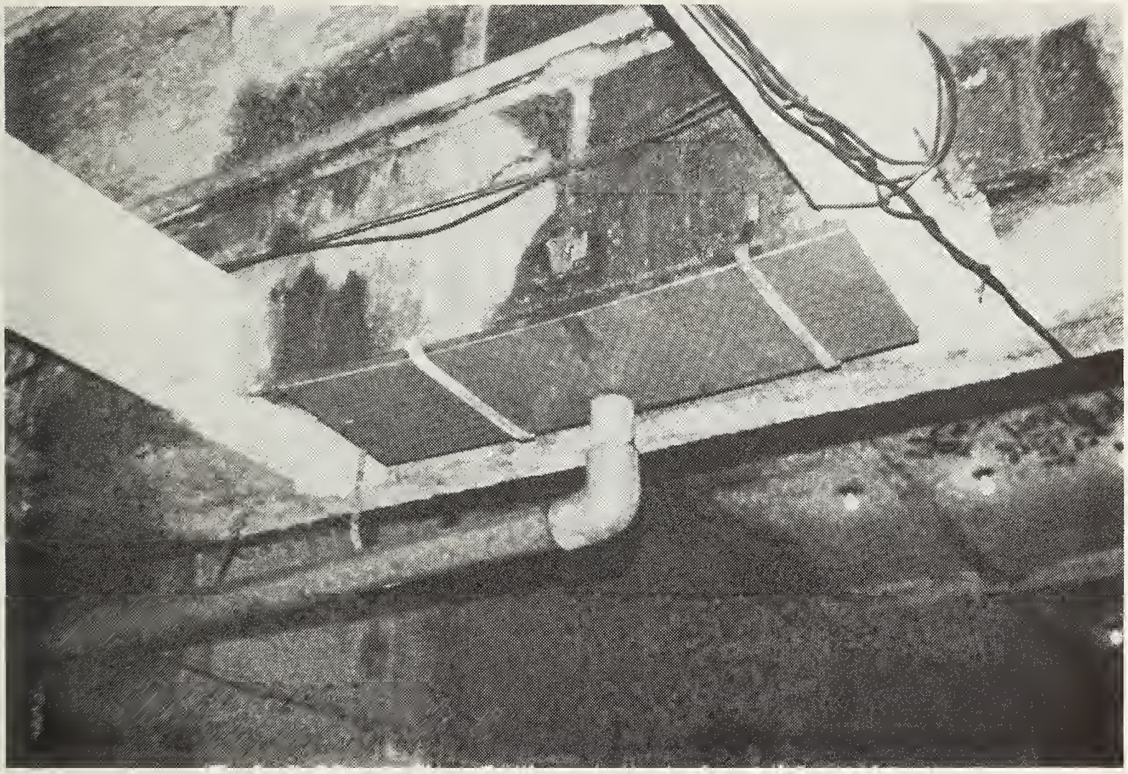


FIGURE 9.12 WATER CHANNELING (BERGEN STREET STATION)

FIGURE 9.13 WATER CHANNELING (BERGEN STREET STATION)

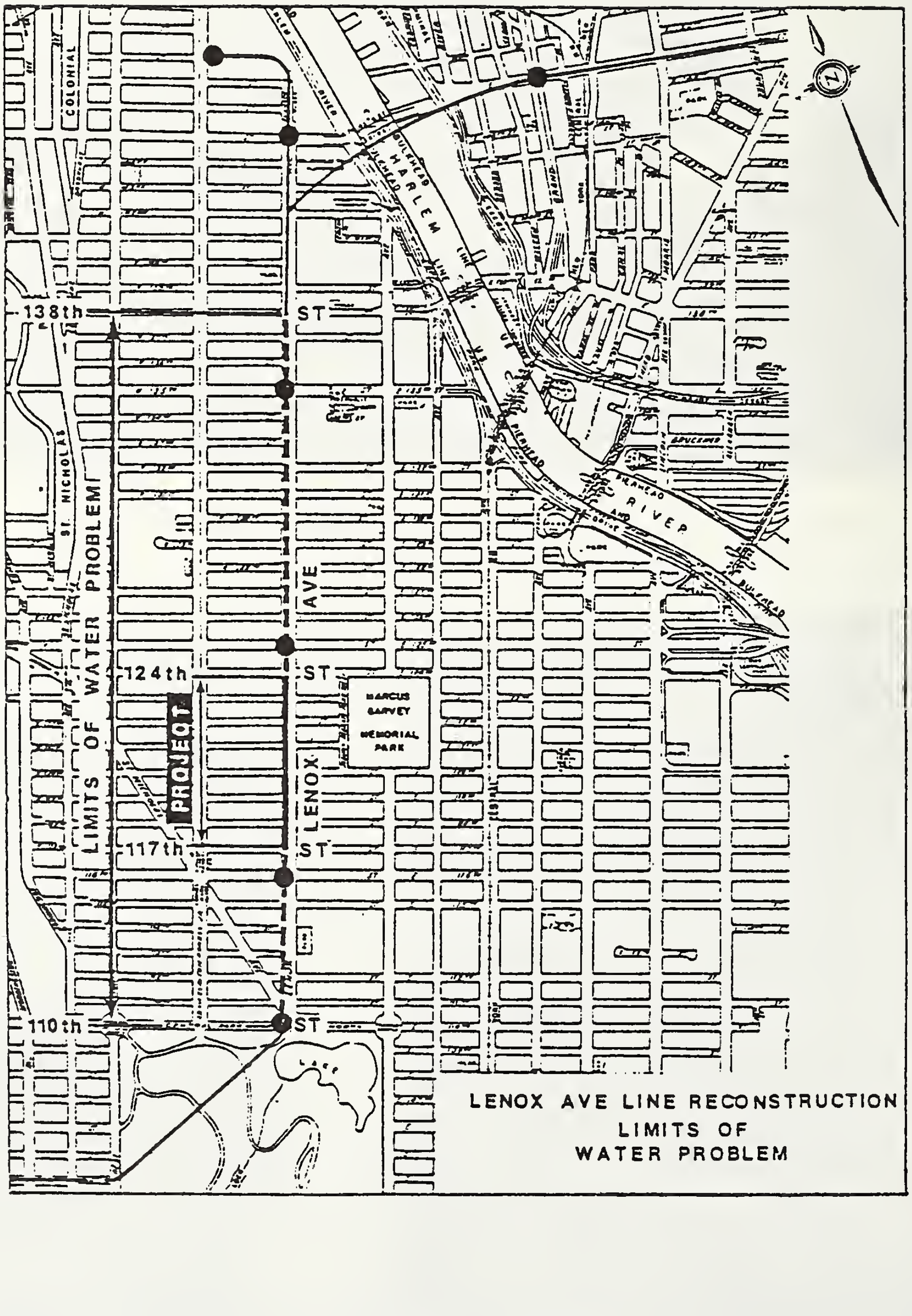


FIGURE 9.14 LENOX AVENUE LINE - PROPOSED RECONSTRUCTION

The quantity of ground water inflow pumped from the 116th Street sump increased from 20 gallons per minute (shortly after opening) to 450 gallons per minute (by 1977). In 1977, 300 cubic ft. of soil were carried in with the water.

The deterioration of the aforementioned segment of the Lenox Avenue Line has reached the point where all transit operations have had to be decreased. Permanent reconstruction measures are required to prevent a possible structural failure.

The estimated cost of the invert reconstruction project is $25 million. The estimated time required to complete that work is about 29 months. During that period, the subway line will be closed to passengers on nights and weekends, requiring a shuttle bus service during the time of closure.

9.4.3 Route-131-A - East 63rd Street (No. 3 at Figure 9.3)

The remodified 63rd Street Station has several levels and large plan and profile sizes. The plans for that station are shown in Figure 9.15.

Shrinkage cracks and joint leaks are the major sources of groundwater inflow at that station. Figures 9.16 and 9.17 show typical leaks through the shrinkage cracks. Figures 9.18 and 9.19 show calcifications in the area of the leaks.

Figure 9.20 also shows leaks through the shrinkage cracks and surface calcification caused by ground water inflow. An attempt to channel or to stop the water inflow using plastic covers is shown. Architectural covering of walls (tile) were removed to allow for water treatment.

There are substantial, although not typical, water deposits at that station, caused by a condensation of water from the humid air. Water drops can be observed everywhere on the structural steel walls and on the equipment. Once train operations begin, air will circulate through the tunnels and station, thus eliminating this problem.

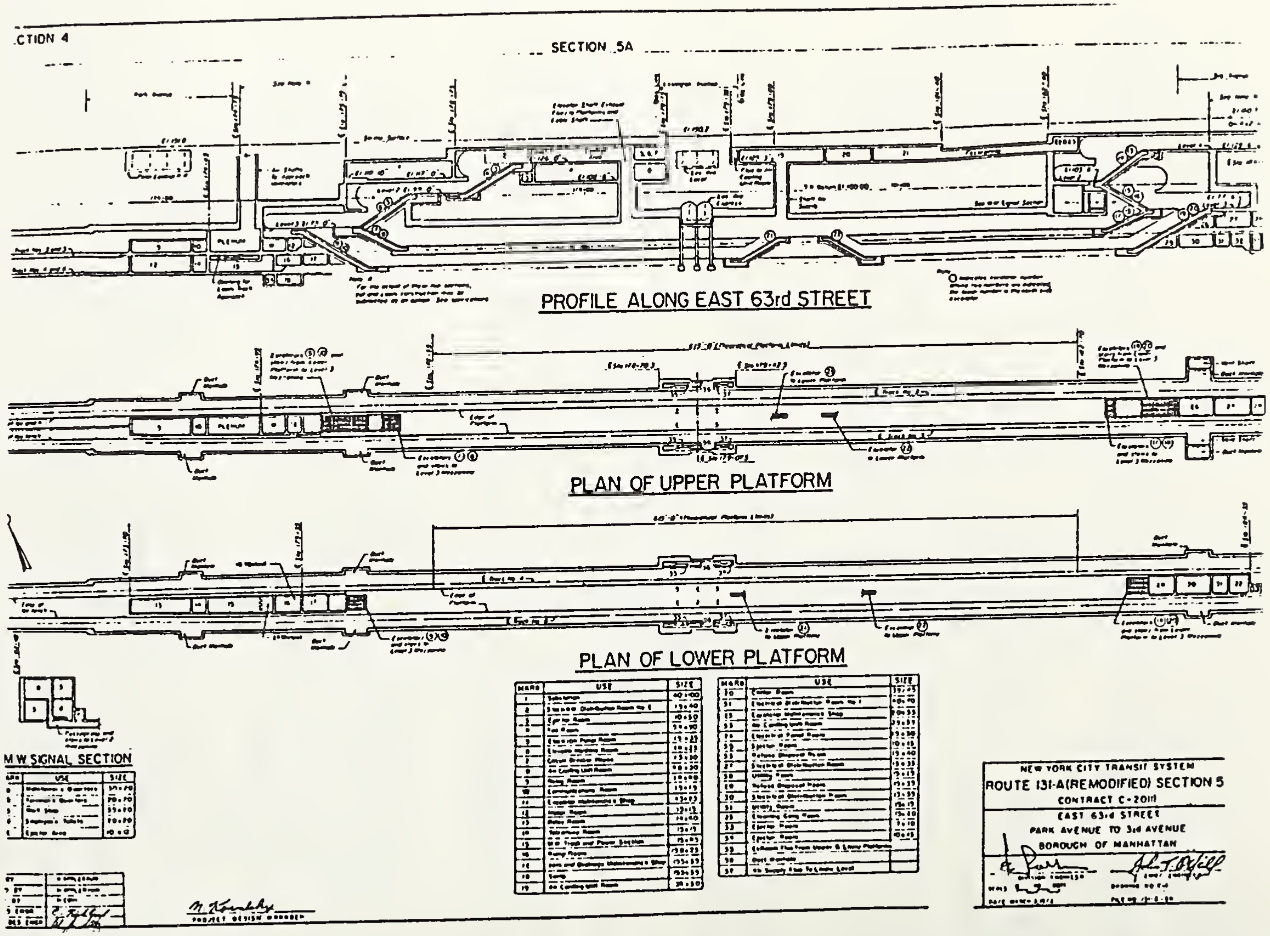


FIGURE 9.15 REMODIFIED PLAN (63RD STREET STATION)

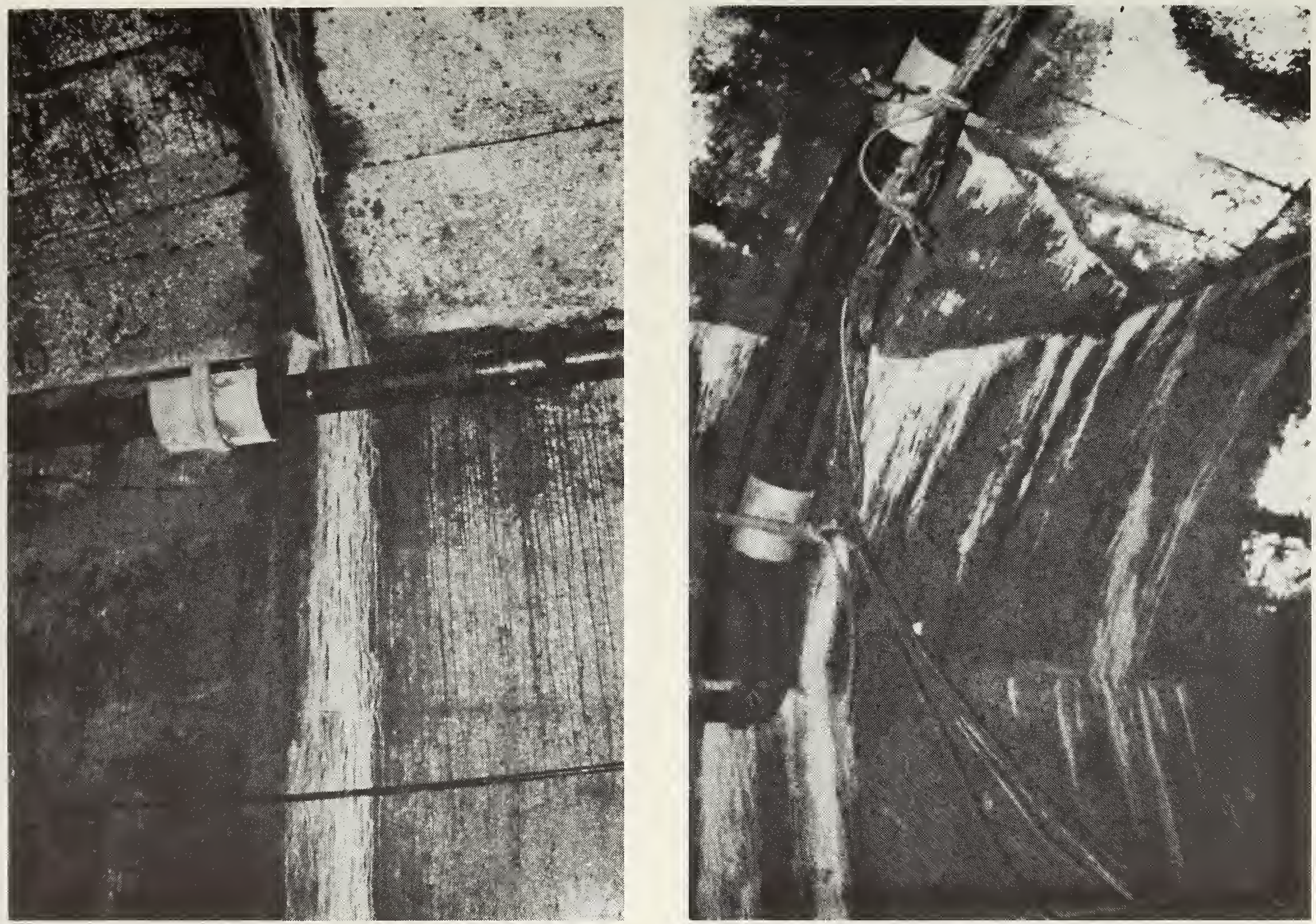


FIGURE 9.16 WATER INFILTRATION THROUGH CONSTRUCTION JOINTS

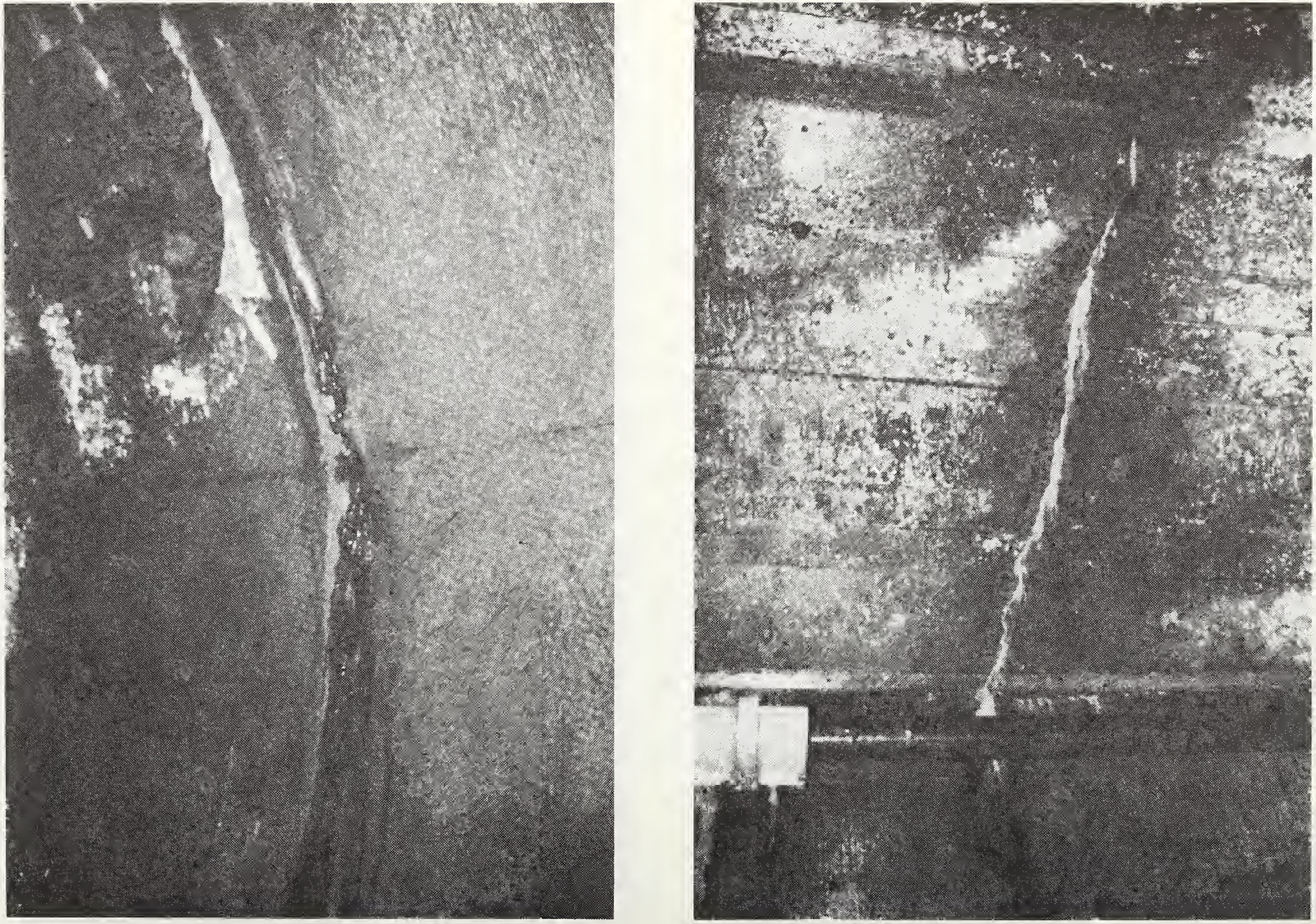


FIGURE 9.17 SHRINKAGE CRACKS (ROUTE 131-A)

FIGURE 9.18 CALCIFICATION AROUND THE CRACKS (ROUTE 131-A)

FIGURE 9.19 CALCIFICATION AND SETTLEMENTS AROUND THE CRACK AREA (ROUTE 131-A)

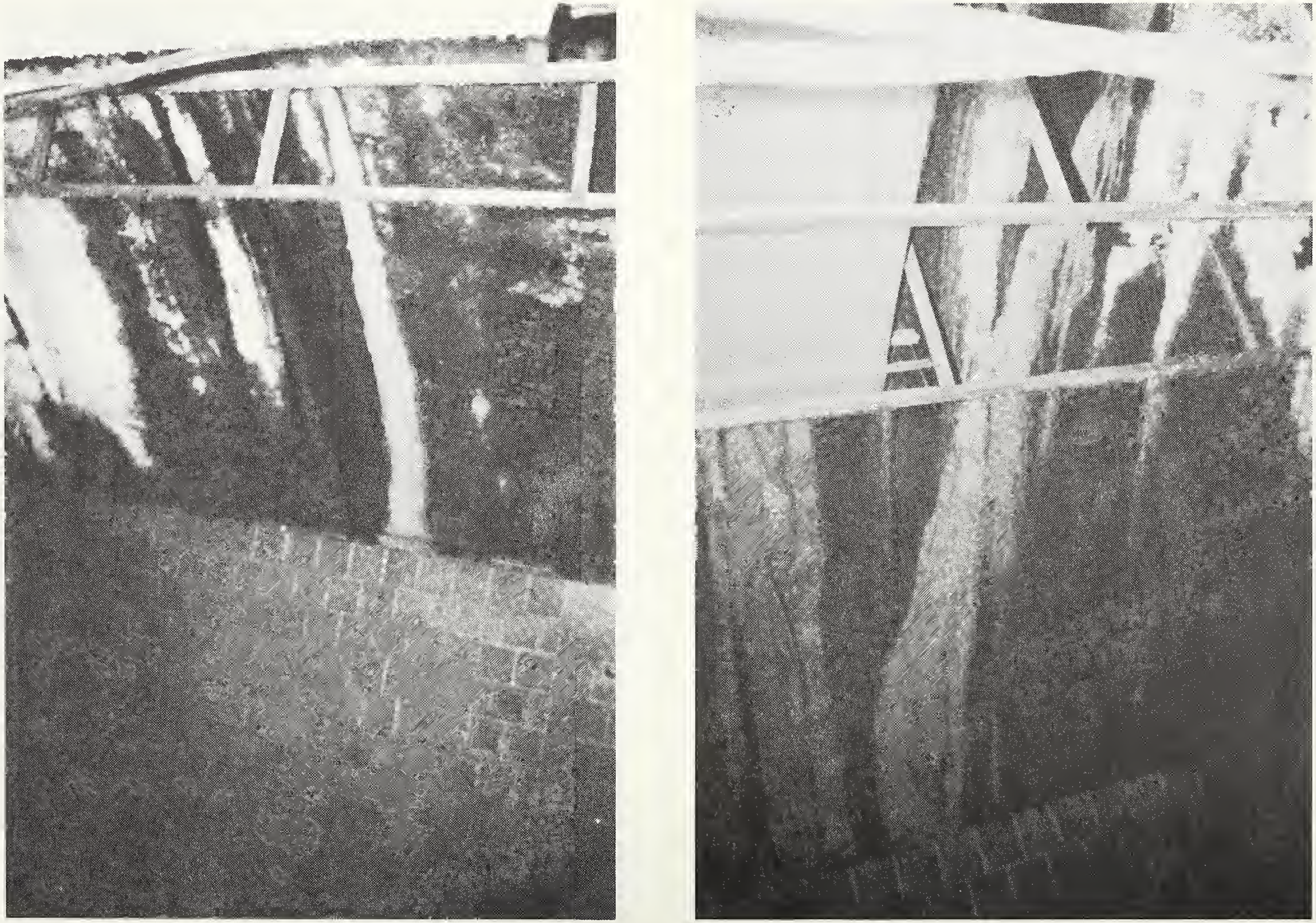


FIGURE 9.20 LEAKS THROUGH THE SHRINKAGE CRACKS BEHIND THE ARCHITECTURAL COVER (TILE WALLS)

9.5 REMEDIAL MEASURES FOR WATER CONTROL

The NYCTA Subway System experiences infiltration by the following substances:

1. Ground water (major factor);
2. City sewer water;
3. Gasoline and oil;
4. Condensed steam from the city underground equipment;
5. Fine soil particles.

The basic methods of water treatment are:

1. Pumping;
2. Channeling (see Figure 5.18);
3. Sealing of cracks by waterproofing materials;
4. Grouting;
5. Total reconstruction of the invert (as proposed for the Lenox Avenue Line).

Pumping is used extensively in cases of high water deposit, as on the Lenox Avenue Line. Channeling is unavoidable at stations where water leaks occur from the arches over passenger sidewalks and platforms. However, channeling by means of steel pipes is not always a good measure because of the proximity of the third rail.

Sealing of exposed cracks is performed by chemical grouting. This filling is widely used in cases where there is not extensive water inflow.

A novel grouting material has been used at the NYCTA Subway System. It is injected into the soil behind the tunnel structure, following a standard grouting technique. It has a low viscosity, which allows injection time to be reduced. In general, it can be used for stopping water seepage into the tunnel as well as for ground stabilization and sealing at headers and joints. There are indications that this new grout material would help in water treatment at the NYCTA Subway System.

On the extension of the East 63rd Street Station of the Route 131-A Line, the concrete tunnel structures were prefabricated on the surface under thorough NYCTA control, and then were sunk to the bottom of the East River. The fact that those tunnels have almost no leaks indicates that pouring and curing processes of concrete, if done properly, may contribute tremendously to tunnel waterproofing.

10. CONCLUSIONS

Based on the results of all the case studies, it has become apparent that structural leaks through concrete floors, walls and ceilings are observed in almost all the subway tunnels and stations studied. Amount of water inflow varies depending on age of tunnels, degree of an invert deterioration, and magnitude of underground water pressure. However, water intrusion was observed even in new tunnels and stations. According to R. W. Permar, Manager of Maintenance of Way and Power of MARTA, "We began having structural leaks through concrete in our new stations almost from the day they were opened in 1979."

The major factors which allow for water inflow through a structure are cracks in the concrete lining. Those cracks are usually caused by either concrete shrinkage or deteriorating joints. Thus, it becomes quite obvious that the principal approach to the water problem solution has to rely on improving the quality of initial concrete construction. All the possible measures of quality control have to be taken to obtain an impervious tunnel lining during the time of its building. Special admixtures have to be studied and used to reduce or prevent concrete shrinkage. The decades of experience of subway construction show that it is more cost-effective to prevent water intrusion in the earliest phases of tunnel construction than to treat the problem later.

It is not possible to give a general recommendation on ways to control water intrusion in subways because an infinite variety of geological and structural conditions exist. Nevertheless, we hope that the practical data collected in the foregoing case studies will be useful in the development of an effective treatment of water leaks in any underground subway structure.

APPENDIX A - DATA COLLECTION QUESTIONNAIRE

CASE NO.____________________________

TRANSPORTATION
SYSTEM LOCATION______________________

NAME OF
PROJECT______________________________

OWNER:____

DESIGNER:____

CONTRACTOR:____

STUDY OF WATER INTRUSION PROBLEMS IN TRANSIT TUNNELS
CONTRACT NO. DTUM60-83-C-71217

A. WATER LEAKAGE PROBLEM IDENTIFICATION

1. Location of water leakage ______________________________
2. Specific details (water characteristics, water pressure, loss of ground) ______________________________
3. Severity of the problem (total in-flow, progressive changes with time) ______________________________
4. Causes of the problem (either identified or suspected) ________
____
5. Related factors and their influence (if any) ______________
____
6. Detrimental effect
   a) on the construction activity ______________________
   b) on the transportation system operation and function ________
   ____
   c) on the surrounding structures ______________________

B. REMEDIAL MEASURES FOR WATER CONTROL

1. Contractual classification of the remedial measures
   a) in-house attempts ______________________________
   b) outside contracts ______________________________
2. Technical classification of the remedial measures
   a) Hydrostatic pressure resistant
      1) exterior and interior (of lining) waterproof coating _____
      ____
      2) air pressure ______________________________
      3) sealing and filling of joints ______________________
      4) grouting (interior or exterior to lining)
      -cracks and leaks
      -types of grouts
      -applications
      -equipment
      -monitoring

2. Technical classification of the remedial measures (continued)

   b) Hydrostatic pressure relieved

      1) water collection
         -panning
         -drainage
         -chases

      2) Provision for the disposition of water according to the expected total in-flow (sump pumps) ______________________

3. Evaluation of remedial measures

   a) Types and volumes of materials being used (generic terms as well as brand names) ______________________

   b) Efficiency of measures ______________________

   c) Side effect on construction or system operation activity ____

      ____

   d) Time required for water control measures (including overtime)

      ____

C. <u>TUNNEL ENVIRONMENTAL DESCRIPTION</u>

1. Structural Description

   a) Types of underground structures (running tunnels, shafts, stations, etc.) ______________________

   b) Method of excavation ______________________

   c) Lining type ______________________

      1) cross section ______________________

      2) materials ______________________

      3) thickness ______________________

      4) joints and details ______________________

2. Geological setting

   a) Tunnel media ______________________

   b) Stratafication ______________________

   c) Permeability ______________________

   d) Category ______________________

C. TUNNEL ENVIRONMENTAL DESCRIPTION (continued)

3. Hydraulic Conditions
    a) Groundwater characteristics
        1) depth____________________
        2) artesian____________________
        3) perched levels____________________
        4) dissolved constituents____________________
        5) corrosion and pollutants____________________
    b) Surface water
        1) flooding____________________
        2) seasonal fluctuations____________________

D. TUNNEL DESIGN AS IT RELATES TO THE WATER PROBLEMS

1. Lining Design
    a) Shape____________________
    b) Thickness____________________
    c) Material(concrete, w/c ratio, admixtures, sand and gravel___
    ____
2. Design of construction procedure____________________
3. Water problem handling design____________________
4. Special design requirements____________________

E. TUNNEL CONSTRUCTION METHODS AS THEY RELATE TO THE WATER PROBLEMS

1. Concrete mix preparation and quality control
    a) Properties of the sand____________________
    b) w/c ratio at various locations____________________
    c) size of the specimen for testing____________________
2. Concrete pouring process and quality control
    a) Concrete delivery to the site____________________
    b) The length of pour____________________
    c) Temperature at the time of pouring____________________
    d) Who supervised the pouring process____________________
    e) What methods were used for installation of concrete________
    f) Concrete workability____________________
    g) Curing procedure____________________
    h) When were the forms removed____________________

2. Concrete pouring process and quality control (continued)

   i) What kind of slumps were used and how they were tested __________________________________

   j) Time interval per number of batches ______________________

3. Special water handling measures

   a) Dewatering during pouring and curing processes ____________

   b) Special dewatering (if necessary) in completed tunnels _____
   ____

F. COST DATA FOR WATER CONTROL

1. Waterproofing program costs ______________________________

2. Costs for additional investigation of geological and hydraulic conditions ____

3. Costs of possible tunnel alignment versus groundwater control measures ____

4. Costs of routine maintenance (labor and materials ____________

5. Cost impact on the system in a case of non-repairing leaks _____
   ____

APPENDIX B - BIBLIOGRAPHY OF GROUTING TECHNIQUES AND METHODS

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