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STUDY OF SUBWAY STATION DESIGN AND CONSTRUCTION

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16. Abstract

Due to the high cost of urban underground transit construction in recent years, construction practices used in other countries were reviewed to determine if construction methods which are commonly accepted there might be adapted to U.S. practice. Design and administrative practices were also reviewed to determine which have the most significant effect on station costs to assure that future system developers are aware of the items that offer the greatest opportunities to control costs.

Using 13 on-site interviews in Europe and North America, unusual construction methods, design considerations, and general considerations which offer opportunities for cost savings were identified. Two basic points for reducing costs were emphasized repeatedly by those interviewed: the basic recommendation for obtaining economy in station design and construction is to take advantage of every opportunity which the locale and site offer; and while final design and construction practices are the most visible sources of expenditure, it is almost universally the early policy, planning, and design decisions which have the greatest effect on the final cost of a transit project.

With the experience and opinions of the many transit authorities and construction agencies and a review of current literature as a base, a set of seven recommended subway station designs were developed. To examine costs, three series of estimates were performed comparing the station types among themselves, comparing the costs of varying major station dimensions, and comparing costs of alternative construction methods, such as slurry walls and other excavation support systems which performed multiple functions.

17. Key Words
Subway Station, Underground Construction, Slurry Walls, Secant Pile Walls, Tunnels, Station Design, Cost-Saving Techniques

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PREFACE

The study of subway station design and construction is part of the Urban Mass Transportation Administration's (UMTA) Tunneling Technology Program. The study was designed to produce guidelines for underground construction for urban transportation planning, design, and construction. The goals of the Tunneling Program are to reduce construction costs, increase rate of construction, insure the optimum use of tunnels in transportation systems, and educate planners in advantages of the proper use of tunnels. The study was sponsored by the Office of Rail Technology, Office of Technology Development and Deployment of the U.S. Department of Transportation (DOT) Urban Mass Transportation Administration.

UMTA's Tunneling Technology work is managed by the Transportation Systems Center in Cambridge, Mass as part of the Urban Rail Supporting Technology Program, R.J. Madigan, Mgr. This report has been prepared by DeLeuw, Cather and Company under contract to the Transportation Systems Center (TSC). Skidmore, Owings & Merrill served as a subcontractor, and their main contribution has been the design of the station types. S.J. Gozzo served as TSC's Technical Monitor on this contract and coordinated the overall effort.

Many transit authorities and industry professionals responded to requests for information, including R. B. Peck, D. U. Deere, J. P. Gould, P. C. Rutledge, W. N. Lucke, W. H. Mueser, and J. Spiegelman.

A panel of engineers and contractors served as a review board for this study. The panel members who reviewed drafts of this report and made numerous constructive suggestions are R. B. Peck, C. H. Atherton, J. F. Hoban, T. R. Kuesel, C. E. Mergentime, and W. H. Paterson. Also as part of the review cycle, an advisory board from the American Public Transit Association read and discussed the draft report.

One of the most important parts of this study, i.e., the onsite visits, would not have been possible without the kind cooperation of the transit authorities and their staffs in Europe and North America. They provided warm receptions to the Study Team, arranged tours of job sites, answered questions, discussed progress, and contributed to the construction activities. Their assistance in this project is gratefully acknowledged.

All photographs appearing in this volume were taken by the staff of De Leuw, Cather & Company unless otherwise stated.

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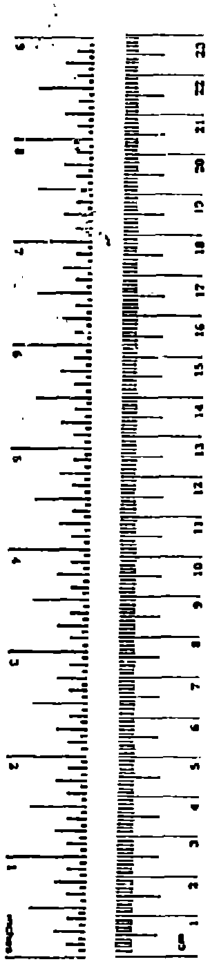
METRIC CONVERSION FACTORS

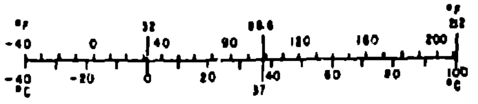
Approximate Conversions to Metric Measures

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



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



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Chapter 1
INTRODUCTION

Over the years, those responsible for urban transportation facilities have recognized that ever increasing street traffic has become a major impediment to efficient flow of transit vehicles. Therefore, urban officials developed additional right-of-way for public transportation in congested areas by placing these facilities underground. Subway systems, or rather urban transit systems constructed underground, have been developed in this country in several cities. The number of potential systems increases each year as traffic congestion, environmental pressures and potential energy shortages rekindle the public interest in urban transportation systems.

Underground stations are an important part of the total cost of an urban transit system. Underground stations can cost two-and-one-half to three times as much as an aerial station, and four to five times that of an at-grade station. Yet, because of the unacceptable impacts of aerial and at-grade stations in central city areas, underground stations are necessary and will continue to be desirable.

Because underground stations will continue to be used, and because the cost of underground construction has increased in recent years, it is advantageous to review construction practices in use in other countries to determine if methods or techniques are commonly accepted which might be adapted to U.S. practice. It is also advantageous to review design practices which might have the most significant effect on station costs to assure that future system developers are aware of the items that offer the greatest opportunities to control costs.

With these thoughts in mind, this study presents the results of case studies of the experience in underground rapid transit systems in the United States and foreign countries. Using on-site interviews, unusual or innovative construction methods, design considerations, and general considerations which offer opportunities for cost savings were identified. With the experience and opinions of the many transit authorities and construction agencies as a base, a set of recommended subway station designs was developed. Finally, cost relationships were developed to assure that system developers can pursue economic solutions by directing their attention to the most cost-significant elements of subway station construction.

STUDY METHODOLOGY

The method used to attain the study objectives consisted of three parts. Industry practice was reviewed using a literature search and on-site investigations to determine design, construction, and administrative practices of selected transit properties. Station types were developed to reflect the observations within the context of particular urban and geotechnical conditions. The cost relationships of the station types and the cost sensitivity of the separate elements were then studied.

On-Site Investigations

By visiting a number of transit systems in Europe and North America, the Study Team was exposed to the planning, design, and construction techniques used in developing these systems. The systems were selected for on-site investigation based on their urban and geotechnical characteristics and the different construction methods used to satisfy these conditions. It is important to recognize that only limited time was available for interviews, usually two days in each city. Also, while much useful information was obtained, not all of the desired information was available in every city.

Experience from on-site visits and the background of the Study Team in rapid transit were supplemented by communications with additional transit authorities, recognized experts in the field, and review of current literature. This combination of data inputs gave the study a sense of perspective of planning, design, and construction practices used in various transit systems.

Station Types

After reviewing design and construction practices in selected cities, seven underground station types were developed to illustrate design responsiveness to different sets of geotechnical and urban conditions. The station types are representative of typical solutions to design problems. These station types were chosen, because they are likely to be applicable to future U.S. conditions. A number of variations were derived from the seven types.

Elements of the stations were contrasted among station types to demonstrate their potential to satisfy sets of urban and geotechnical conditions. The potential application of various kinds of construction techniques and other practices to each station type was examined. This effort was limited to practices which are not widely used today for U.S. transit projects.

Cost Considerations

After development of the seven station types and discussion of their various applications to selected conditions, costs of the typical stations were compared. The significance of the cost impacts of basic planning or early design decisions was developed to show the relative importance of cost awareness at the early stages of project development.

Finally, conclusions and recommendations are presented which lead to the goal of more economical underground subway stations. Recommendations for the direction of future research into this aspect of urban transportation systems are presented.

Chapter 2
SUMMARY AND CONCLUSIONS

The cost of underground stations is an important part of the cost of an urban rapid transit system. Urban rapid transit systems in other countries were studied to determine if these costs, which have increased steadily in recent years, could be reduced for future U.S. transit systems. The objective was to determine if there were construction methods presently being used which were either unknown or known but not commonly used by U.S. system developers, designers, and contractors. The Study Team concluded that certain construction methods have been used to a greater extent in other countries, depending on site conditions and other local controls. In several cases, there was an element of experimentation with these methods, indicating no universal acceptance of their applicability.

The investigation showed that cost-savings opportunities lie in three general categories: administrative, design, and construction. These three are summarized, as are the conclusions reached as a result of the analysis of estimates of cost for seven station types developed for the study. Aside from these findings, two basic points for reducing costs were emphasized repeatedly by those interviewed during the on-site investigations:

1. The basic recommendation for obtaining economy in station design and construction is to take advantage of every opportunity which the locale and site offer.

2. While final design and construction practices are the most visible sources of expenditure, it is almost universally the early policy, planning, and design decisions which have the greatest effect on the final cost of a transit project.

ADMINISTRATION

1. In many countries, contracting procedures encourage the construction contractor to use innovative methods, and provide incentives for him to ensure that his ideas and experience are brought to bear to save money. Contracting procedures in the

United States have recently been studied by the U.S. National Committee on Tunneling Technology. The procedural changes recommended in the study should be given careful consideration.

2. A major transit project can benefit immensely from the full support of the leaders of the urban community. Local leadership is vital to assure timely decisions and cooperation of local pressure groups and urban agencies.

3. An identifiable sense of commitment from the community to urban rapid transit or an underground transit project removes major obstacles from the path of transit progress. This attitude minimizes delay and thus results in large savings.

4. The organizational structure of the agency constructing the transit system should be designed to promote the full support of existing urban public works agencies. Interagency requirements, such as traffic maintenance and depth of cover for future utility installation, should be decided on a case-by-case basis, keeping in mind the cost implications and the overall benefit to the community.

5. Scheduling of critical work elements should be recognized as a potential source of time and cost savings. Advance contracts for utility and underpinning work should be utilized where cost savings are indicated.

DESIGN

1. Good design and proper selection of station type and configuration recognize the importance of site restrictions and maximize the opportunities at the station site.

2. Decisions on station characteristics made early in the planning and design phases offer the most significant opportunities to control costs of underground stations. These decisions include the determination of station location, volume and depth of excavation.

3. Geotechnical conditions have a significant impact on construction costs, sometimes determining the feasibility of station locations. Sufficient geotechnical data should be obtained early in the planning phase to preclude commitments to station locations which might be impractical or costly.

4. For open cut or cut-and-cover stations, depth of excavation should be minimized. For mined stations, the volume of excavation should be minimized to reduce costs. For both types of construction, station width and length should be established realizing their ultimate impact on station cost.

5. Earth mined excavation is almost always more costly than open cut or cut-and-cover at normal depths. However, mining in competent rock can be competitive with open cut construction. The option to use mined excavation in an urban environment is vital to develop more acceptable solutions to the problems of locating underground stations in intensely developed areas.

6. Urban conditions (land use, traffic, street patterns, right-of-way widths, and utilities and other subsurface development) have a major impact on design decisions and construction costs. Mining satisfies or accommodates the constraints imposed by urban conditions better than cut-and-cover construction.

7. Architectural quality with construction economy can be achieved by utilizing a relatively compact and simple station shape; modest dimensions for length, width and height; minimum depth of cover; repetitive structural formwork or structural shapes; and repetitive finish elements.

8. Station finish should be designed to recognize that water penetration of the structure is almost inevitable. Finish materials which stand free from the structure permit control of groundwater seepage and accommodate generous construction tolerances.

CONSTRUCTION METHODS

1. Certain construction methods have been used to a greater extent in foreign countries than in the U.S. These methods include slurry walls and

secant pile walls serving several functions simultaneously, such as excavation support, underpinning, and final station structure. However, each potential application of these techniques is a site-specific decision. The economics of each situation must be studied considering all controls and restraints.

2. For shallow, open cut stations where ground conditions and site conditions are favorable, economies can be realized by using cast-in-situ or precast concrete semi-rigid excavation support systems to perform multiple functions.

3. In open cut construction, under-the-roof techniques have been used to minimize the duration of impact to the surface. Even with this technique, significant surface disruption is necessary, and costs of excavation are increased.

4. The most cost-sensitive factors in open cut construction are site conditions (underpinning, utility work and traffic maintenance) and volume of excavation. Attempts to achieve significant cost savings should focus on those items.

5. Tunneled stations and their normally greater costs are becoming more acceptable due to their reduced impact on the urban area.

6. The most cost-sensitive element of mined stations is the volume of the excavated opening, assuming reasonable ground. Mined stations are more dependent on geotechnical conditions than are cut-and-cover stations. Changes in ground conditions or the presence of large amounts of groundwater can have serious cost implications for mined stations.

7. Shotcrete, mesh and steel ribs have been used successfully in earth tunnels and in rock tunnels with rock bolts as temporary and permanent excavation support.

8. In many cities, ground improvement techniques are used together with semi-rigid walls to preclude underpinning. Ground improvement is used extensively for mined station construction in earth.

STATION COSTS

1. Seven station types were developed to represent the range of solutions available. Innumerable variations exist, and several variations are discussed in Appendix A.

2. Estimates showed a variation in cost of over 100 percent for the extremely shallow cut-and-cover station compared to the station mined as a large single opening in earth. Tunneled stations were generally more costly than cut-and-cover stations for the conditions assumed. However, multiple chamber rock tunnel stations were virtually identical in cost to the reference station.

3. Estimates indicated that of total station cost for the reference station, about 40 percent is site-controlled items and excavation, 35 percent is structural items, and 25 percent is finish and equipment. The most significant opportunities for cost savings lie in the site selection and proper use of the site opportunities and restrictions.

4. Cost is very dependent on station volume for mined stations, and station volume and depth of excavation for open-cut stations. Consequently, design and planning decisions should minimize these elements where possible.

5. For specific locations where site conditions are favorable, semi-rigid excavation support systems combined with the station structure can offer cost savings opportunities at current U.S. construction prices and should be given consideration in shallow cut-and-cover stations.

Chapter 3

ON-SITE INVESTIGATIONS

The basis for this study was the on-site investigation of a selected group of transit properties to determine if there are unusual or innovative design or construction techniques which might be applied to future transit system development in the United States. As a result, much of the commentary, suggestions, and opinions in other chapters of the report was derived from recent Study Team experiences during visits to transit systems in North America and Europe. Information gained from literature on underground station design and construction and from data on transit systems worldwide also contributed to this study.

The project was generally limited to the investigation of stations constructed in the past 15 years and included underground stations worldwide. Time and cost constraints required the worldwide survey to focus on a limited number of transit systems. Systems which were not visited were not necessarily outside the interests of this study.

The selection of systems for on-site visit was guided by three general considerations:

1. Accessibility of the site and availability of technical information.
2. Variety of urban and geotechnical conditions.
3. Variety of construction techniques available for observation.

Using these considerations, the Study Team reviewed data available for transit systems throughout the world, and recognizing the time and budget constraints, selected thirteen systems for detailed inspection. Accordingly, transit systems in these cities were visited and transit system officials informally interviewed. Where possible, construction sites were visited. Transit systems were observed in London, Paris, Brussels, Munich, Stockholm, Milan, Rome, Montreal, Toronto, Mexico City, Chicago, San Francisco, and Washington, DC. Transit authorities who received the visiting Study Team are listed in Appendix B.

As a step in the selection process, the Study Team indentified those characteristics in each potential system which might be investigated to satisfy the objectives of the study. The selection matrix for the thirteen systems chosen for on-site inspection is shown in Table 1. The different rapid transit systems were studied by concentrating on factors which appear to have the most influence on total time and cost to produce a station and the general conditions which influence cost factors. Judgments by the Study Team on the degree of success of each transit system in meeting cost objectives were avoided. In fact, detailed cost information was generally not available to the Study Team.

One of the major objectives of the on-site interviews was to determine if cost saving techniques exist that might be used in future U.S. transit system development. During the course of the investigation, it became obvious that all of the systems visited had the common objective of constructing an acceptable transit system in the most economical manner. The Study Team observations, based on the interviews, were that:

1. Each system developer believes his system is being constructed using the most economical solutions.

2. Once the decision is made to construct a transit project underground and the station site is selected, cost effective design and construction solutions become site-specific. General rules or standards or systemwide solutions tend to lessen opportunities to take advantage of conditions peculiar to the site.

3. Cost saving efforts are centered in three particular categories: administrative, planning and design, and construction methods.

The next three chapters of the report address these three categories of cost saving practices. Study findings are presented which result from data search, on-site visits, and interviews, as well as the personal experience of the Study Team and of those interviewed in the systems selected for on-site investigation.

Table 1
Significant Elements of System Selection

I. Urban and Geotechnical Conditions	Chicago	San Francisco	Washington, D.C.	Montreal	Toronto	Mexico City	London	Stockholm	Munich	Paris	Brussels	Milan	Rome
1. Urban Influences													
(1) Intensity of development	○	●	◐	○	●	◐	●	○	◐	●	◐	○	◐
(2) Range of surface conditions	○	◐	◐	●	●	●	●	◐	●	●	◐	●	●
(3) Integration of transit with commerce and urban development	○	◐	○	●	●	○	●	◐	●	◐	●	◐	◐
(4) Environmental considerations	●	●	◐	●	●	●	◐	◐	●	◐	●	◐	●
(5) Community influence	○	○	○	○	○	○	○	○	○	○	○	○	○
(6) Cultural effects	◐	○	◐	○	○	●	○	●	●	○	○	○	○
(7) Public dependence on transit	◐	○	○	◐	●	●	●	◐	◐	●	◐	◐	○
(8) Functional requirements on transit	○	●	○	◐	◐	●	○	○	○	●	◐	●	○
(9) Transit operational characteristics	◐	○	○	●	○	◐	●	○	◐	●	●	○	○
2. Geotechnical Categories													
(1) Rock	○	○	●	●	○	○	○	●	○	○	○	○	○
(2) Earth	◐	●	○	○	◐	●	●	○	●	◐	◐	◐	●
(3) Mixed face	○	○	●	○	○	○	○	○	○	◐	○	○	◐
(4) Significant groundwater influences	○	○	◐	○	◐	●	○	◐	●	●	●	○	◐
(5) Combination of unusual difficulty	○	●	○	○	●	●	○	○	○	◐	◐	○	●

● Major Attraction

◐ Moderate Attraction

○ No Particular Contrast Relative To Others

Table 1 (Continued)
Significant Elements of System Selection

II. Administrative and Design Considerations	Chicago	San Francisco	Washington, D.C.	Montreal	Toronto	Mexico City	London	Stockholm	Munich	Paris	Brussels	Milan	Rome
1. Administrative Opportunities and Constraints													
(1) Legal and institutional environment	○	○	○	○	◐	●	●	●	◐	○	○	○	○
(2) Organizational framework	◐	●	◐	◐	●	●	●	◐	●	●	◐	◐	◐
(3) Contracting procedures	○	○	○	○	○	●	◐	●	◐	●	○	○	○
(4) Multiple agency relationships	◐	○	○	○	○	○	○	○	●	●	◐	◐	◐
(5) Construction management practices	○	●	◐	◐	◐	◐	◐	◐	●	◐	◐	○	○
2. Planning and Design													
(1) Planning and design in progress	○	○	●	●	◐	○	◐	◐	●	◐	●	●	◐
(2) Expansion plans	●	○	○	●	◐	◐	◐	●	●	●	●	●	◐
(3) Influence of patron volumes	◐	○	○	◐	◐	●	●	◐	◐	●	◐	◐	○
(4) Influence of surface activity	◐	◐	◐	●	●	●	●	◐	●	◐	◐	◐	●
(5) Influence of travel corridors	◐	●	●	○	●	○	○	○	◐	○	●	●	○
(6) Influence of street patterns	○	◐	◐	◐	◐	●	●	○	○	◐	●	●	○
(7) Subsurface development	○	◐	◐	○	◐	○	●	○	◐	●	◐	◐	●
(8) Variety of station component layout	◐	●	○	●	○	◐	●	◐	○	●	○	●	●
(9) Station geometry and space relationships	◐	◐	●	◐	●	●	◐	◐	◐	○	◐	◐	◐
(10) Finish techniques and materials	◐	○	●	○	●	●	◐	◐	◐	○	◐	●	◐
(11) Integration of travel modes	◐	○	○	◐	●	◐	●	◐	●	●	◐	◐	○
(12) Patron security	●	◐	●	○	○	○	○	○	○	○	○	○	○
(13) Facilities for the handicapped	●	●	○	○	○	○	◐	●	○	○	○	○	○

Table 1 (Continued)

Significant Elements of System Selection

III. Construction Methods	Chicago	San Francisco	Washington, D.C.	Montreal	Toronto	Mexico City	London	Stockholm	Munich	Paris	Brussels	Milan	Rome
1. Major Practices													
(1) Quantity of work in progress	○	○	●	●	◐	○	●	●	●	●	●	●	●
(2) Rock mining	○	○	●	●	○	○	○	●	○	◐	○	○	○
(3) Enlargement of shield driven tube	○	○	○	○	◐	○	●	○	◐	○	○	○	●
(4) Earth mining large openings	○	○	○	○	○	○	○	○	●	●	○	●	○
(5) Under-the-roof sequence	○	○	○	○	◐	○	◐	○	○	◐	●	●	○
(6) Slurry wall	○	◐	○	○	○	●	◐	○	○	●	●	●	●
(7) Secant pile wall	○	○	◐	○	○	○	●	○	●	○	○	○	○
(8) Precast wall	○	○	◐	○	○	○	○	○	○	●	○	○	○
2. Specific Techniques													
(1) Variety of uses for shotcrete	○	◐	●	○	○	○	○	●	●	◐	○	●	○
(2) Variety of techniques to support existing structures	◐	●	●	○	○	◐	◐	◐	●	●	●	●	●
(3) Chemical and cement grouting	○	○	○	○	◐	○	○	◐	●	●	◐	●	◐
(4) Earth stabilization by specialized techniques and equipment	○	◐	○	○	○	●	◐	○	○	◐	◐	◐	◐
(5) Groundwater control	○	●	◐	○	●	○	○	○	●	●	●	○	◐
(6) Leakage and infiltration control	○	○	○	○	○	●	○	●	○	○	○	○	○
(7) Traffic umbrella	○	○	○	○	○	○	●	○	○	○	○	○	○
(8) Precast/prefab structural liners	○	○	◐	◐	◐	○	◐	○	◐	●	○	◐	◐
(9) Precast roof/framing	●	○	●	○	●	●	◐	○	◐	○	◐	●	○

Table 1 (Concluded)

Significant Elements of System Selection

IV. Factors of Significant Cost	Chicago	San Francisco	Washington, D.C.	Montreal	Toronto	Mexico City	London	Stockholm	Munich	Paris	Brussels	Milan	Rome
(1) Geotechnical influence on type of basic structure	○	○	◐	●	○	●	●	●	○	○	◐	●	●
(2) Cost effects of station depth, width, length	●	●	●	◐	◐	●	◐	◐	◐	●	●	◐	◐
(3) Station clear spans and open space	●	◐	●	●	○	●	○	○	○	◐	●	○	○
(4) Support of adjacent structures	◐	●	●	○	◐	○	○	○	●	●	●	●	◐
(5) Utilities handling	◐	●	●	○	◐	●	○	○	○	○	●	●	◐
(6) Traffic patterns and handling	○	●	◐	○	◐	○	●	○	●	◐	◐	◐	◐
(7) Right-of-way influence on structures	○	○	○	○	◐	◐	●	○	○	○	○	○	○
(8) Operations and maintenance influence	●	◐	○	●	●	●	●	○	○	○	●	◐	○
(9) Station environment control	◐	○	●	●	○	◐	●	○	○	○	○	○	○
(10) Degree of standardization	●	○	●	○	●	●	◐	○	◐	○	◐	●	○

Following are descriptions of the Study Team's observations during its brief visits to the selected cities. The descriptions reflect their general impressions and opinions. Detailed descriptions of these transit systems are available in other sources and are not presented in this report.

LONDON

Since the beginning of underground operations in 1863, the London rapid transit system has grown steadily to over 250 route miles, approximately 40 percent of which is underground.

On the London system, virtually all existing underground stations were constructed in earth tunnel (Figure 1). The basic approach toward station construction in London centers about the superior quality of the ground, the irregular street pattern, and extensive development of the city. For

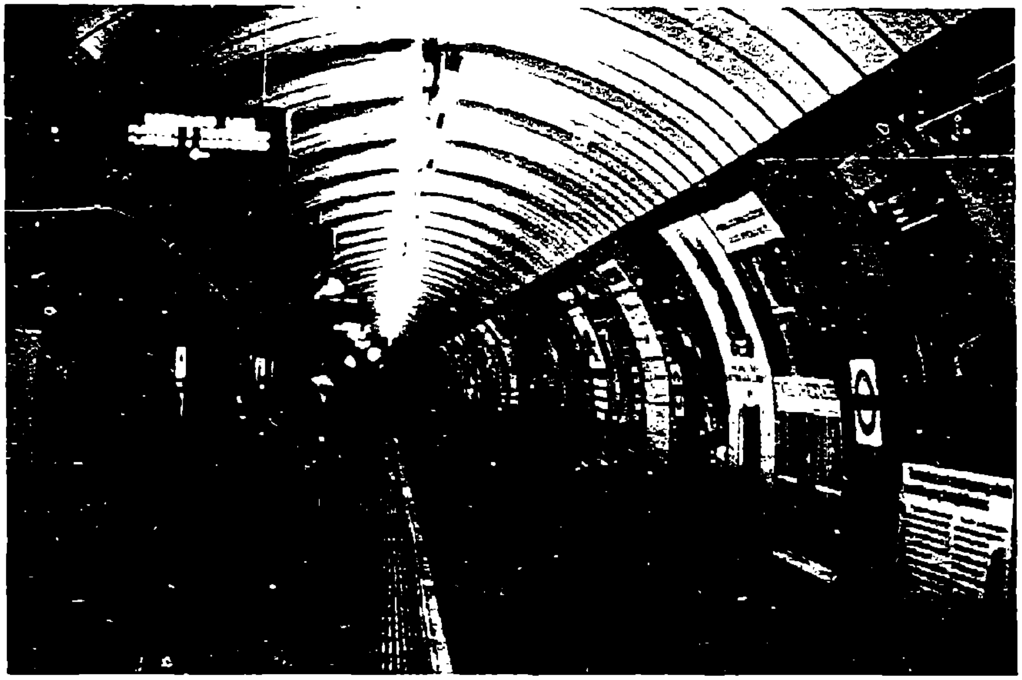


Figure 1

London Multiple Chamber Tunneled Station

these reasons, the typical approach is to drive the stations as soft-ground tunnels. Earth mining is feasible due to the consistent quality of the ground and the availability of experienced miners. Underground transit lines do not generally follow street alignments. Deep tubes are shield-driven under intense urban development. Mined excavation takes place under private property, structures, and public streets. Underground space is generally available for public use regardless of surface ownership.

For mined stations, the line structure is driven through the station reach using conventional methods. The line tunnel is then enlarged to trainroom size. Mezzanines are individually adapted to each site.

Recent system expansion has included the Victoria and Fleet lines in intensely developed areas and the Heathrow extension of the Picadilly Line in a more lightly developed residential and industrial area. On the recently completed Victoria Line, all stations were tunneled in earth. Presently, stations are being constructed on the Fleet Line in tunnel and on the extension to Heathrow Airport in open excavation.

The Heathrow extension is being constructed from the surface. Even with the geological advantage of relatively trouble-free mining, shallow cut-and-cover stations are considered more economical where the degree of urban intensity will allow excavation from the surface. Therefore, they are currently being constructed on the Heathrow extension. There are three stations on this extension: Hounslow West, Hatton Cross and Heathrow Central. The three are constructed by cut-and-cover methods, and all have the temporary excavation support system incorporated into the final structure. Using this technique, London Transport believes that they construct the most economical station structure.

London Transport's approach to underground stations is to construct the simplest basic structural shell and then attach the architectural finish to that shell. The result is a simple, functional station with an attractive interior. More recently constructed stations have the same appearance as older stations, but colors and patterns vary to give each station its own distinctive characteristics.

PARIS

The Paris rapid transit system is undergoing many changes and additions. The original Metro system, which basically follows street patterns, is being extended toward suburban areas. A dense network of about 150 route miles mostly underground, the Metro system has 16 lines with average station spacing of about one-third mile. A new regional express system, the RER, crosses under the Metro system in east, west, and south lines. The RER, designed for much higher speeds than the Metro system with much greater station spacing, interfaces with the Metro system and the National Railway at a number of multi-modal stations.

To extend lines, the Regie Autonome des Transports Parisiens (RATP) submits feasibility studies for government approval and then performs preliminary engineering. They specify the type of excavation support system and design the underpinning. Most of the work is shown on the contract plans, but RATP is open to proposals from the contractor and his engineer, especially when new techniques are involved. The contractor must bid on the RATP design, but he can also submit other designs with a bid price.

All Metro stations are constructed in open cut. At one station, St. Denis/Basilique, a slurry wall temporary excavation support system is also used as part of the permanent structure. The St. Denis/Basilique station is a shallow, simple, column-free box with side platforms and a mezzanine inside the trainroom. RATP experienced reasonable results using this technique, and would consider the combined excavation support/permanent structure again for a shallow station. However in general, RATP considers the soldier pile and lagging technique to be the most economical method of excavation support.

The RER system is a second generation system, and its stations might better be termed transporation centers. A notable feature of several RER stations was their construction in extremely large earth tunnels. For example, the excavation for the Charles de Gaulle station was eliptical, 24 meters on the horizontal diameter and 14 meters on the vertical diameter. The station was tunneled using precast concrete segments which were bolted and grouted. Extensive ground improvement was used.

One RER station, Gare de Lyon, has tied-back slurry walls for excavation support. The station excavation (Figure 2) is alongside the Gare de Lyon railroad station which was not underpinned but was extensively grouted.

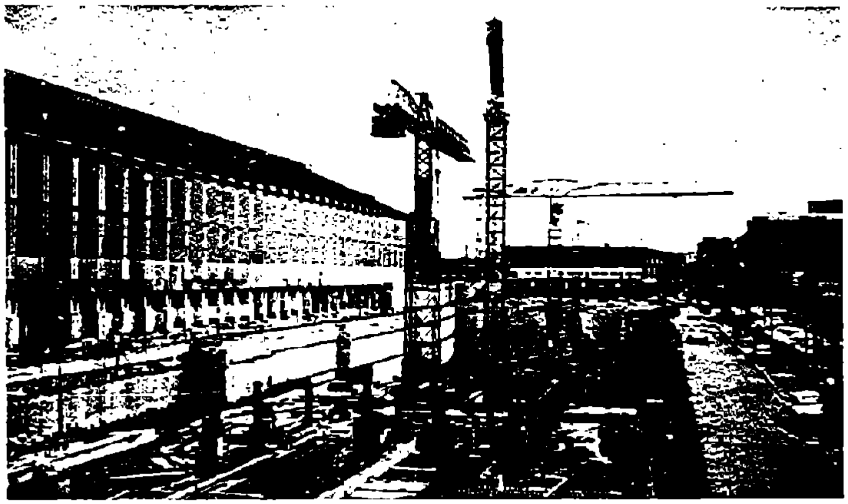
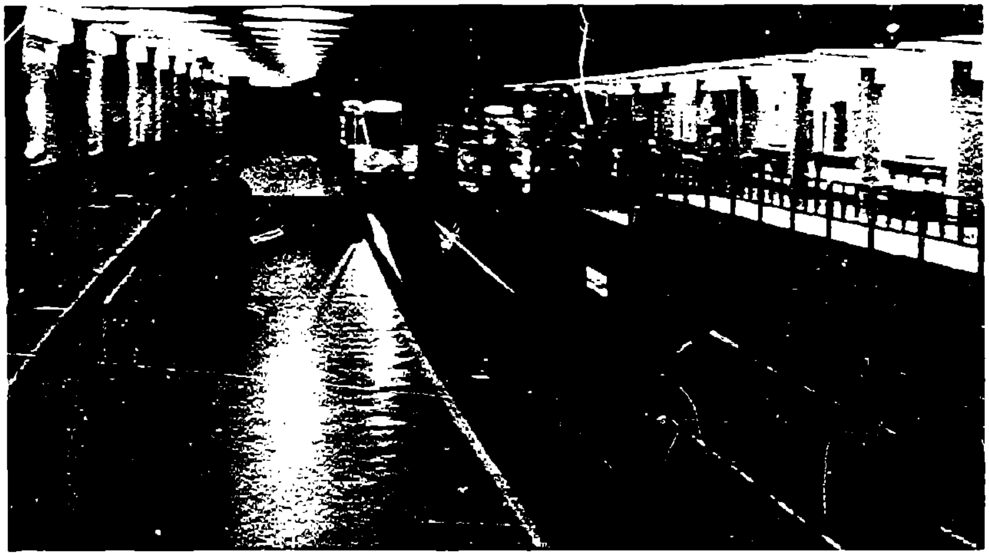


Figure 2
Paris Gare de Lyon Station Under Construction

BRUSSELS

The Brussels metro system is being constructed according to a carefully staged master plan. Begun in 1965, the entire system of approximately 45 route miles with 105 stations is scheduled for completion in the year 2000. At present, the system encompasses all phases of planning, design, and construction, including some completed stations.

Brussels was the first city to develop the pre-metro concept, initially running trams in the subways which would eventually be converted to conventional rapid transit operation. By operating the trams underground, surface congestion is reduced and capital costs for rapid transit vehicles are being spread over a longer period of time than would be otherwise possible. To accommodate trams at the underground stations, platforms have both high and low level loading (Figure 3). The low level portion of the platform can be reconstructed when conversion to conventional rapid transit vehicles takes place.



Source. Dr. V. R. Vuchic

Figure 3

Brussels Pre-Metro Station

Several stations along a heavily patronized line are being constructed with both center and side platforms. Passengers will board the vehicle from the center platform and alight to a side platform, reducing passenger congestion and station dwell time.

The alignment of the initial segments of the Brussels system is that of the existing tram system. Station locations below ground approximate the surface locations of tram stops, with station spacing averaging less than one-half mile. To retain patron convenience similar to the rapid boarding and alighting of trams operating on the surface, stations are shallow for rapid patron access.

Slurry wall construction is a common practice for both stations and line structures. The walls provide support for the excavation, ground settlement control, and the permanent walls of the station. After station excavation is completed, the roof slab is placed on top of the slurry walls. Traffic is then restored on top of the roof slab.

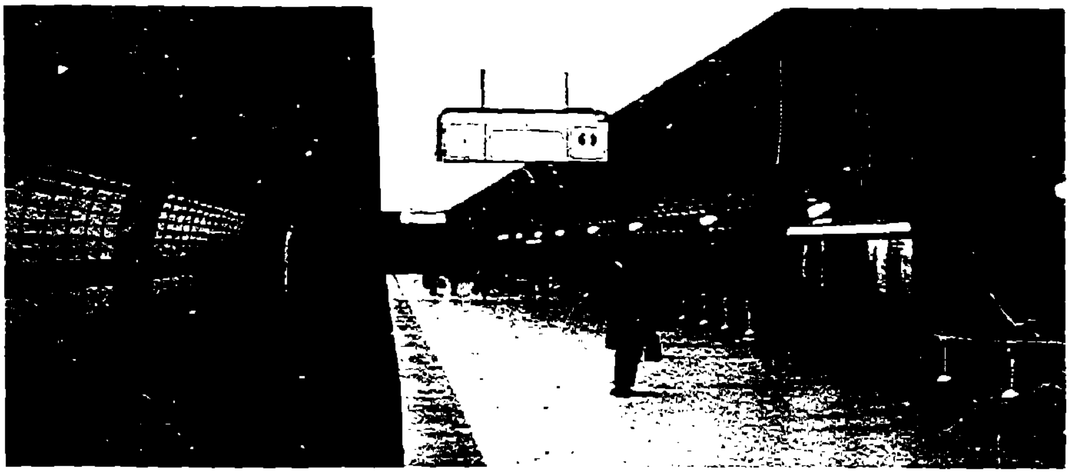
A variation of under-the-roof excavation is used on line structure. To reduce the period of surface disruption, permanent roof slabs are placed on the slurry wall tops before excavation is completed. Remaining excavation and framing take place under the roof. Tram and automotive traffic is restored on top of the roof and diverted around contractors' work areas and accesses.

MUNICH

The Munich U-Bahn rail rapid transit system has about 10 miles of operating line with about eight miles underground. Originally opened for the 1972 Summer Olympics, present construction will approximately double the system's route miles by 1980. Future plans are for staged expansion through 1985.

The U-Bahn is integrated with three other modes of city-owned public transportation: S-Bahn, tram, and bus. Much of the central portion of the subway system was constructed in open cut. In selected locations, traffic was diverted permanently, and extensive pedestrian malls were constructed to replace the streets.

The stations are spacious, attractive, and well-lighted (Figure 4). Almost all station construction is by cut-and-cover techniques. A basic structural shell is constructed, and colorful, simply designed architectural finishes are used. Center platforms are preferred for operational flexibility. Trainrooms are remarkably quiet. A distinguishing characteristic contributing to the ease of circulation in



Source W. N. Lucke

Figure 4
Munich U-Bahn Station

the stations is the barrier-free fare collection system, which has no fare gates or barriers separating the free area from the paid fare area. Patrons are checked randomly for possession of the proper tickets.

The basic excavation support technique is the standard soldier pile and lagging system, which is considered to be the most economical. Steel sheet piling is used in water-bearing gravel. Slurry walls or secant piles are used when buildings are close to the excavation. In this case, extensive foundation grouting is used in lieu of underpinning.

One S-Bahn station was constructed using the excavation support system integrated with the final structure. This technique is being considered for use on one future U-Bahn station.

One very large crossover structure is being tunneled in soft ground without a shield using a multiple drift technique with shotcrete, steel ribs, and steel mesh as temporary support. The results have been satisfactory in the sandy clay soil at the site.

STOCKHOLM

The Stockholm T-bana system, approximately 48 route miles in length, is roughly 60 percent underground. By 1977, it is anticipated that about 68 miles will be operating, extending to an 81-mile total network by 1985. Some transit lines are extended into undeveloped areas, and development follows. Patronage is increasing as the system serves more "new towns" which are dependent on the central business district for employment. Activity centers are developing around other stations distant from the central city.

Underground stations are constructed using cut-and-cover techniques in earth and by tunneling in rock (Figure 5). The significance of urban disruption in open cut construction was demonstrated when businesses failed along a considerable reach of one of the early transit lines. Surface disruption at recent station construction sites was minimal. The present cut-and-cover technique is based on the use of tied-back sheet piles. In Stockholm, the cost of mining in rock is significantly lower than cut-and-cover construction, and considering the significant reduction in surface impact, the location in rock is the preferred solution.

Figure 5
Stockholm Station Tunneled In Rock

Recently constructed underground stations are notable for their large tunneled openings deep in competent rock. In new rock stations, the permanent support of excavation is rock bolts and shotcrete. An effective drainage system is installed under the shotcrete layer. Because of the competency of the rock and the control of water, the shotcreted rock surface can also serve as the finish surface. After being decorated by artists, the painted shotcrete serves as the station finish. Excavation contours, color combinations and large open spaces combine to create a striking impression.

In rock stations, mezzanines are generally located in surface structures permitting surface openings to be limited to the shafts for vertical access to platforms and construction and ventilation shafts.

Since 1970, facilities for the handicapped have been incorporated into stations. A program is underway to make the entire system accessible to the handicapped by adding inclined and vertical elevators to older stations. Of the systems visited, only this system, aside from the new U.S. systems, has a program to make the system completely accessible to the handicapped.

Although conventional construction methods, by U.S. standards, are generally used, the effort to limit costs includes contracting procedures which allow the construction contractor to direct final design toward his preferred construction techniques, available equipment, and particular skills.

MILAN

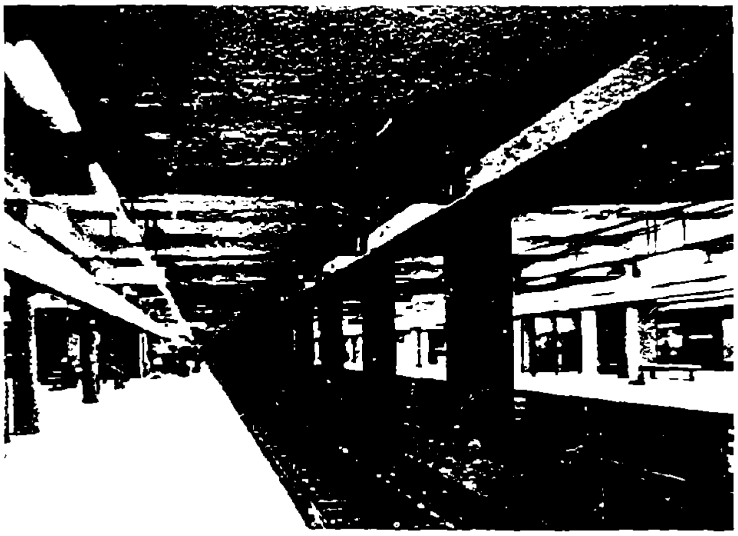
The Milan Metro system presently consists of two lines with a total of approximately 16 route miles and 50 stations underground. Begun in 1958, the system is projected to expand to approximately 44 miles. Nearly all of the current or planned Metro network is situated in fully developed urban or heavily populated residential areas.

Stations are relatively shallow and closely spaced, averaging less than 2,000 feet between stations. Most of the operating stations were constructed by cut-and-cover methods using slurry walls as combined support of excavation and permanent structural shell. Earth mining methods have frequently been used on line structures to limit surface disruption.

Stations typically have unobstructed platforms with spacious mezzanines and passageways. Architectural finish consists of colored artificial stone in metal frame panels, simply attached to the structural shell.

The combination of slurry structural walls with early restoration of traffic over the permanent roof was used extensively for line structures on the initial line. However, the period of surface disruption (from the beginning of site preparation to completed roof slab) caused an adverse public reaction. Difficulty was experienced with cave-ins of the slurry wall trench. These factors were apparently influential in the choice of earth mining as the construction technique for Line 2 (Figure 6). The line structures are predominantly shield driven or earth mined by combining chemical stabilization, shotcrete and rib support techniques.

The ground conditions in the area permit pre-excavation stabilization by chemical and grout injections, both to support existing structures and to stabilize the face of line structure excavation. Rapid support of the tunnel walls and face is achieved by the use of shotcrete. When a full heading is excavated around the arch surface, support



Source: Azienda Trasporti Municipali

Figure 6

Milan Line 2 Station

ribs are erected and immediately covered by shotcrete. This method resulted in less settlement than shield tunneling or slurry wall methods.

The Moscova station is being mined in a single heading using chemical injections for earth stabilization. Injections were made from the street where street width and building-to-building dimensions were relatively small. Utilities which were vulnerable to the pressure injections were removed or protected.

ROME

The new line of the Rome Metropolitana transit system is approximately nine miles long, almost completely underground, with 22 underground stations. Scheduled for completion in 1978, this line and one other line completed prior to 1955 will total about 15 miles with 28 stations.

The geology of the area and the wealth of archeological material generated serious problems which led to delays in construction. The geology along the line is difficult, with both volcanic and sedimentary deposits. There are also many buried structures and voids. Ancient block foundations and utilities required careful attention, especially at mined stations, to control damage from settlement.

The variety of urban and geotechnical conditions along the new line emphasized the need to adapt station configuration and construction methods to the needs of the individual sites. The contractor's designs were developed as the nature of the geotechnical conditions was discovered; they also reflected the density of urban development. Portions of fixed facilities had to be redesigned because of archeological discoveries.

About half of the stations are constructed using mining techniques and half by excavation through open cut. In the open cut portions of line, both conventionally formed concrete and tremie concrete in slurry trench were used. Slurry walls were used in developed areas, while formed concrete in conventionally supported open cut was favored in more open areas.

Furio Camillo station is representative of the line's eleven mined stations. It is very similar in general appearance and configuration to London's deep twin tube stations. In Rome, stations having twin tubes for trainrooms are generally below the water table, where a combination of sealant methods and seepage collection systems are integrated with the architectural finish.

Variable geology and site requirements necessitated some major deviations in mined station construction. At least two mined stations required slurry wall bulkheads to control geotechnical problems and to accommodate the urban conditions of the site.

MONTREAL

The initial network of the Montreal rapid transit system is 16 miles long with 26 stations. Twenty-nine miles of extensions and 49 stations will be added to the system by 1980. The entire system is underground, although several station mezzanines are located on the surface. Approximately 70 percent of the total network, including extensions, is mined in rock.

In Montreal, rock excavation is less expensive than open cut for stations and considerably less expensive for line structure. To take advantage of favorable geologic conditions, tunnel profiles are designed to locate stations as close to the surface as possible while permitting line structures to remain in rock. The line structure is a single tunnel carrying two tracks. Stations have been constructed by both cut-and-cover and rock tunnel methods. For tunneled stations, the line structure is driven through the station before the station contractor begins work. Underground construction methods are conventional in terms of U.S. practice.

Considerable emphasis is placed on station design. Stations are colorful, distinctive, and individual, although structural shell dimensions are repeated as often as possible (Figure 7). A separate architectural firm is chosen for each station. The architect is given a budget and minimum design criteria; he then submits a design program and model for approval.

Figure 7

Montreal Station

One system characteristic which affects station design is the use of a rubber tired vehicle which is narrower than customary for U.S. rapid transit systems. This narrow vehicle allows decreased station width and smaller line structures.

TORONTO

The 26-mile Toronto rapid transit system was begun in 1949 and has been incrementally expanded since that date.

Heavily used surface traffic corridors became the first routes for the original system. A new line is presently under construction, and extensions to existing lines are being designed.

The Spadina line, now under construction, is located in parkway and expressway rights-of-way. Some significant cost savings have been demonstrated due to easier access to station sites, less urban disruption (utility relocation, traffic handling), and less concern with settlement.

The area geology is conducive to cut-and-cover construction for stations and line structure. Shallow stations are preferred, and all except two of the underground stations have been constructed using the cut-and-cover method. Two stations in the central area were constructed in mined tunnel, using a cross section similar to that used in London, a twin tube with center concourse configuration.

Stations project a sense of uniformity due to repetitive layouts and architectural finishes (Figure 8). Cut-and-cover stations typically have a center row of columns. Mezzanines are located outside of trainrooms, permitting a shallower depth of construction for the station trainrooms.

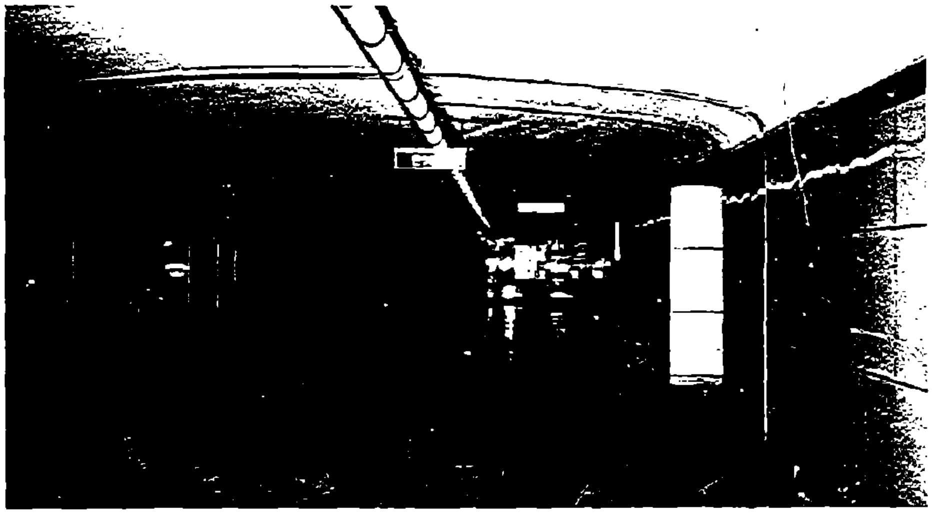


Figure 8
Toronto Station

The Toronto subway system is the core of a well integrated public transporation system. Rapid transit stations serve as multi-modal transfer points for trolley, bus, and private vehicle modes. Special consideration is given to accommodate movements between modes through the design of fixed facilities and configuration of station components.

MEXICO CITY

The Mexico City metro system, which is approximately 27 miles long, serves up to two million passengers per day. Forty-six stations (almost all of them underground) were completed in a 40-month construction period. Operations began in 1967, two-and-one-half years after construction began; the full network was operational in 1970.

The short time period for design and construction of the system was due to a number of factors. A single firm completed final design and constructed the system. Construction was begun prior to completion of final design. By using early construction data in the on-going design process, final design was adjusted to actual site conditions. Stations were constructed in an 18- to 24-month period using three shifts.

The geology of the area presented a number of problems. Most of the system is situated on a lakebed of soft, compressible material. Building movements took place for approximately five years after construction, and a significant amount of underpinning was required. Potential seismic activity also required consideration.

Three basic methods of construction were used for underground stations: laid-back, slurry wall as support of excavation, and slurry wall as support of excavation and permanent structure. The first station was constructed using open cut, laid-back excavation; there were significant problems with movement and settlement of adjacent structures, and this technique was given no further consideration. Next, slurry wall as temporary excavation support was tried; a structural wall was then constructed inside the slurry wall. About 50 percent of the stations were constructed in this manner.

What evolved as the most successful method of construction, however, was the use of slurry wall as both support of excavation and permanent structural wall. Approximately 50 percent of the underground stations were constructed using this technique. In these stations, finish materials were applied to panels attached to but standing free from the wall (Figure 9). Leakage is drained off behind the panels. All of the stations on the most recently constructed line, Line 2, use slurry walls as integral parts of the permanent station. All new stations will be constructed using this structural system.

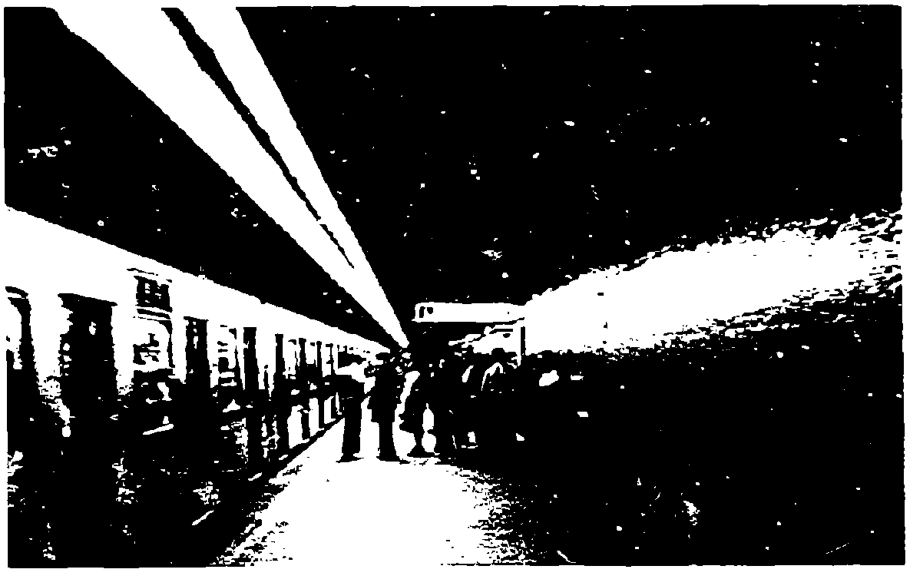


Figure 9
Mexico City Station

Because of the extremely difficult ground conditions, the stations were kept as shallow as possible. For this reason, the mezzanines are either at ground level or at platform level. The basic station configuration is side platform with fare collection at the platform level. Passengers enter the station, pay their fares, and then proceed either directly to the platform or to a below-track underpass to the opposite platform.

CHICAGO

The Chicago Transit Authority has been expanding its system, incrementally renovating stations, as well as developing and extending new routes. About ten percent of the approximately 90-mile transit system is underground. Two stations have been constructed underground in the past 15 years, Logan Square and Belmont stations. The line extension which includes these two stations began operation in February, 1970.

One of the two recently constructed stations in Chicago, the Logan Square Station (Figure 10), is an excellent example of an established transit system's approach toward design of new facilities. By applying past experience to present cost constraints, a design solution was achieved which optimized station design and construction. The result was a cost-efficient, functional station.

Figure 10

Chicago Logan Square Station

The Logan Square Station, constructed by the cut-and-cover method, has a mezzanine at each end of the center platform. The mezzanines are within the trainroom and above platform level. Overall trainroom length is 1,030 feet, and platform length accessible to patrons is approximately 860 feet. The sense of openness on the platform contributes to passenger circulation and a sense of security for the patrons. A center platform was selected for operational flexibility and for optimum use of a limited platform width. The shape and area of platform was minimized to obtain savings on the construction cost of adjoining line structure. Conventional construction methods, by U.S. standards, were used.

SAN FRANCISCO

The Bay Area Rapid Transit (BART) system is a 75-mile regional rapid transit system serving the San Francisco metropolitan area. About 30 percent of the initial system is underground with 14 of the 34 stations underground. A set of architectural design standards was developed for the entire system; however, each station is individually designed to reflect the character of its environs while still satisfying system design standards.

All 14 underground stations are basically rectangular concrete structures constructed by the cut-and-cover method. These stations have center platforms 700 feet long to accommodate ten-car trains. Columns support the structural roof slab. Mezzanines are usually separate from the trainrooms. Wherever possible, a sense of spaciousness was created by such devices as skylights, open space around stairwells, and floor openings for sight lines between platforms and mezzanines (Figure 11). A multitude of finish materials was used to individualize stations.

Although utilities, traffic, and support of adjacent structures were most troublesome to construction progress, many BART stations had additional major groundwater and geological problems. Potential seismic activity was also a factor in station design.

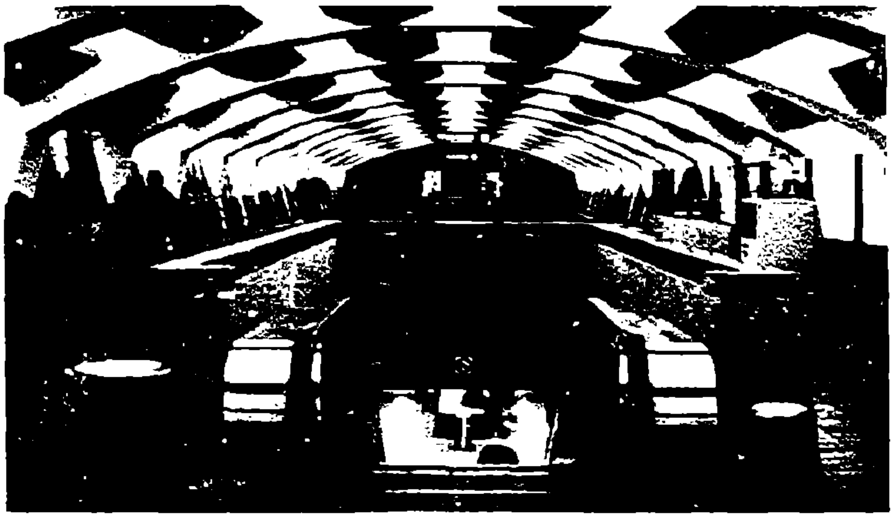


Figure 11
San Francisco BART Station

The major construction methods used on BART were generally those common to U.S. practice. One technique of interest was the soldier pile-tremie concrete (SPTC) wall, which has been used during construction of foundations for high-rise buildings. The decisions to use the SPTC wall at three stations were based on site-specific cost estimates. The major differences between an SPTC wall and a typical tremie concrete wall is that the SPTC wall is reinforced with soldier piles (which are also used as trench excavation guides), while the typical tremie concrete wall is reinforced with cages of reinforcing bar.

The application of the SPTC wall for BART stations defined their basis for success: the wall must be capable of performing more than one function or conventional methods will be cheaper. The SPTC wall at the Civic Center Station serves a number of functions: support of excavation and of adjacent structures (thus avoiding underpinning); groundwater cutoff to the excavated area; and the major structural portion of the permanent wall of the station structural shell.

WASHINGTON, D.C.

The initial segment of the Washington Metro transit system began operating in March, 1976. This 4.6-mile section contains five stations. The total system, which will be placed into operation in phases, will be approximately 100 miles long with 87 stations. At the scheduled completion date of 1983, 48 miles and 50 stations will be underground.

Underground stations are constructed by cut-and-cover method in earth or by tunneling in rock. The typical station is a concrete arch structure, approximately 30 feet high and 60 feet wide (Figure 12). Platform configuration varies depending upon the type of construction between stations; however, center platforms are preferred for operational purposes.

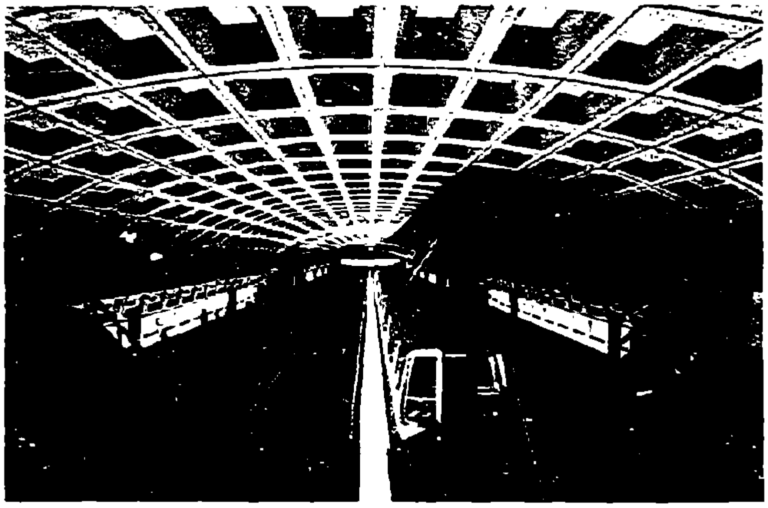


Figure 12
Washington, D.C., Metro Station

The underground stations are all similar in design and feature mezzanines located inside the trainroom, platforms standing free from the walls, column-free construction, indirect lighting, and air conditioning.

Cut-and-cover construction has proceeded using soldier piles and lagging as the basic excavation support system; however, slurry walls have been used in certain instances to minimize underpinning.

Two stations have been constructed in rock using the system-standard large span opening, and eight additional rock tunnel stations will be constructed. The decision to construct deep in rock was based on the desire to minimize surface disruption and attendant impact on traffic, utilities and surface development. The rock tunnel station excavations are 45 feet high, 60 feet wide, and about 700 feet long. Constructed using multiple drift methods, the station structure consists of rock bolts, shotcrete, and steel sets. The composite structure serves as both initial and final support.

After the station excavation is completed, a precast concrete shell is erected inside the rock chamber to serve as the finish structure. In earth stations, the coffered arch exposed concrete structure serves as the finish structure. To accommodate this design approach, careful attention has been paid to waterproofing the station structure.

Access for the handicapped will be provided throughout the system.

Chapter 4
ADMINISTRATIVE CONSIDERATIONS

In addition to the more obvious and direct influences of planning, design, and construction techniques, several other factors can have a major effect on subway station costs. Observations and interviews showed that significant opportunities for reducing costs are commonly found in the areas of contracting procedures, urban leadership, interagency relationships, and scheduling. Cost and time saving benefits realized from these elements are usually the result of early recognition of the value of these opportunities. Commitments and action plans are normally established prior to design and construction, and have an influence that permeates the program, particularly in their effect on the duration of design and construction.

CONTRACTING PROCEDURES

In several of the systems visited, particularly the European systems, construction contracting procedures presently being used are purposely arranged to encourage the development of innovative techniques by the contractor. The general practice in these countries is for the transit authority to show considerably less detail and less development of structural design on bid documents compared to U.S. practice, while depending on functional requirements and criteria to govern final design. By this approach, the design period leading to the bidding process is shortened significantly. The bidding period, on the other hand, is lengthened to permit contractors to accomplish the necessary level of structural design and detail for reliable bids. This contracting procedure results in a two-fold advantage when compared to practices for U.S. transit work:

1. The overall time from the beginning of the owner's design effort to construction completion is decreased.

2. The contractor is encouraged to use most appropriate or innovative construction techniques to gain advantage over his competitors.

These two advantages offer the potential for significant savings. Indeed, where this approach was used, the authorities interviewed generally considered these elements to be essential ingredients of the working environment, not merely the rewards for using this approach to contracting.

Procedures for contracting for underground construction in the United States have recently been the subject of extensive discussion and study. In its 1974 report, Better Contracting for Underground Construction, Standing Subcommittee No. 4., Contracting Practices, of the U.S. National Committee on Tunneling Technology made seventeen specific recommendations for improvement of United States contracting practices. The subcommittee report also gives details of many European contracting procedures. Those involved in underground transit facilities should review and give consideration to these recommendations.

Details of contracting practices vary among countries and certainly among the cities visited by the Study Team. Characteristics of prevailing European practices which may be of value for future U.S. construction include the following factors.

1. A team relationship between owner and contractor is sustained. The risks of underground construction are shared by the contractor and owner. The owner is largely able to depend on the contractor to solve unexpected problems without unusual construction delay.
2. The owner is able to award a contract to the contractor who demonstrates to the owner the greatest advantage (defined as true cost advantage considering all conditions rather than low bid). A major change can be negotiated expeditiously after construction is underway to obtain advantages for the owner.
3. The construction contractor can obtain competitive advantage by basing the bid on his particular ability to perform his selected technique at a lower price than other specialists with other methods. The owner and contractor have a keen interest in making innovation successful. The contractor, to compete successfully, must also establish a record of cooperation with owners.

These characteristics create a working environment which is radically different from conditions that exist in the U.S. on large transit projects. They also point to the crucial reason why there is less innovation in U.S. station construction: the institutional environment is not conducive to innovation.

The U.S. contracting procedure is such that the owner is encouraged to develop very detailed bid documents. The level of detail in the plans and specifications virtually assures that construction will proceed with conventional methods, and the potential and reward of introducing new techniques is minimized. In other countries, this situation is avoided by contracting procedures which range from the construction contractor performing all final design to administrative procedures which encourage and expedite contractor-proposed changes to any part of detailed plans and specifications. The consensus of those interviewed is that any point on this range offers a savings potential to the transit owner. The correct mix of design detail and procedures to facilitate contract change depends on the custom and attitudes of the particular locale.

URBAN LEADERSHIP

The implementation of a subway system from planning to operation is a long-term process. Recent urban transit systems have been developed over a wide range of time spans. Since cost of labor and materials has been subjected to extreme inflationary pressures, those systems that have been able to compress their total system development time have been able to achieve the most construction for any given amount of funds. Government officials and leaders of the urban community who make commitments to a common goal give the project a sense of priority and urgency which can significantly shorten the period for planning, design, and construction.

Recent examples of such commitments are the transit systems in Mexico City and in Montreal. In both cases, major outside influences created strong incentives for the timely completion of the system. The 1968 Summer Olympics in Mexico City and Expo '67 in Montreal encouraged community endorsement of transit projects which produced a favorable climate for rapid progress. Community leaders and transit officials were able to marshall resources and induce cooperation on a scale commensurate with the physical proportion and economic importance of an urban transit system.

Urban leadership can also provide direction for improved interagency relationships to create an atmosphere which encourages significant opportunities to save cost and time. When a municipal government has a measure of direct responsibility and commitment to achieve transit project goals, the pressures for interagency cooperation become favorable.

INTERAGENCY RELATIONSHIPS

By its nature, development of an urban transit system requires extensive coordination with agencies at all levels of government and with public and private utility owners. Interest groups, advisory committees, and political factors have strong influence on the transit authority's preferred methods and options to manage and administer projects.

The organizational arrangement used in several of the transit systems visited featured the municipalities as the builder of the transit system. A special agency is commissioned to operate the system. The department of public works, in consultation with the operating agency, has prime responsibility to see that fixed facilities are designed and constructed. A special task group within public works may be formed to concentrate responsibility for transit work. This agency already holds clear lines of authority and coordination with existing agencies, utilities, and interest groups. It is relatively easy for those with primary transit responsibility to reach uncomplicated arrangements with utility owners and with those responsible for streets and traffic. Procedures can be simplified to permit public agency contributions to transit work according to established schedules of progress.

Transit system developers have many advantages when a project is administered through an organization similar to that described above. This example is not advocated as the only organizational arrangement which can be efficient, and therefore reduce time and cost. It is one which is capable of responding effectively to potential problems. Transit organizational structures can be tailored to bring many interests into active cooperation with the transit project. For example, traffic staging and requirements for minimum depth of cover are two areas where what appear to be rather routine requirements of outside agencies can have a severe impact on construction costs.

Staging of street traffic over open cut subway station construction can be a costly element of construction. When all public agencies involved in the implementation of a subway system in an urban area are called upon to coordinate their interests, unnecessary traffic staging is minimized. In cities where route location decision makers give full consideration to off-street locations to minimize traffic staging requirements, adverse impact on traffic is considerably reduced. Of course, this alternative location should be carefully considered for its total impact on the community. Where traffic patterns are frequently changed, impact on the traveling public and on area businesses can be great; community support of the transit project may be damaged.

The construction cost of underground structures is particularly sensitive to the total depth of excavation. In some cities, government agencies have established requirements for a minimum depth of cover over stations to assure that future utility work can be accommodated. For example, in a recent system, the municipality has established a ten-foot minimum for depth of cover over underground subway facilities constructed in public space. In other systems, the approach was taken that each situation should be judged on its individual merits and the depth of cover established for each specific site. In this manner, the construction cost to the community is minimized.

SCHEDULING

Advance Utility Contracts

The scheduling relationship of various elements of a major urban transit construction project can have a significant effect on station construction cost. An outstanding example of the cost significance of scheduling is advance utility relocations. The uncertainties of underground construction are severely compounded by interference from utilities. The construction time of a station is very sensitive to the manner of handling utilities at the site.

Contractors have indicated that construction time for stations can be shortened and overall stations costs reduced when utility relocations are completed in advance of the major structural contract for the station. Major utility work becomes a critical element when included in the structural contract and tends to have an overall delaying effect, therefore becoming a considerable liability. A delay to structural progress can become very expensive.

Utility work properly selected, scheduled, and performed under separate contracts in advance of the station structure contract has consistently shown cost and time savings, relative to similar experiences with combined structural/ utility contracts.

Advance Underpinning Contracts

Another type of construction contract which sometimes can be awarded prior to the main structural contract is one for the underpinning of adjacent structures. This element of work is time-consuming and must be accomplished prior to opening the main excavation. In some cities, advance contracts for underpinning are considered appropriate. In others, there is concern regarding definition of responsibilities between underpinning contractors and structural contractors; in these cities, underpinning work performed by a subcontract to the structural contractor is favored. If it is possible to separate the responsibilities, critical construction time can be saved by performing the underpinning work in advance of the main structural contracts.

Public Input

The requirement for environmental impact analyses and public participation in the planning process through public hearings is now a fact of life in the U.S. Transit system planners can minimize the adverse effects of potential delays by accomplishing these analyses and hearings early in the planning stages of the project.

Station location is almost always the principal issue in system impact analyses for underground transit. The site of the station experiences considerable construction period disturbance. A new transit station is often a catalyst to introduce changes in land use near the station.

Public resistance or the environmental analysis process may cause a station, the focus of most public attention, to be relocated or changed in some major way. The total cost implications of relocation include the effect of change on line structure, real estate, transit service and system progress. Costs and delays of the magnitude inherent in major changes to station design or location can have a severe impact to a transit project. It is essential that the station and all of its construction and operational aspects be sufficiently defined for public hearings and impact analyses to avoid this type of costly setback.

Chapter 5
DESIGN CONSIDERATIONS

Decisions made early in the planning and design phases are significant in establishing the final station cost; in fact, design commitments made early in the system development process will have a more significant effect on ultimate cost than refinements made later in the program. Once the decision is made to construct underground and the station site is selected during the planning phase, design and construction solutions become site-specific. Consequently, general rules or guidelines for economic design or construction can be misleading unless they are responsive to site opportunities and constraints.

The selection of the most suitable design and construction techniques for a particular station is a complex matter which should be considered by an experienced technical team including planners, designers, construction specialists, and transit operating personnel. While this team will find that general guidelines are useful to establish a methodical and iterative process to solve questions of design, specific site controls must be given full consideration to maximize economic benefit.

GENERAL PLANNING AND DESIGN CONSIDERATIONS

The possibility of introducing cost savings into the development of a rapid transit system is greatest during the planning stage when decisions are made on route location and number, spacing, and location of stations. The decision to locate a route and its stations underground is a basic determinant of the cost of the fixed facilities of the transit system. For example, on one system the cost of an underground station has been as much as two-and-one-half to three times as great as that of an aerial station and four to five times that of an at-grade station.

Once the decision is made to locate a station underground and the general station location is selected, design and construction solutions and the cost of construction become controlled by urban conditions at the site, geotechnical conditions, station size and depth. For these reasons, the design of each station is considered a site-specific solution. Rules for design or construction must be carefully weighed against site conditions to obtain optimum cost-effectiveness.

Balanced Design

In the design of a transit station, it is desirable to provide a system of station components (platforms, accessways, and mezzanines) that are balanced from a patron capacity standpoint. In the planning stage, transportation planning techniques are used to project patronage at each station. The inherent limitation in the accuracy of such projections is due to factors beyond the control of planners, e.g., changes in land use that are likely to occur near transit stations with corresponding changes in passenger volumes.

After construction is completed and the system is operating, it is virtually impossible, or at best extremely expensive, to enlarge the station or its elements, such as platforms, access passageways, and mezzanines. During design, it is judicious to provide ample capacity at these critical points, either by providing excess initial capacity or the means to modify the structure easily in the future. For reasonable design, then, it is necessary to have a balanced design with sufficient flexibility to efficiently handle variations from the anticipated traffic patterns.

TYPICAL TRANSIT STATION FEATURES

Figures 13 and 14 illustrate two basic station types and identify the major activity areas. Figure 13 shows a typical cut-and-cover station; Figure 14 is a typical mined, multiple chamber station. (Station types are fully developed in Chapter 6.) The typical urban rapid transit station has four major activity areas: access or entrance areas, mezzanine areas (usually the control area or ticket hall), trainroom or platform areas, and ancillary spaces. The transit patron has access to the first three. The ancillary spaces house service areas, such as electrical and train control equipment rooms, mechanical equipment rooms, and cleaners rooms. They are accessible only to maintenance and operating staff. In most cases, the three public activity areas are on separate levels, although it is not unusual to combine several of the areas on one level. The Mexico City transit system, for example, has been able to reduce the depth of excavation throughout the system by placing the mezzanine at platform level. In other cities, the volume and depth of excavation have been reduced by locating mezzanines at surface level.

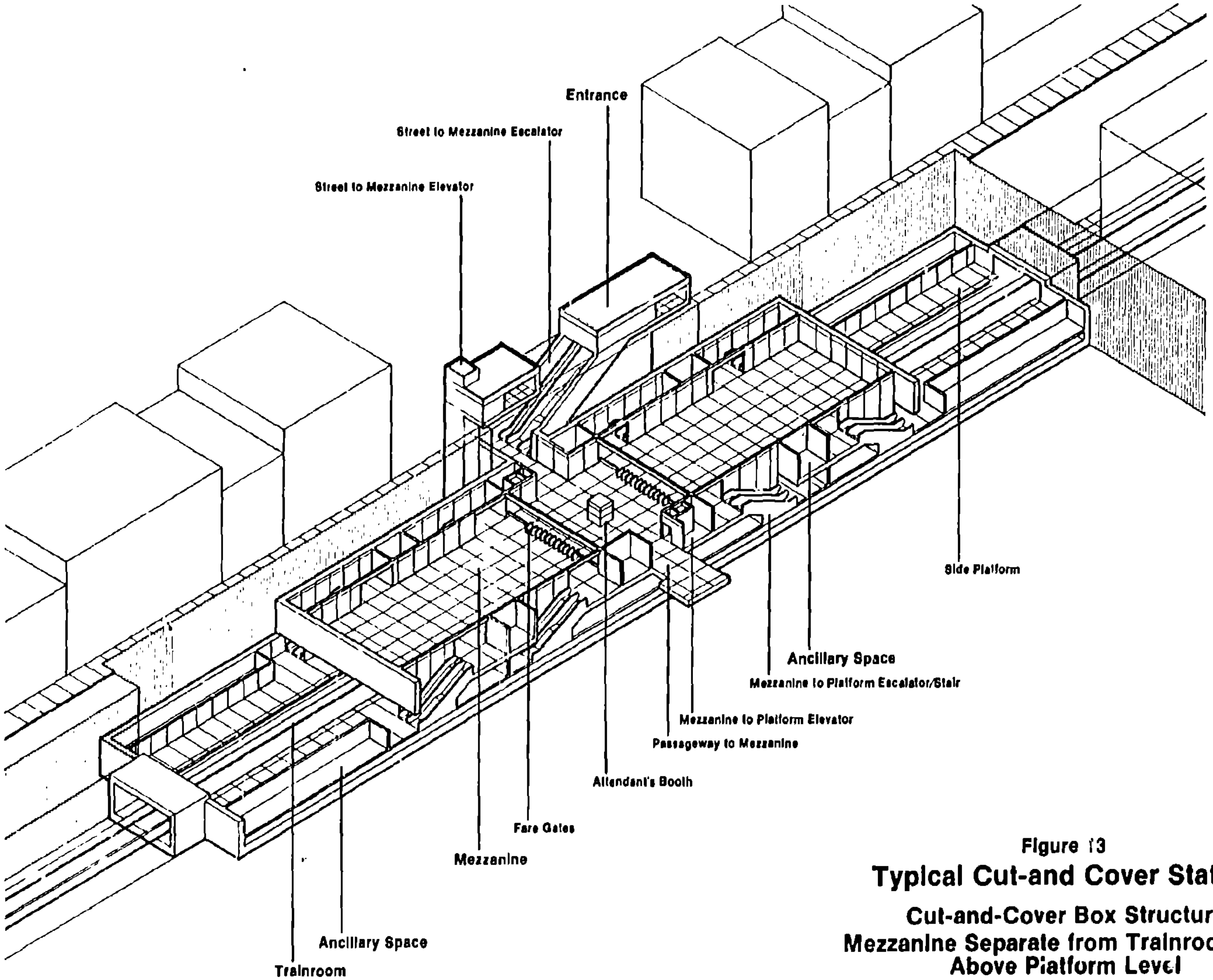


Figure 13

Typical Cut-and Cover Station

Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and Above Platform Level
Side Platform

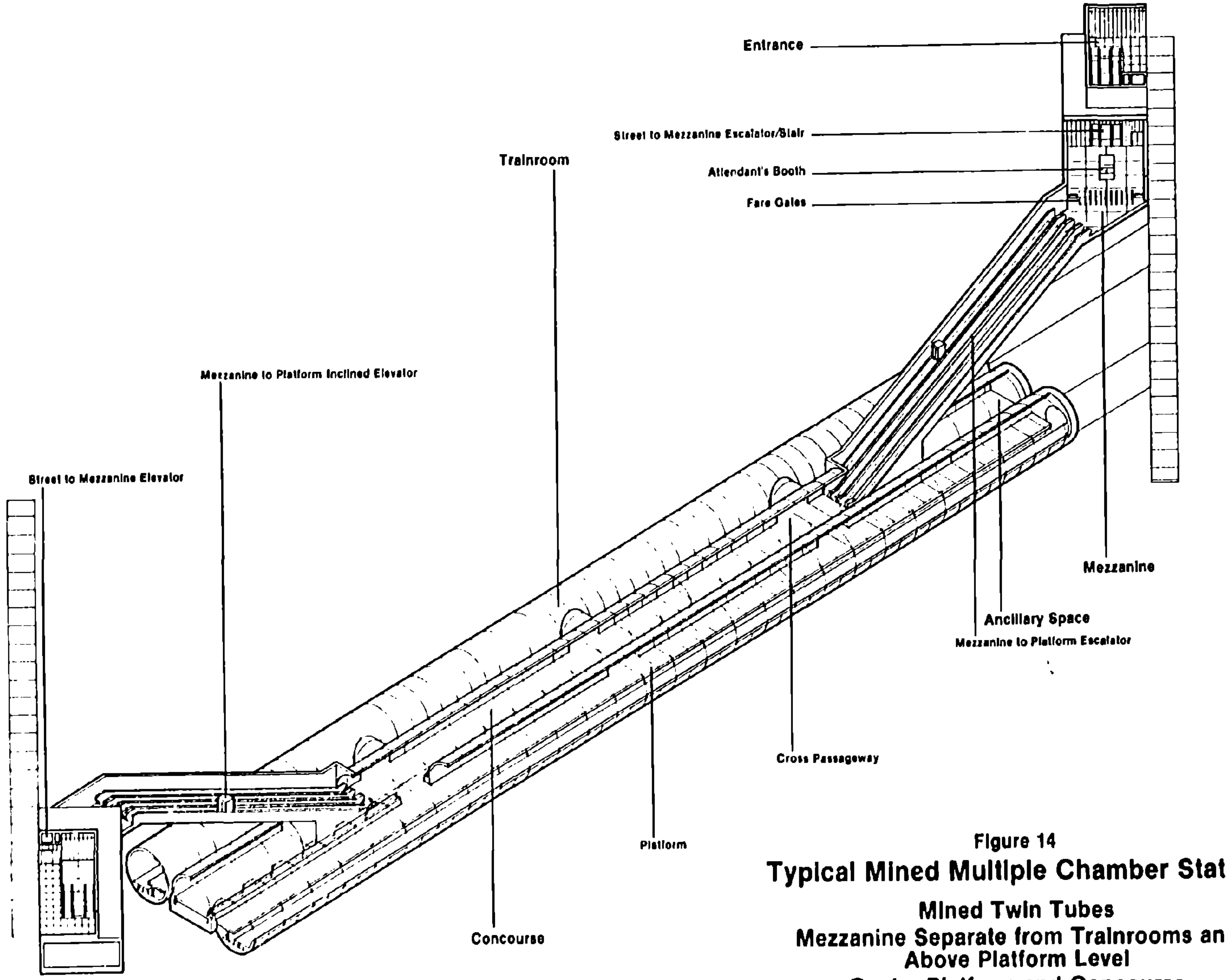


Figure 14
Typical Mined Multiple Chamber Station
Mined Twin Tubes
Mezzanine Separate from Trainrooms and Above Platform Level
Center Platform and Concourse

Station Size

One of the major determinants of the cost of an underground station is the volume of the underground space. The size of transit stations for a given system is determined to a great extent in the planning phase. During this phase, ridership is estimated using transportation modeling techniques. At this point, system planners establish the line-haul capacity as a function of the estimated demand, and patronage is projected for each station. Using the level of service decided upon (e.g., a seat for every 1.5 patrons in peak hours) and the minimum train headway, the desired train capacity and length and, to some extent, width are established.

The maximum train length determines the length of platform. Length is the first parameter affecting the scale of the station. The overall station length is finally determined after ancillary spaces are positioned according to the site opportunities to minimize excavation volume. Usually platform length is slightly greater than train length to allow tolerance for stopping trains, although in some cases, platform length and train length are identical.

The second parameter of station volume, the width of the station trainroom, is a function of train width and platform width. While train width for urban underground transit has varied from system to system (approximately eight feet to ten feet), most subway system vehicles are approximately ten feet wide. While some system developers believe it advantageous to utilize narrower vehicles, present pressures in the U.S. are toward standardization of transit cars. Recent transit vehicle bid prices have reflected the high cost of varying car designs from system to system. These high vehicle unit costs lead to the conclusion that for future U.S. systems, standardized transit vehicles, rather than vehicles of varied width to minimize station width, will provide cost advantages.

With train widths fixed, station platform width becomes the major variable factor in the basic determination of total station width. During planning, a patronage figure is estimated for each station. The station designer then starts with this load, consisting of an estimated number of passengers moving through the station to and from trains. Projections are normally based on peak hour volumes and then adjusted for 15 minute peaks within the peak hour. Using this patronage figure, the occupancy of a station at any given time may be calculated. A standard width for station platforms throughout the system is normally based on crowd-handling criteria and safety requirements rather than peak demand. Widths are increased at centrally located stations, transfer stations, or other locations where patronage might be exceptional. Approximate platform widths on the systems observed range from 11 to 35 feet for side platform stations, and 18 to 38 feet for center platform stations.

The third determinant of station volume is height. For tunneled stations, the minimum vertical clearance above platform, platform width and vehicle size are the determinants of station tunnel diameter. For open cut or cut-and-cover stations, two distinct vertical configurations have emerged.

In the first, the station mezzanine is above and outside of the trainroom or alongside the trainroom. The trainroom height is then determined by structural invert thickness, trackwork depth, distance from top-of-rail to platform, clear height above platform, and structural roof thickness. Stations of this general configuration are predominant in Mexico City and Toronto. Generally, this type of station component layout is capable of dramatically minimizing the total depth of excavation and, accordingly, the construction cost.

In the second type of vertical configuration for open cut stations, the mezzanine is inside the trainroom above the platform. The mezzanine clearance requirements are then added to the total height. This type of design normally requires a greater depth of excavation, with corresponding increased cost of construction. The advantages of this scheme are optimum circulation and operating characteristics, patron security, comfort, and aesthetics. Washington, D.C.; Paris; San Francisco; Chicago; and Montreal utilize this type of design to varying degrees.

Platform Configuration

One of the earliest design decisions is the choice of center versus side platform. Transit operators generally agree that, from the operating standpoint, the center platform is more desirable. Center platforms provide more area to handle peak hour volumes, especially when volumes of passengers peak in one direction. They require fewer accessways, stairs, or escalators than side platform stations and, as such, are more efficient. And, center platforms permit clear directional signing and facilitate movement of patrons from the mezzanine area. The first directional decision the patron makes is at platform level.

One of the major determinants of platform configuration is the type of construction between stations. If construction between stations is twin tunnels, the minimum spacing between tunnels dictates that tracks be spaced at 24- to 30-foot minimums. It is usually possible to increase the spacing and enter the station with tracks widely spaced. The center platform configuration becomes more natural.

On the other hand, if construction between stations is open cut or cut-and-cover, the most economical configuration for the line structure is closely spaced track centers. A side platform station allows the most straightforward transition geometry between line section and station, since side platform stations do not require flaring the tracks at the station ends. Thus, the consequent increase in excavation, spans and construction costs associated with flared line sections are avoided.

To analyze the trade-offs between center and side platform designs, station costs and line section costs should be analyzed together. Savings in line section costs associated with close track spacing in cut-and-cover may be offset by station costs caused by increased spans and width, decreased patron flexibility, increased vertical circulation requirements, and quite possibly increased long-term operating costs.

At stations that will be operated as temporary or permanent terminals, operating personnel prefer a center platform for increased flexibility and capacity. This configuration eliminates the problem of directing passengers to the next scheduled departing train and permits much greater platform capacity for heavy traffic volumes.

GEOTECHNICAL CONDITIONS

During the planning phase, routes are selected and stations are located on the basis of providing transit service attractive to potential patrons. One of the most critical site-specific considerations that affects the design, construction method, and cost of construction is the particular geotechnical conditions at the station site. As initial plans are developed, it is not unusual that minimal subsurface information is available. Normally, as the design location becomes more specific, additional detailed subsurface investigations are made.

Using this subsurface data, station locations are adjusted, but pressures are great to maintain the locations selected in the planning process on the basis of service to users. As a result, the geotechnical conditions become one of the site-specific conditions that has a major impact on selection of station configuration and on determination of the method of construction.

Some of the disadvantages of this approach could be reduced by greater subsurface exploration early in the planning phase. Although rapid transit station location and orientation are related more to user needs than to geotechnical conditions, adjustments in location to minimize costs are usually possible without significant inconvenience to patrons. Explorations on a smaller scale than those needed for final design can easily detect at an early stage the need for gross profile changes, for horizontal movement of a station along the line, or for a lateral shift of the alignment. Geotechnical conditions almost never override the other variables that contribute to selection of station site and configuration. Other variables, particularly station depth and width, are subject to greater control and management than the physical constraints of geotechnical and urban conditions.

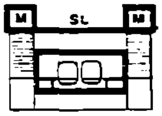
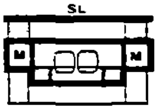
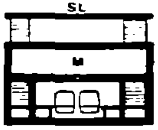
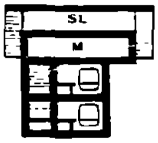
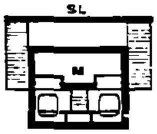
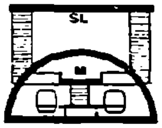
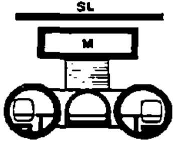
Of course, underground construction methods are very closely related to ground conditions and groundwater. Some construction techniques are applicable to a wide range of ground and groundwater, with varying economy; others are applicable only to a narrow range of geotechnical conditions. The relationship between the seven station types developed in Chapter 6 and the geotechnical conditions discussed in the following pages is shown on the matrix in Table 2.

Ground Conditions

The nearly infinite combinations of ground and groundwater can create unique conditions at each site. What may appear to be a mild degree of change in site conditions may substantially change construction techniques or costs. For example, the presence or amount of water may require compressed air to support a tunneled face, thereby dramatically increasing costs. Because of this influence of ground conditions, the cost of underground construction is subject to extraordinary

Table 2

Station Types Related to Geotechnical Conditions

	Geotechnical Conditions Station Type	Earth	Rock	Mixed Face	Groundwater Problems
Open Cut Excavation	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and at Street Level Side Platform **1** 	●	◐	●	●
	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and at Platform Level Side Platform **2** 	●	◐	●	●
	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and Above Platform Level Side Platform **3** 	●	○	◐	◐
	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and Above Platform Levels Stacked Platforms **4** 	●	○	◐	○
	Cut-and-Cover Box Structure Mezzanine within Trainroom and Above Platform Level Center Platform **5** 	●	○	◐	○
Mined Excavation	Mined Single Arch Mezzanine within Trainroom and Above Platform Level Center Platform **6** 	○	●	○	Earth ○ Rock ●
	Mined Twin Tubes Mezzanine Separate from Trainroom and Above Platform Level Center Platform and Concourse **7** 	◐	●	○	Earth ◐ Rock ●

● Most Appropriate ◐ Sometimes Appropriate ○ Least Appropriate variations from site to site. This fact is magnified as station volume, depth of open cut or height of overburden increases.

For these reasons, then, this study does not define geotechnical conditions in any detail; rather, gross categories are defined.

Rock - Rock is naturally occurring material that is hard and consolidated; when excavated, it is customarily removed by blasting or other mechanical means. Truly massive and competent rock would have few structural weaknesses and would be able to stand unsupported in large excavations. In the rock normally encountered at station sites, the inherent weaknesses are numerous enough to require some form of man-made support, perhaps shotcrete and rock bolts in the most favorable situations. As the weaknesses increase (and the rock competency decreases), added support becomes necessary.

The first major reason for incompetency in rock mass is the presence of interlacing discontinuities or fractures. The most common weakness consists of fractures, called joints, which occur in several groups or sets in all rock types. Joints may originate through cracking in a cooling igneous rock, by stress relief as overburden is removed, or by cracking when the rock is subjected to flexural or tensile stresses. Joints are usually more numerous near the surface of a rock mass than deep in the interior, because the lesser burden permits incipient fractures to open. Rock in which a relatively large number of discontinuities intersect at different angles causing chunks or blocks to fall out is referred to as blocky.

The second major reason for incompetency in a rock mass is weathering, the intense physical and chemical alteration caused by the action of air and water. Weathering along joints helps to create a high degree of blockiness in rock close to the surface. In highly weathered rock, the fabric itself has been attacked and has deteriorated. Weathering is the process that creates soil from rock. Highly weathered rock, although more competent than a loose soil, is much less competent than even highly jointed rock. There are generally no sharp boundaries between these different conditions. An idealized geologic profile taken from deep inside a rock mass to the earth's surface would show variation, often irregular, from sound rock to highly jointed rock to highly weathered rock to soil.

Earth - The terms earth and soil define any soft, unconsolidated, deformable materials that can be excavated without resort to blasting. In construction, earth materials can be placed into two major categories, cohesive and non-cohesive. Cohesive materials possess strength even when not subjected to pressure. They are typified by clays which contain extremely small plate-like particles that impart plasticity to the mass when wet.

As clay dries out, it shrinks, the particles come into closer contact, and the mass can become rock-like in its hardness. Heavy loads may also squeeze the water from a clay mass, decreasing its volume and increasing its strength considerably. But once the load has been removed and the clay is exposed to water, moisture is reabsorbed and part or all of the strength is lost. Sometimes, the tendency to swell is accompanied by considerable pressure.

Clays that have never been subjected to heavy loads (preconsolidated) will likely have low shear strengths, will be difficult to support in excavations, and will be poor foundation materials due to their tendency to compress under loads. Bottom heave, in particular, is a problem with soft clays during excavation; the movement is associated with settlements of the surrounding ground. Even preconsolidated clays of high strength may be troublesome in excavations if they lose their good qualities due to unloading or exposure to excessive moisture.

Noncohesive materials are typified by sand and gravel. In a moist condition, the surface tension of the water at the points of contact between the grains creates an apparent cohesion in the mass. But if the mass is either completely dry or submerged, the apparent cohesion disappears, and the strength of the mass is dependent upon the frictional forces that tend to prevent the particles from sliding past each other. Thus, sand can actually lose strength upon drying, whereas clays become stronger. Cohesionless materials tend to run and must therefore be fully supported in the sides and roof of an excavation. A small amount of cohesion permits temporary exposure of the material as construction is advanced.

Most construction sites in earth will be dealing with materials that are somewhere between purely cohesive and purely noncohesive. The most characteristic example is silt. Some sand deposits can be considered cohesive, because enough clay particles in the pore spaces act as a binder for the entire mass. And even where pure sand and pure clay strata exist, they will generally be interlayered with other materials of different characteristics. An excavation the size of a rapid transit station in earth is generally expected to have to cope with a wide variety of geological materials.

Mixed Face - Mixed face is a situation in which the upper part of an excavation is in earth while the lower part is in rock hard enough to require blasting for removal. The contact is likely to be irregular and is often gradational. Open excavation in such conditions is complicated by the necessity to change from an earth-support to a rock-support system before reaching the bottom of the excavation. Tunneling in mixed face involves totally different construction techniques in the earth and rock portions and may be many times more expensive than construction in either material alone.

Groundwater - Groundwater is water at varying depths under the ground surface which fills the pores in the soils and the openings in the underlying rock. When an excavation penetrates this zone of saturation, the final structure has to be designed to resist or relieve the resulting hydrostatic pressure. During construction, the water tries to enter the excavation. As it flows toward the opening, it exerts a seepage force that reduces the stability of the material surrounding the excavation and produces raveling, running or flowing of cohesionless or slightly cohesive soils. Under these conditions, some form of groundwater control is necessary.

In rock excavation at the depth necessary for rapid transit construction, little or no groundwater control is necessary during excavation. The water is found only in the fractures whose volume is relatively small compared to the total rock mass. The pressures at such shallow depths are not particularly high. Thus, the small quantities, low pressures, and general invulnerability of the hard rock to water tend to minimize the problems during construction.

Construction in earth may be aggravated considerably by the presence of groundwater. Groundwater tends to flow freely through the coarser grained, noncohesive soils. Cohesive soils, on the other hand, are relatively impervious and are barriers to groundwater flow. They can drain slowly, however, and are sometimes inadvertently drained when adjacent pervious zones are being dewatered. Such drainage can cause settlement of the cohesive layers if they are soft and compressible, and can cause damage to nearby buildings.

Inadequate groundwater control invariably leads to problems in the sides of excavations if noncohesive soils are present. The high permeability allows the water to leak through, often with enough velocity to carry finer particles into the excavation. This loss of material may also cause damaging settlements in the soil surrounding the excavation site.

Groundwater control is particularly difficult in the presence of alternating strata or in lenses of pervious and impervious materials, such as clays, silts, and sands. Since water cannot migrate freely through the clay, each sand layer may have to be individually drained for effective dewatering.

URBAN CONDITIONS

The urban characteristics of the area in which the underground transit station is to be constructed influence the design and impose physical constraints to construction and, as a result, have a significant influence on cost. Urban conditions are those combinations of physical, man-made elements which will have an impact on the design, construction, and cost of the station. These elements include:

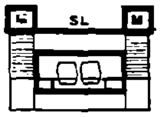
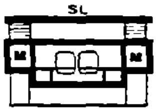
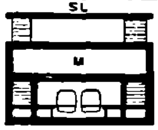
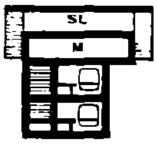
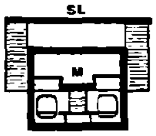
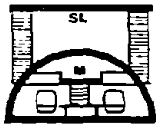
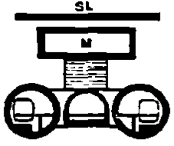
1. Intensity and type of surface development
2. Traffic
3. Street patterns
4. Right-of-way configuration
5. Utilities and other subsurface development.

While there are many additional items that might be included as urban conditions, these have been commonly recognized by those interviewed as major influences on station design and construction and, accordingly, on station costs. The relationships between seven typical station types developed in Chapter 6 and the urban conditions described in the following pages are shown on Table 3.

Intensity and Type of Surface Development

The first urban condition affecting the design and construction of subway stations is the intensity and type of land use at the station site. Urban land uses can be classified

Table 3
Station Types Related to Urban Conditions

	Objectives Station Type		Maintain Traffic	Maintain Utilities	Opportunities For Joint Development	Minimize Impact To Adjacent Structures
Open Cut Excavation	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and at Street Level Side Platform	1 	○	○	◐	●
	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and at Platform Level Side Platform	2 	○	○	●	◐
	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and Above Platform Level Side Platform	3 	○	○	●	○
	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and Above Platform Levels Stacked Platforms	4 	◐	◐	●	○
	Cut-and-Cover Box Structure Mezzanine within Trainroom and Above Platform Level Center Platform	5 	○	○	●	○
Mined Excavation	Mined Single Arch Mezzanine within Trainroom and Above Platform Level Center Platform	6 	●	●	○	●
	Mined Twin Tubes Mezzanine Separate from Trainroom and Above Platform Level Center Platform and Concourse	7 	●	●	○	●

● Maximum Achievement At Objective ◐ Moderate Achievement At Objective ○ Minimum Achievement At Objective as primary or central business district, outlying business areas, institutional development, residential areas, recreational locations, and other areas.

The categories used are primarily based on the intensity of urban development. They reflect the range of land uses and development intensity traversed by a transit system in transporting patrons from their origin to destination. Both the type and intensity of land use are major urban influences on underground station design and construction. Intensity and density consider not only the number and scale of buildings but streets, sidewalks, and special structures found in the urban scene.

Primary or Central Business District - The primary or central business districts (CBD) are those portions of an urbanized area in which the land use is dominated by intense business activity. This district is characterized by high-density building development and is usually the city center or the central business district. Structures tend to be massive and multi-story. Buildings contain a variety of retail, office, institutional, commercial, and even residential uses. Building foundations tend to be deep and substantial. The area is characterized by large peak hour traffic movements and transit travel, a large daytime population with many pedestrians, and generally minimal parking areas and limited open spaces. Stations designed for these locations must serve large peak hour passenger volumes effectively and efficiently.

Wider platforms are necessary to handle the large passenger volumes. Additional station entrances become necessary to increase the service area of each station and limit the size of each entrance. Surface facilities (entrances, elevators) must be designed to minimize infringement on street and sidewalk space, yet be conveniently located, visible, and attractive to the potential patron.

The large volume of peak hour passengers requires increased station scale to facilitate the wider platforms, increased size of corridor areas, and more extensive fare collection facilities. Transit routes usually converge in the primary business areas, thus requiring transfer capabilities between routes in these stations.

Because of the volumes of passengers and correspondingly large underground areas, CBD stations tend to be constructed from the surface rather than in tunnel unless other controls, such as geology (particularly competent rock) and street patterns, make tunnel construction either economically worthwhile or environmentally or socially imperative. CBD stations are extremely difficult and costly to construct. Restricted working areas for contractors, complicated vehicular and pedestrian traffic staging, extensive utility maintenance and reconstruction, restricted access for delivery and storage of construction materials, and extensive building underpinning or support make construction of CBD stations disruptive and costly. Examples of CBD stations constructed by opening the surface were observed in virtually every city visited. Common difficulties with constricted working space and added street congestion were observed.

Surface congestion was less apparent at the sites of mined stations in the CBDs of London, Rome, and Milan. The trade-off decision was apparently to sustain a higher construction cost to avoid the cost of urban disruption. There was no evidence that firm figures were placed on the cost of disruption. Milan generally has the opportunity to place stations in street right-of-way. Mined stations in the CBDs of London and Rome have the additional constraint of irregular street patterns or narrow public right-of-way.

If there is a solution contained in these observations, it would appear that open cut construction is the compromise solution where some urban disruption is tolerated.

Although imposing the severest construction constraints and requiring special design standards, these principal business district stations offer several development opportunities. Interfacing of retail operations by direct subway access to stores has occurred in isolated instances in Washington, D.C., and Chicago. Montreal has extended an underground walkway system throughout the principal business area, connecting it with underground transit stations. San Francisco, in several instances, has undertaken joint station access development with adjoining building developments to enhance the visual design elements and permit access to adjoining buildings.

Outlying or Secondary Business District - An outlying business district is an area generally separated from the CBD in which the land use, although principally business and commercial activity, has a higher level of residential density than the CBD. Development in this outlying or secondary business district is less dense than in the CBD. Structures tend to be mid-height or low rise, mostly on shallow footings. Street areas may be wider, and buildings are primarily retail business or smaller office spaces. Transit system patronage is lower at peak hours than in the CBD, with higher off-peak percentages. Through traffic is concentrated on a few arterials, rather than on all streets, with local traffic movements superimposed on the through movements. Parking areas are usually ample. Pedestrian volumes are relatively small. Included in the general category of outlying business district is the urban or suburban shopping center.

From the design standpoint, underground stations located in these districts present no unusual problems. Station accessways are simple. If station sites are restrictive, building underpinning and protection can become more involved than expected because of shallow footings. Traffic maintenance can be difficult; but in these less intensely developed areas, alternative routings or space for temporary detours are usually available. These stations are usually simpler to construct than CBD stations, because more working space and access areas are available.

Development opportunities to interface the underground station with adjoining retail establishments are generally nonexistent, nor does the magnitude of potential retail sales encourage such development.

Institutional District - An institutional district is an area of educational, religious, health, correctional, or military facilities. These areas are characterized, from a transit viewpoint, by rather steady traffic flows through the station. Existing structures tend to be massive with variable foundation types but set back from the streets. Parking areas are available, and surface pedestrian traffic is minimal.

From the design standpoint, land use or surface development is not a significant determinant. If access facilities for the handicapped are not provided systemwide, special efforts are made to provide that access at this type of development.

Institutional area stations usually have large work sites available. Utilities are normally not a problem. Environmental factors require more than normal consideration in institutional districts, particularly control of noise and vibration and restrictive nighttime working hours.

Residential Districts - Residential developments range from high density, high-rise structures to medium-to-low density development. Transit ridership is peak hour, work trip oriented. Street traffic is concentrated on major arterials, and light pedestrian volumes can be expected. As residential density decreases, intermodal transfer facilities become necessary. Parking is normally provided in areas of medium-to-low density development.

Design controls are focused on peak hour directional ridership. Residential property takings can be sensitive issues. The sensitivity increases as additional takings are required for intermodal facilities. Size, location, layout, and access and egress for bus facilities and parking lots are prime factors requiring detailed analysis. Utilities, traffic rerouting and pedestrian movements are normally not significant cost problems.

In medium-to-low density areas, construction constraints become less limiting; substantial work sites are available; and in many cases, street closings are permitted. Noise, vibration, night work, dust and street litter become increasing irritants to neighborhood residents which must be overcome by construction contractors.

Recreational Areas - Recreational areas include major public parks, stadiums, arenas and similar facilities. Park and recreational areas, such as metropolitan zoological gardens, which attract large crowds may require transit services.

Stadiums and arena requirements are characterized by extremely heavy surge loads at the termination of activities, heavy loads extended over a longer period at the beginning of the events, and very light patronage at other times.

Design criteria stress maximum flexibility in station operation, and an evaluation of the trade-offs between infrequent surge loads and a reasonable capacity throughout the remainder of the service period. Center platform stations are desirable at these stations because of their flexibility and storage capacity.

Construction activities can usually be accomplished with a minimum of interruption to scheduled events. The substantial parking areas, in most instances, offer adequate space for construction activities.

Other Areas - Examples of the areas not previously classified are industrial neighborhoods and open space.

Transit stations, usually aboveground, have been constructed in open areas to encourage and accommodate development. Transit service to industrial areas is complicated by the usually substantial plant sites and extended distances between the station entrances and passenger destinations. The design and construction of underground stations in these areas are conditioned by adjoining land uses.

Construction activities can generally proceed with minimal attention to maintaining low levels of noise, vibration, and dust. Adequate work areas are generally available.

Development opportunities are minimized in industrial areas. The greatest potential for the joint development of transit and induced growth is present at sites involving major vacant lands.

Traffic

By their nature, transit routes follow existing transportation corridors. This routing creates a conflict between the construction of new facilities and the existing transportation system. Nevertheless, during construction, surface traffic must be accommodated. When a transit station is located underground in public right-of-way, street traffic is accommodated by rerouting or by providing a temporary roadway using decking when constructing open cut stations, or by constructing the station in tunnel and locating construction shafts out of the traveled way.

Traffic staging and maintenance have significant influence on design decisions. In Toronto, for example, the Bloor-Danforth subway line was located one-half block off the major arterial street to avoid traffic disruption and to minimize utility problems. In Washington, D.C., one of the considerations for locating sections of the subway in rock tunnel was the desire to minimize traffic disruption.

With cut-and-cover or open cut construction, extensive disruption of traffic is necessary. Traffic is disrupted initially for utility work, again for construction of the excavation support system and decking, and finally for restoration of the utilities and pavement. Even if the entire width of the street is not closed, detours and extensive staging of construction is required.

With tunnel construction, impact on traffic is considerably less than with cut-and-cover or open cut. However, tunnel construction does not preclude surface disturbance and traffic interruption. Contractor's work areas, construction shafts, accessways from surface to station, mezzanines and ventilation shafts all cause surface disruption and can require careful consideration for their impact on traffic.

Street Patterns

Another urban condition affecting the design and construction of underground transit stations is the street pattern. Street patterns vary considerably from city to city and, in almost every case, vary within the city itself. Street patterns can be classified as irregular, rectangular grid, or grid with radials.

Older cities often have irregular street patterns in the central or original city area. Sometimes centuries old, these meandering streets are usually very narrow and lined with buildings that must be preserved. Central London, for example, has a street pattern that would be impossible to use as an alignment control for locating transit routes. For this reason, much of the London system, including the stations, has been constructed in tunnel rather than from the surface. The tunneled stations and routes are located under occupied city blocks. London has had great success with this approach, because geotechnical conditions are favorable, and because the labor market includes skilled tunnel workers. Stockholm has similar conditions in the original city area with an accompanying opportunity to mine stations in rock without regard to the relationship between street and station alignment.

Newer cities and younger areas of the very old cities are usually expanded using a more regular street pattern, permitting route locations in street right-of-way. This pattern gives more latitude for design and construction decisions for transit stations in these areas. Cut-and-cover stations become practical without destroying existing land uses, although they can have a significant impact on them. With the irregular street pattern, both tunneled stations and tunneled routes become more desirable for construction without major impact on the city.

The street pattern in almost every city is a combination of these patterns and varies from one part of the city to other. The most advantageous pattern for locating transit routes is the grid system with diagonals, particularly when the diagonal streets are radially oriented. Washington, D.C., has made good use of its wide, radially-oriented streets in locating elements of its transit system.

Right-of-Way Configuration

Right-of-way width and length are physical controls which influence transit station design and construction, together with street patterns.

Wide street right-of-way provides the contractor with working space. For tunneled stations, shafts can be located to best advantage. For open cut stations, traffic can be staged during the phases of excavation, and utilities can be relocated outside the limits of excavation. Excavation support systems can be constructed without interfering with access to adjoining buildings.

Station length is always a function of line capacity. Right-of-way length from cross street to cross street is not a determinant of station length, but it can become the source of significant construction costs if stations extend through several cross streets. The length of a city block can have considerable effect on station location. If station length, including ancillary spaces and ventilation shafts, is less than the length of the typical city block, the designer can sometimes minimize the conflict between station elevation and utility profile, where utilities are located in streets crossing the station longitudinal axis.

Utilities and Other Subsurface Development

Existing subsurface development at the transit station site influences design and construction in two significant ways. Subsurface development, such as utilities, existing tunnels, or vehicle underpasses, can control the profile of underground transit routes and the depth of the underground transit station. Also, utilities and other man-made subsurface developments must be maintained, supported, restored, or relocated.

By their nature, urban transit systems and underground stations are constructed in heavily populated areas. In these areas, the development of underground utilities is most intense. When possible, utilities and other subsurface development should be relocated so that depth of excavation for the transit station can be minimized. For many facilities, particularly gravity-dependent utilities, such as storm and sanitary sewers and other underground civil works, relocation is not possible. In this case, these urban conditions control the transit system profile.

Utilities affected by transit construction are normally handled in a variety of ways. They may be supported and maintained complete, in place, during construction and continued in service following the completion of construction, or utilities may be temporarily relocated and maintained. Then upon completion of transit facilities, they may be replaced and restored to service, or utilities may be permanently relocated to a new location beyond the immediate limits of transit construction.

The policies affecting the performance of utility work are significant. When due consideration is given to the needs of the transit system and the public served by transit, total costs to the community are reduced. Circumstances which favor overall economy and a faster rate of progress result from compromises which accommodate the needs of utility companies, traffic flow, service to abutting properties and the transit owner.

In addition to the significant impacts on design, utilities and other subsurface development have a major impact on construction. In virtually every city visited, emphasis was placed on the time and cost implications of utility work. Contractors emphasized that significant time and cost savings could be realized if utilities could be relocated by contracts awarded prior to the main station contract.

Utilities are not generally a determinant in the selection of station type or construction type. However, they should be given careful consideration in the selection of a station site.

Other man-made subsurface developments can be determinants in the selection of station type. For example, one of the considerations leading to the decision to tunnel several of the very large RER stations in Paris was the fact that the RER system was to underlie the existing Paris Metro system. While the RER stations were constructed, Metro service was to be maintained. This fact led to the decision to tunnel the RER stations.

ARCHITECTURAL CONSIDERATIONS

The predecessors of today's subway systems were located underground to provide additional right-of-way for street railways operating on congested surface streets. However, the cost of underground construction was many times higher than that of surface construction. As a result, the tendency in early systems was to attempt to control costs by emphasizing utilitarian design.

The tendency in recent years has shifted toward more consideration of architectural quality in stations. The difference in approach becomes apparent when comparing extensions of older systems with the original system. System developers and public officials in every city visited recognize that the total transit environment must be pleasant and attractive to entice people to use public transportation. This recognition has resulted in a willingness to invest in good design.

While the development of an urban transit system emphasizes extensive heavy construction and complex engineering, the patrons of the system perceive the system basically through its vehicles and the architecture of its stations. As a result, much of the impression a system leaves is a function of the design of these two elements.

The purpose of the subway station, of course, is to provide a means for patrons to gain access to the system. The designer should attempt to make the experience of entering the facility attractive; to aid in patron understanding of how the system works; and to make going below ground, paying the fare, and boarding the train as attractive, comprehensible, smooth, and safe as possible. Station design should achieve these goals in the most effective manner. Architectural quality with construction economy can be achieved as long as the architectural design of the station allows a relatively simple overall station shape; fairly modest dimensions regarding length, width, height, and depth of cover; and significant opportunity to repeat elements of both structural formwork and interior finish, while preserving appropriate design latitude for each individual station.

Conversely, architectural decisions which affect such major systemwide factors as the depth of the overall system or the major shape or dimensions of the station can significantly increase systemwide construction costs. Potential architectural objectives to be achieved by such decisions should be tested to determine if they can be achieved by other means that have a smaller effect on systemwide costs.

System Design Philosophy

In the development of rapid transit station design in recent years, two design philosophies for systemwide architectural design of stations have emerged: the system concept philosophy and the unique solution philosophy.

In the system concept, a standard architectural design concept is developed and utilized for all subway stations, usually by a single designer or firm. In some cases, one concept might be developed for stations in rock, another for stations in earth. Variations are site-specific, centering about platform configuration, access location, and mezzanine layout. Systemwide finish details, such as graphics, lighting, station furniture, and station finishes, are also standardized.

In the unique solution philosophy, each station is designed as an entity considering the specifics of the site. Systemwide components, such as station graphics, lighting, station furniture, floor finishes, fare collection equipment, and similar items are standardized to achieve a unifying motif and a sense of identification. These items become a system signature.

Of the cities visited, Washington, D.C., Toronto, and the new Stockholm stations in rock seem to best represent the system concept, whereas the unique solution concept is best represented by San Francisco and Montreal.

There are advantages and disadvantages to both schemes. Properly handled, the system concept can produce economies by standardizing repetitive structural configurations or construction procedures. However, rigidly enforcing systemwide design concepts can be costly.

Conversely, the most cost-effective elements of both design philosophies may possibly be integrated into a blend of both attitudes which standardized only small scale construction and design elements, allowing a unique solution to be applied to a unique site. In practice, most transit system developers recognize that some combination of the two approaches is the optimum condition. In both cases, good design is a matter of best utilizing the site opportunities to the maximum advantage.

Major Station Elements

The size, character, and functional relationships of the major subway station elements vary substantially among different typical subway station types. Their architectural design can contribute significantly to total station construction costs or savings.

Success in achieving desirable architectural objectives does not necessarily vary directly with station size or complexity. However, the construction cost of the basic structure nearly always increases directly with increases in station size, depth, and complexity of basic structure shape. As has been frequently noted, station construction costs can differ dramatically with different site conditions, but certain architectural considerations related to the design of basic station spaces merit discussion.

The economies of repeating simple structural formwork for structural shell construction may be realized while allowing great diversity for each station design to satisfy unique site conditions. Within the structural shell, repeating interior finish elements, equipment, lighting, escalators, and fare collection facilities can assist in systemwide cost savings while their specific design achieves a unique solution for each station.

The integration of ancillary spaces into the overall design of the station can help simplify the basic shell form and thereby materially reduce construction costs by reducing the necessity to construct special structural shapes or to extend the station space beyond the platforms.

Station graphics, interior lighting and structure or interior finish elements can be used in combination to effectively orient the patron and assist in creating a unique solution within standardized design criteria.

Water penetration into a subway station is an unavoidable fact of underground construction. Where structure and interior finish are integrated, major steps must be taken to assure nearly perfect waterproofing. In addition, to assure very high quality finishes, careful attention must be paid to formwork. Both requirements will contribute inevitably to significant capital and maintenance costs. Substantial savings in waterproofing and structural formwork can be achieved if interior finishes are hung from the structural shell in a manner which allows moderate water seepage and collection as well as the normal dimensional variations that occur in large scale underground construction. Maintenance and operating costs can be significantly improved if interior materials are selected for their durability and maintainability. Modest increases in initial capital costs can be more than paid back in the long run in improved appearance.

Architectural Finishes - Architectural finishes directly affect the lightness, character, quality, and durability of the station. The finishes and the station layout essentially constitute the perceived design of the station. The finishes are a very small share of the total station cost, and in general, finishes of the very highest quality more than justify their initial investment by maintenance and operating savings.

The appearance of the station is vital to patron acceptance of the system. It must be clean, attractive, and in good repair. It is the designer's responsibility to develop materials that will be attractive, resistant to vandalism, and easily and economically replaced when necessary. The responsibility for a clean, attractive station rests with the transit authority and its commitment to a realistic, comprehensive maintenance program which the station should be designed to facilitate.

Chapter 6
CONSTRUCTION METHODS

The identification and study of unusual construction methods for subway stations being constructed outside of the United States were major elements of this study. The Study Team was to determine if there were construction methods presently being used which were either unknown or known but not commonly used by U.S. system developers, designers, and contractors. The Study Team concluded that certain construction methods have been used to a greater extent in other countries, depending on site conditions and other local controls. The Study Team found that specific techniques which might be acceptable in one city or at one site in a city are not acceptable at other sites or in other cities for a variety of reasons, basically geotechnical and urban conditions. There was also an element of experimentation with these techniques, indicating that there is no universal acceptance of their applicability.

These findings reflect the basic tenet that no given construction method can be considered sound for all circumstances, even in one city, much less for all cities. Site variables, such as geology, groundwater, traffic, utilities, and physical characteristics of adjacent structures, as well as the influence of community pressures, lead to the one basic rule expressed by most of those interviewed: each design and construction solution is site-specific. The most important single consideration is to take advantage of the opportunities available at the site.

No attempt is made in this report to chronicle construction techniques which are considered standard practice in constructing underground transit stations. Rather, concentration is placed on construction methods which are unusual, which are being used in the systems investigated and which might offer opportunities for cost savings in future U.S. construction.

Construction methods have been considered for both cut-and-cover stations, which include open cut stations, and for tunneled stations. Several aspects of ground improvement techniques are also discussed.

CUT-AND-COVER STATIONS

The most commonly observed method for constructing underground rapid transit systems is that based upon opening the excavation from the surface. Termed cut-and-cover construction, this technique is in use throughout the world. The cut-and-cover technique in its most customary form is a multi-step procedure in which the contractor diverts traffic and utilities, constructs an excavation support system as he makes the excavation, constructs the station, and backfills and restores utilities and surface features. Opportunities for cost savings observed during the on-site inspections centered about excavation support systems, multiple usage of the excavation support system, variations in the normal order of construction, and prefabricated decking systems.

Excavation Support Systems

A large number of techniques are in use worldwide to support open excavations. These support systems can be broadly classified as flexible and semi-rigid systems.

Soldier pile with lagging and steel sheet piling are flexible support systems. Flexible systems are extensively braced to minimize deformations of the relatively light support wall. In a highly developed urban area, it is the ground movement which accompanies deformation of the flexible system that causes great concern. A further concern with the soldier pile and lagging system is the lagging itself, which permits the movement of waterborne soil particles into the excavation with accompanying loss of support for adjacent structures. These systems are in common use in virtually every system inspected. In general, the soldier pile and lagging system is considered the most economical solution for excavation support unless an opportunity exists to utilize the excavation support system for more than one function, e.g., to reduce direct underpinning as well as support the excavation.

Semi-rigid systems also require extensive lateral support, usually in the form of tie-backs or cross bracing, but have additional stiffness in the wall section itself. In addition, if properly constructed, the wall acts as a cut-off and prohibits the movement of groundwater and waterborne material. Cast-in-situ concrete walls in slurry trenches (widely termed slurry walls), precast concrete walls erected in a slurry-supported trench, and secant (or interlocking) concrete pile walls are semi-rigid excavation support systems. While more rigid than the so-called flexible excavation support systems, they require the same care in the design and installation of bracing systems and in opening the main excavation to avoid damaging ground movements outside the support walls.

Cast-in-situ Concrete Walls in Slurry Trenches - Cast-in-situ concrete walls constructed in slurry-supported trenches are commonly referred to as slurry walls. The sequence for the construction of these walls is as follows:

1. Lay out and construct guide walls (Figure 15), and set up excavating equipment and slurry mixing and handling equipment.
2. Excavate the trench or slot, normally one panel at a time (Figure 16). During excavation, trenches or slots are supported against cave-in by the liquid pressure of the slurry mixture.
3. Install steel reinforcement.
4. Fill with tremie concrete while slurry is displaced and removed from the trench.

In normal practice, slurry walls are constructed in panels one section at a time. Continuous trench walls have been constructed using specialized equipment.

Difficulties associated with this type of construction have been noted by many of those interviewed. Determining and controlling the loss of groundwater or ground into the slurry trench can be difficult, as can the control of the flow of slurry into the soil formations or into adjacent utilities. Control of slurry density and surface elevation is critical. Boulders and other obstructions can make excavation difficult. Utilities interfere with wall construction and are commonly relocated temporarily or permanently. Although the wall face is expected to be irregular, at times the irregularities are so great that remedial work is necessary.

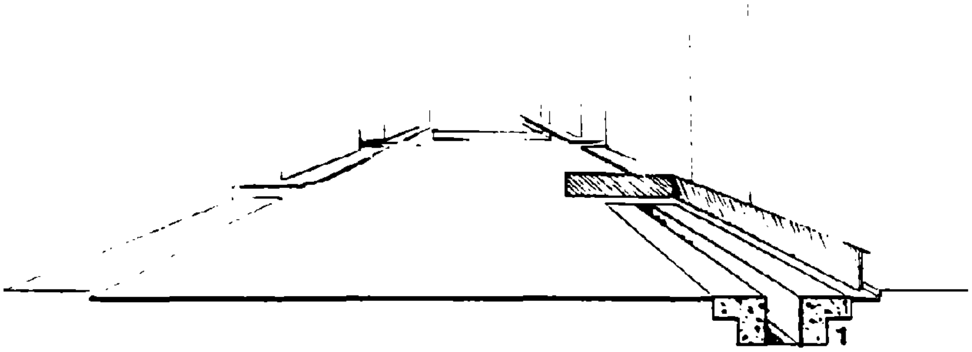


Figure 15
Construction of Guide Walls For Slurry Trench

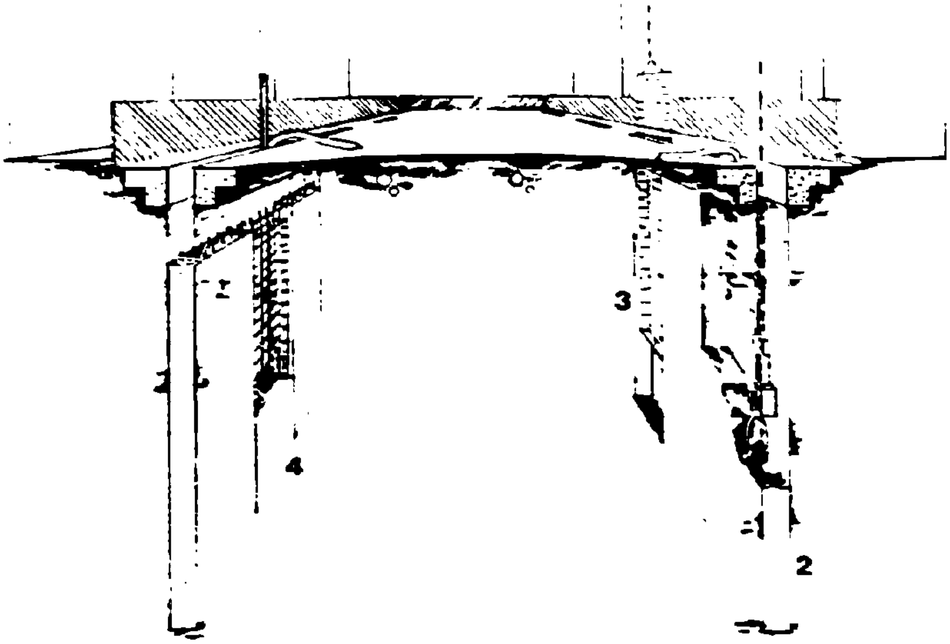


Figure 16
Slurry Wall Construction Sequence

<u>Precast Walls in Slurry Trenches</u> - In this variation, steps 1 and 2 are identical with the procedure used for cast-in-situ walls. However, after the slurry-filled trench is excavated. a precast concrete wall panel is lowered into the trench (Figure 17). The slurry solution between the panel and the earth is then allowed to gel, setting the panel firmly into proper alignment.

The difficulties noted for constructing cast-in-situ walls also apply to this variation, except that the structural alignment of the wall and dimensional tolerance of the surface can be closely controlled. Also. panels have practical limitations to their size because of their weight and handling difficulties.

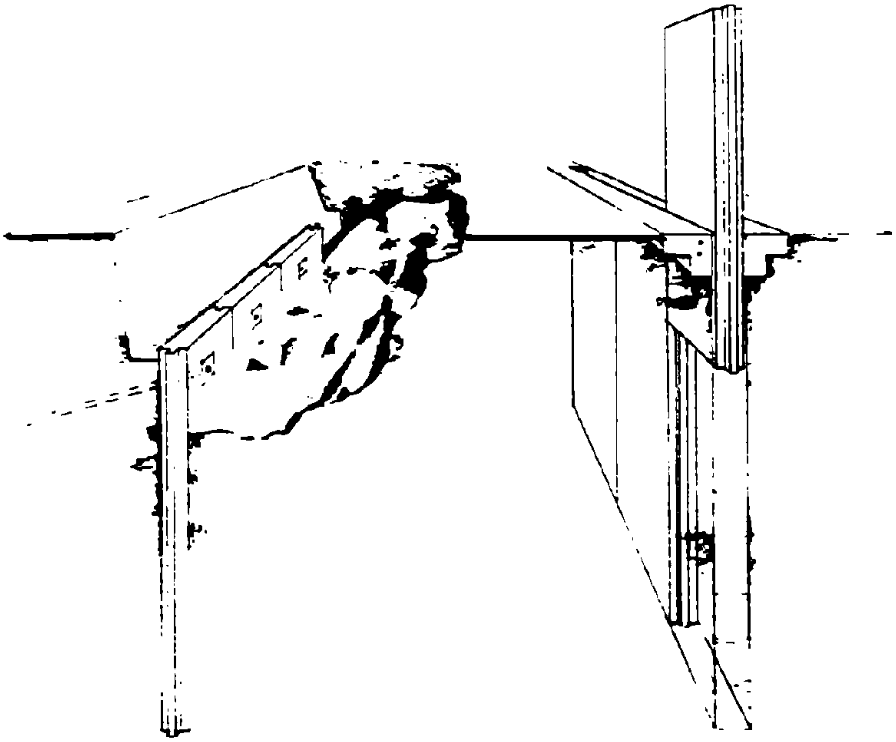


Figure 17
Installation of Precast Panel

Secant or Interlocking Concrete Pile Walls - Interlocking concrete pile walls, usually called secant pile walls, have been in use for a considerable time. The construction sequence of this type of support system is typically:

1. Drill primary holes at slightly less than two diameter spacing between centers of holes (Figure 18).

2. Support hole during excavation either by slurry mixture (Figure 19) or by inserting a casing as the excavation progresses.

3. Set reinforcing steel.

4. Place tremie concrete in drilled hole; if casing is used in lieu of slurry, pull casing as concrete is placed in drilled hole.

5. Drill filler pile holes between primary piles; edges of primary piles are cut away by drilling the filler pile hole, thus providing an interlocking between the piles and making the wall continuous.

6. Support filler pile hole with slurry or casing during excavation, similar to the primary pile sequence.

7. Place reinforcement and concrete as in steps 3 and 4 above.

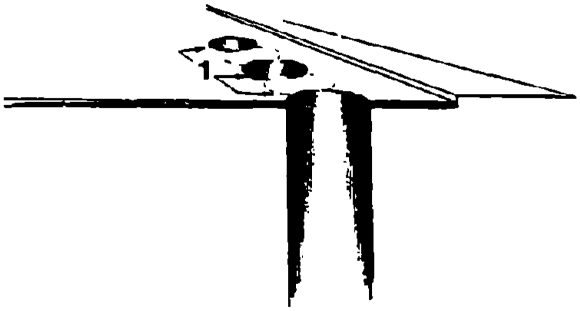


Figure 18
Secant Pile Wall Primary Holes

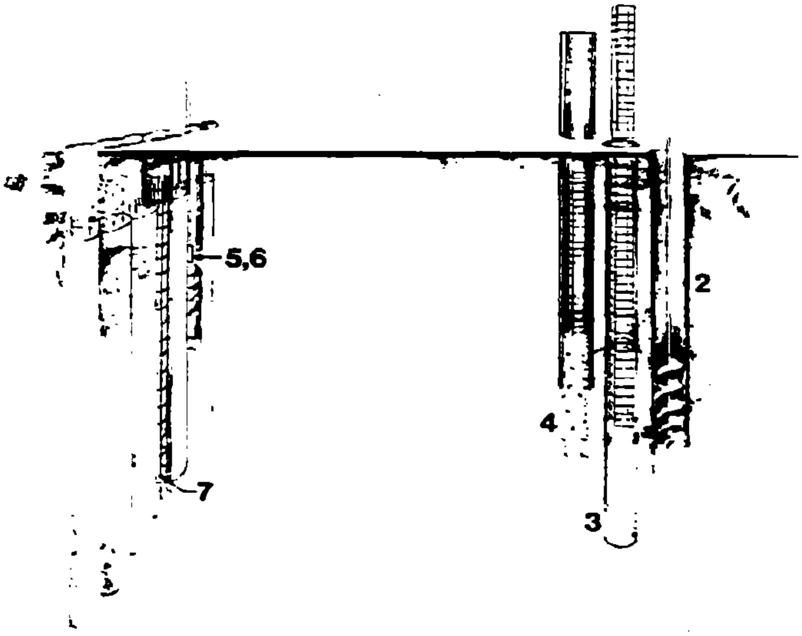


Figure 19
Secant Pile Construction Sequence

Multiple-functions of Excavation Support - The use of these semi-rigid excavation support systems to perform multiple functions has been recognized as a source of cost savings by many contractors and transit authorities. Several transit systems investigated during this study have used semi-rigid walls to achieve cost savings by using the excavation support system in lieu of or to complement direct underpinning. Concrete walls cast in-situ in slurry-supported trenches or secant pile walls (Figure 20) have been used in this manner in San Francisco; Washington, D.C.; Mexico City; Munich; London; Paris; Milan; Rome; and Brussels. The use of these walls is not a panacea for underpinning problems, but they do have several advantages, particularly:

1. The wall acts as a cut-off wall, controlling groundwater flow and movement of fine particles through the support system.
2. The wall is completely in place before the main excavation is initiated.
3. The wall has an inherent stiffness.

Source: W [illegible] Lucke

Figure 20

Secant Pile Wall In Munich

Perhaps the most significant economic advantage observed during the course of the study was that obtained by using the excavation support system as the permanent structural wall of the station structure. After the excavation support system is constructed using one of the semi-rigid wall techniques, the following sequence is typical:

1. The excavation is opened and braced (Figure 21).
2. The invert is then constructed as part of the wall bracing system.
3. A seat is constructed along the top of the excavation support wall to support the roof structure.
4. The station roof structure and intermediate levels are constructed (Figure 22).
5. The station is then backfilled, and the surface is restored.
6. Station finish work and fitting with station equipment then proceeds in the normal manner.

As a variation of this technique, the seat and roof structure can be constructed prior to opening the main excavation. The surface can then be restored and both excavation and inside framing can proceed under the roof.

It was mentioned repeatedly that the construction of continuous walls for excavation support is facilitated by utility relocation prior to construction. An alternative tactic when utilities are light to moderate in density is to lower the top-of-wall elevation of selected panels or piles and concentrate the relocated utilities or service lines where the wall is lowered.

In addition to a satisfactory resolution of utility conflicts, the use of the excavation support system as the permanent structure is dependent upon provision for collection of groundwater infiltration between the station finish and the structural wall without damage to station finish material (Figure 23); station finish, such as decorative panels, is designed to stand free of the structural wall to accommodate the inherent irregularities in the slurry wall.

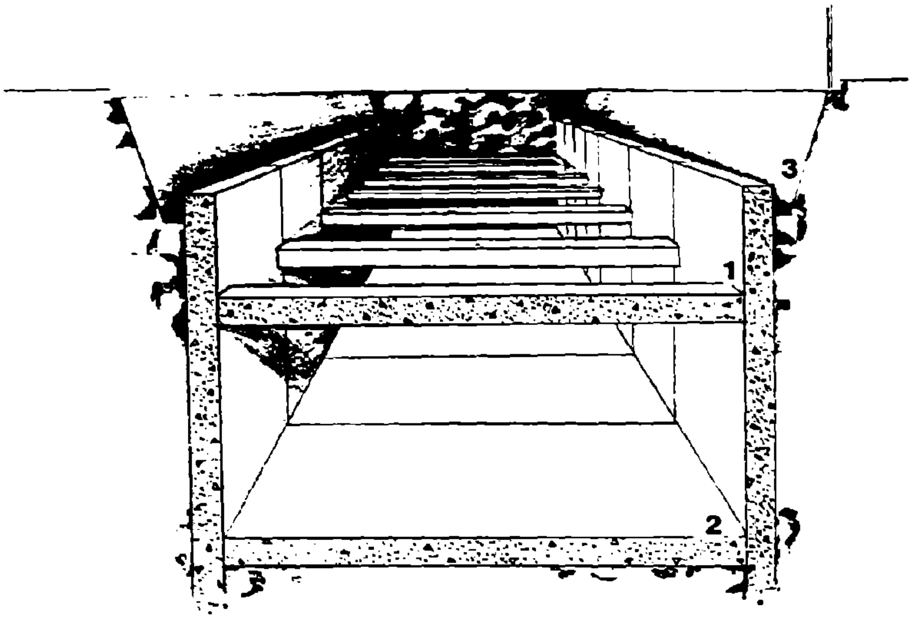


Figure 21

Cut-and-Cover Construction Sequence with Slurry Wall Used as Permanent Structural Wall

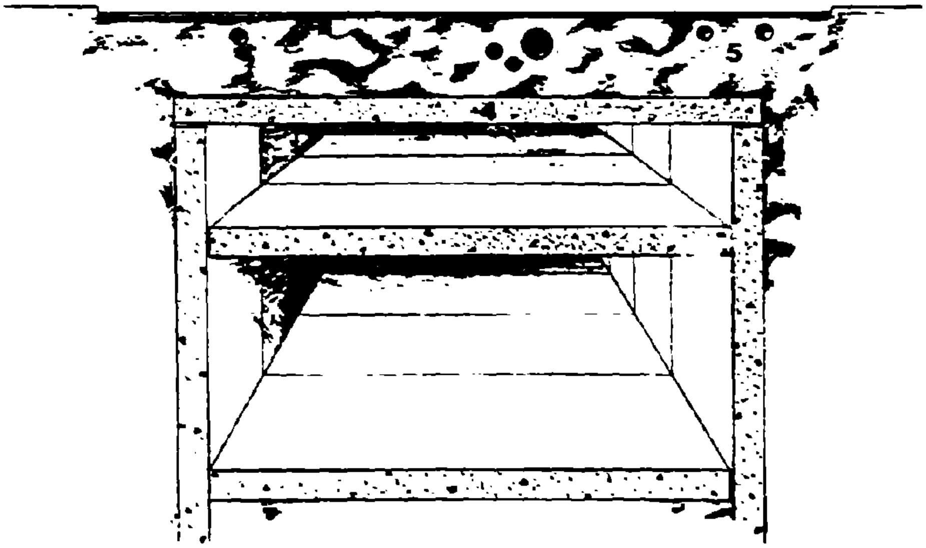


Figure 22

Cut-and-Cover Construction Sequence Structure Completed and Surface Restored

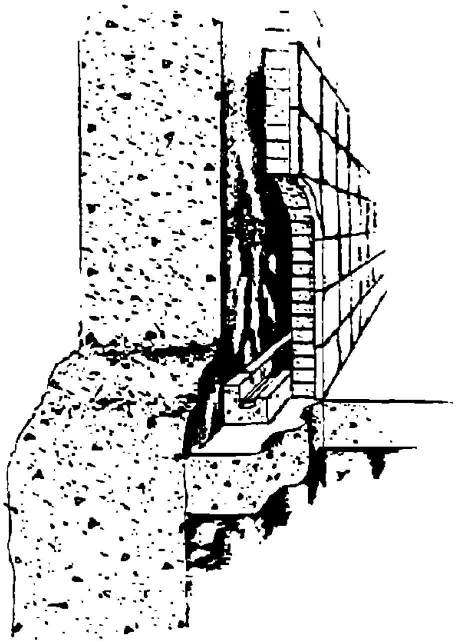
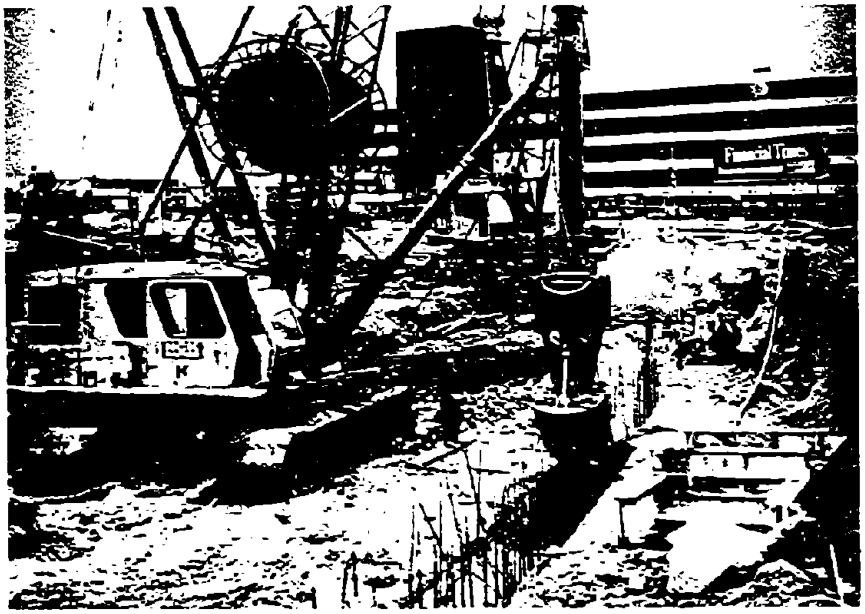


Figure 23

Wall Finish and Drainage Trough with Slurry Wall

The most extensive use of the excavation support system as the permanent structure was found in Mexico City. Initial station construction proceeded in laid-back, open excavations. Problems with construction space, ground movements, and settlement of adjacent structures led to the adoption of a reinforced concrete slurry wall system for excavation support. The station structural walls were constructed as formed inner walls and keyed into the excavation support system constructed with slurry walls. After successful experience with the slurry wall technique, it was decided to use the slurry wall as the combined support of excavation and station structural wall. Almost of all of the underground stations constructed later in the system development period were constructed using the slurry wall as an integral part of the permanent structure, with about half of the total number of stations constructed in this manner. Indications are that all future underground stations will be designed and constructed using this technique.

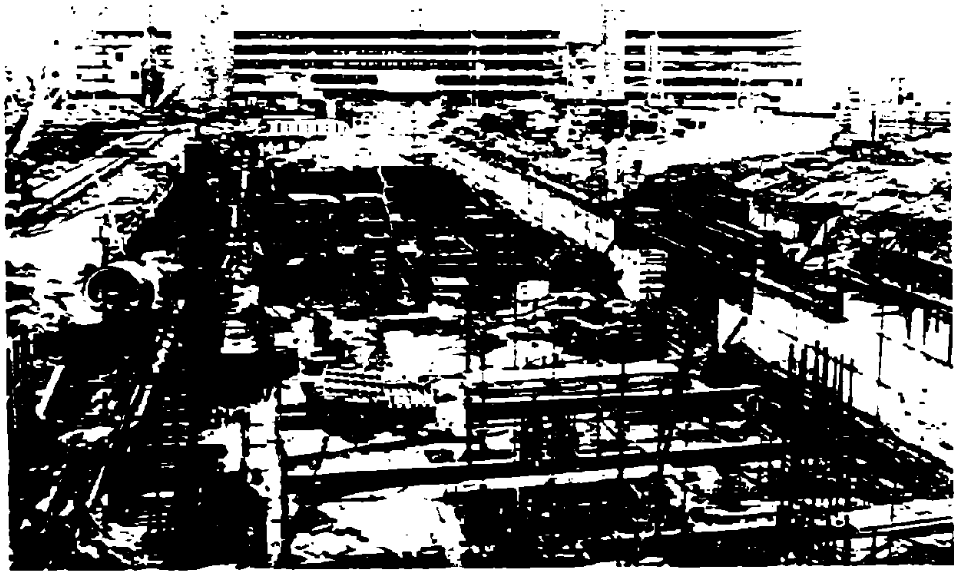
London Transport is presently extending the Piccadilly Line westward to Heathrow Airport. Whereas the majority of the recent London underground stations are constructed in soft-ground tunnels, the three stations on the extension to Heathrow Airport are constructed using cut-and-cover methods. In all three cases, the excavation support system is used as



Source: London Transport Executive

Figure 24

Slurry Wall Construction at Heathrow Central Station



Source: London Transport Executive

Figure 25

Heathrow Central Station Slurry Wall in Place
Excavation Open

the permanent station structural wall. In two of the three stations, Hatton Cross and Hounslow West, the secant pile technique was used for the excavation support system and the permanent structural wall. The third, Heathrow Central Station, was constructed using the cast-in-situ slurry wall as the permanent station structure (Figures 24 and 25).

The secant pile technique used in London is the cased pile (Benoto) system. London Transport used 6500 Benoto piles 880 mm. in diameter on this project. Vertical accuracy was specified at 1:120; the contractor had no difficulty meeting this control.

At Hounslow West and Hatton Cross Stations, the station roof was constructed using precast box beams placed contiguously and bearing on a cap beam topping the exterior secant pile walls (Figure 26). The box beams were supported by a longitudinal beam placed on cast-in-place center columns running the length of the station.

One station under construction in Paris, Basilique-St. Denis, utilizes the excavation support system as the final structural wall. The system uses a cast-in-place slurry wall for the trainroom wall. Although the initial results

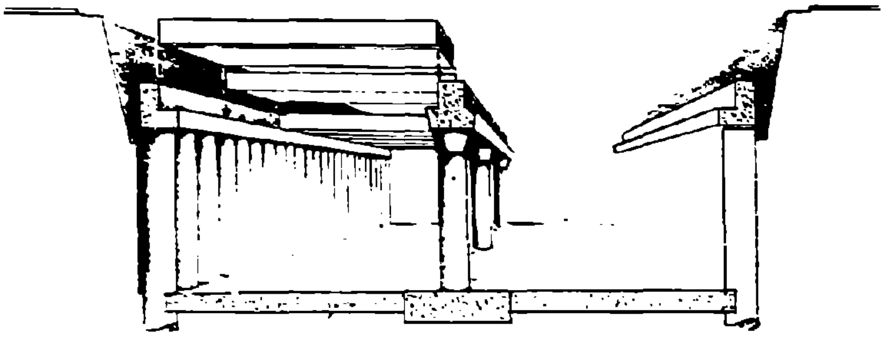


Figure 26

Cap Beam and Precast Roof Beams

appear satisfactory, a final evaluation of this design approach will be made before adopting slurry walls incorporated with the permanent structure as a major construction method. The Paris Metro system has recently constructed a reach of line structure using precast panel walls erected in slurry trenches with satisfactory results.

Several stations in Brussels have been constructed using the excavation support system as the permanent structure. Stations are being constructed using the slurry wall technique, with the wall designed to act as the final structural wall of the station.

Under-the-Roof Construction

The normal sequence of construction of stations in open excavations is based on proceeding upward from the invert after the excavation is completed. This procedure reflects the practice on most major building construction projects.

Because subway stations and routes normally are located in existing transportation corridors, underground station sites are many times located in city streets or under traveled ways. In these circumstances, it is sometimes advantageous to vary the normal construction sequence and construct the station roof structure after the excavation support system is in place and before excavating to invert level (Figure 27). By doing this, inconvenience to the public and the expense of temporary decking and long-term maintenance of street traffic can be reduced by sustaining the additional expense of under-the-roof excavation and framing.

After the roof structure is completed:

1. The site is backfilled (Figure 28).
2. Utilities are restored.
3. The street pavement and other surface features are reconstructed and opened to traffic.
4. The remaining excavation is performed under the station roof and removed from the site by side-street access ramps or other means.

While this system, which is sometimes called the Milan Method, is usually more expensive than traditional cut-and-cover methods, it has the advantage of minimizing the duration of disruption to surface traffic and to other urban activities.

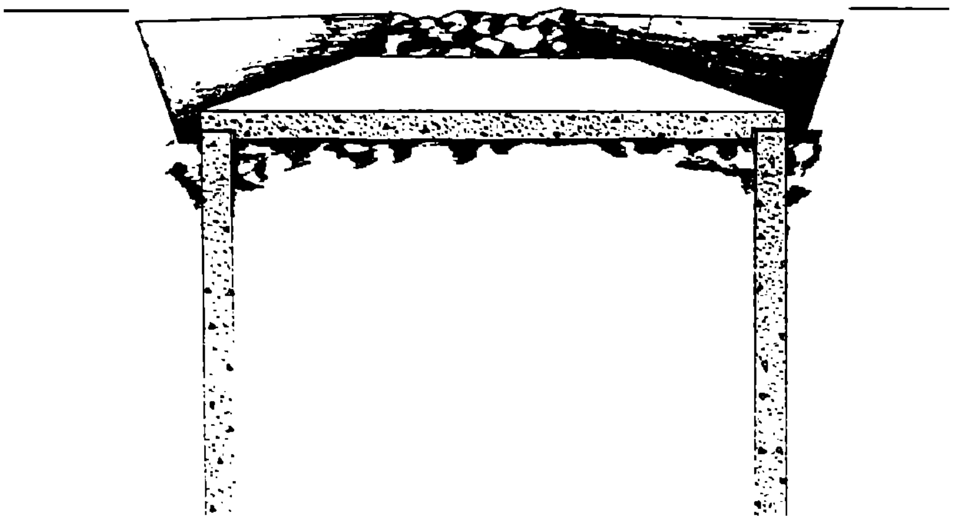


Figure 27
Under-the-Roof Construction
Structure Walls and Roof Slab in Place

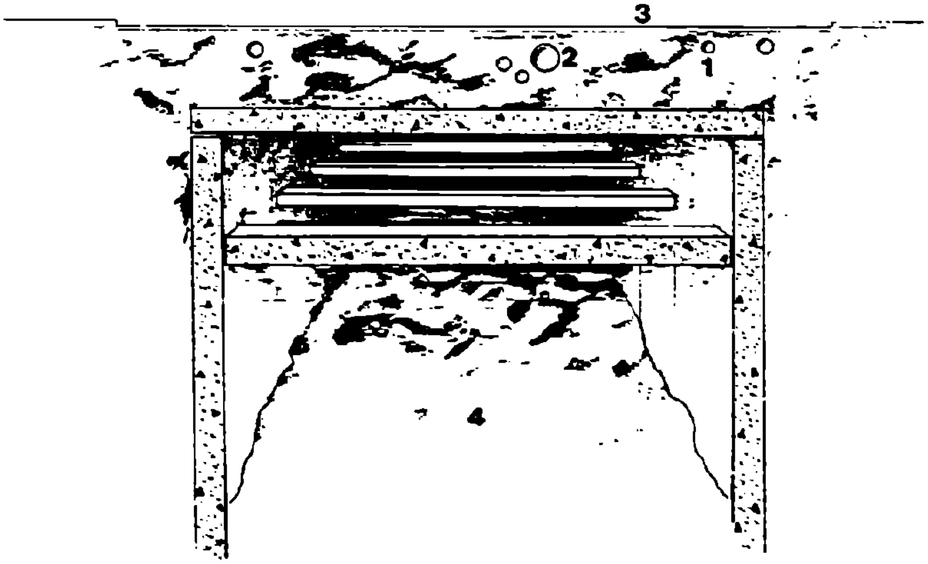
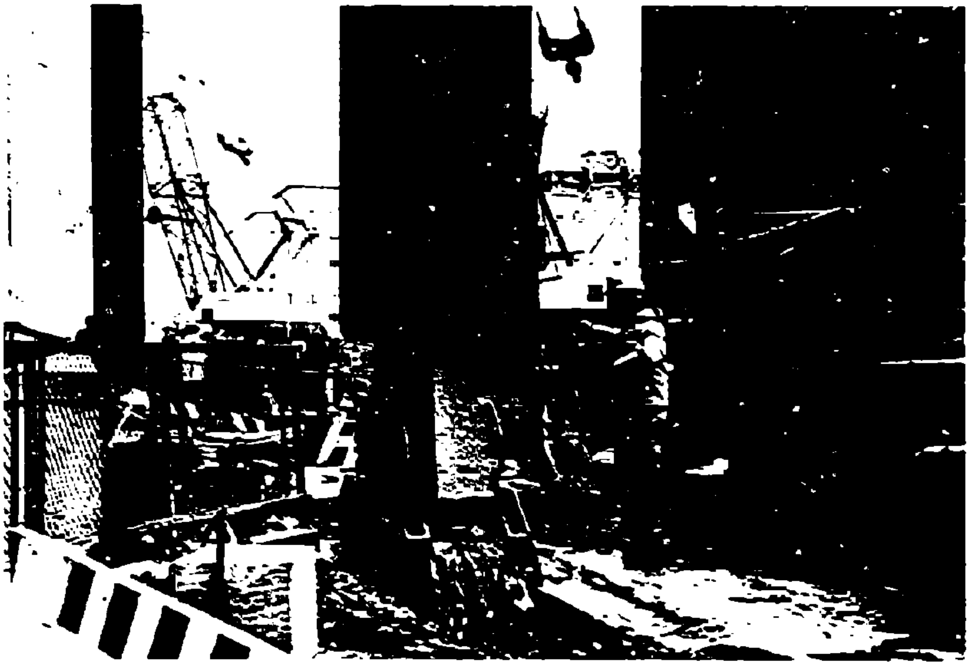


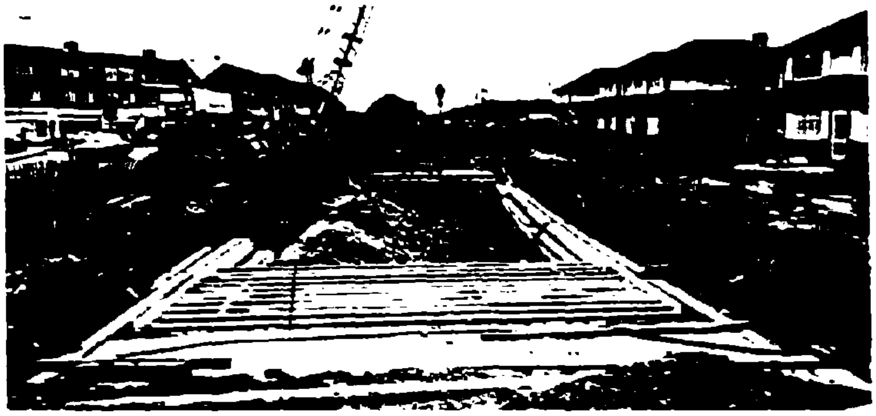
Figure 28
Under-the-Roof Construction
Surface Restored; Excavation in Progress



Source: Washington Metropolitan Area Transit Authority

Figure 29
Excavation For Slurry Wall

In London, the Heathrow extension project used under-the-roof excavation for a considerable reach of line structure. Although slurry wall was the initial design at the time of construction contract bidding, the contractor negotiated a change to secant piles. The overall cost remained essentially the same, and the job experienced one particular benefit. Slurry wall sites tend to become covered with bentonite fluid (Figure 29). In this case, the slurry could have become a hazard to nearby traffic. Since the secant pile system selected utilized continuously cased holes, there was no need for slurry to be used for temporary pile hole support, allowing a slurry-free jobsite. The under-the-roof construction sequence used on the Heathrow extension is shown on Figures 30, 31 and 32.



Source: London Transport Executive

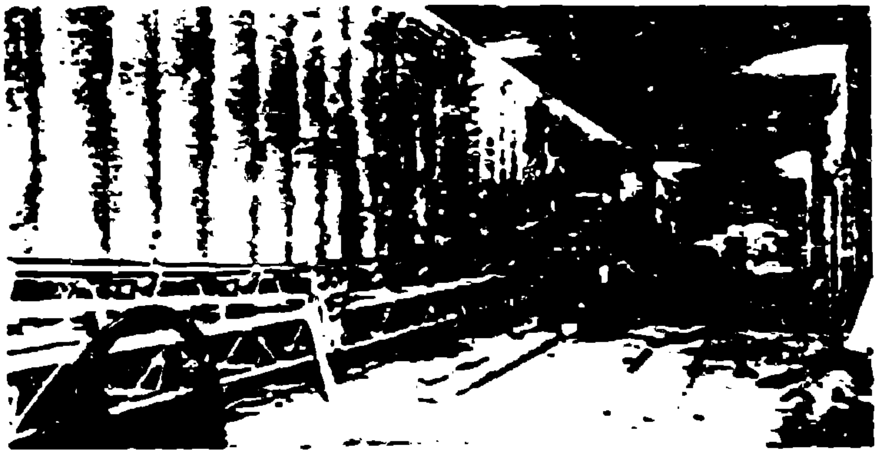
Figure 30

Heathrow Extension Roof Beams Being Placed On Benoto Pile Walls

Source: London Transport Executive

Figure 31

Heathrow Extension Excavation Under The Roof



Source: London Transport Executive

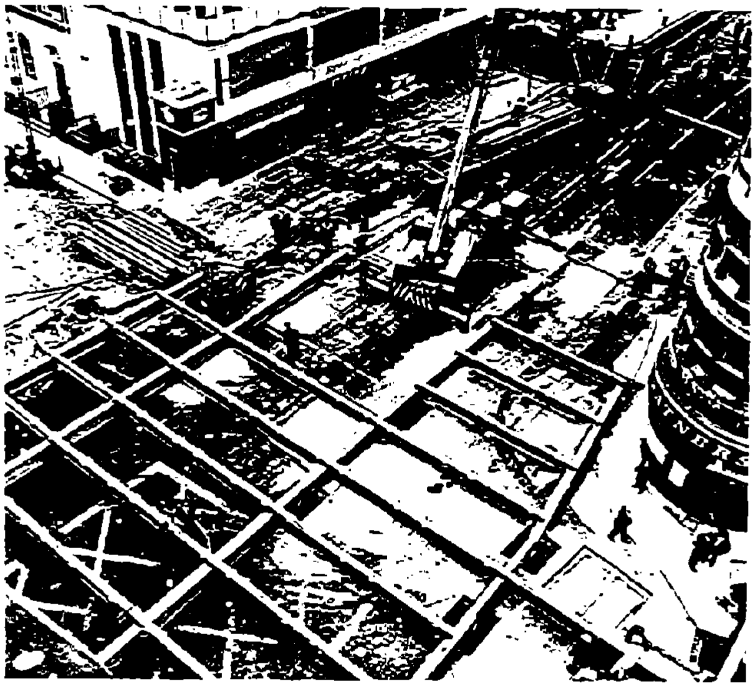
Figure 32

Heathrow Extension Excavation Completed Invert In Place

Prefabricated Decking

Decking to carry traffic over the station excavation during construction is usually constructed of timbers preassembled in panels. The panels are lifted into place and rested on a system of steel deck beams, forming the roadway. Precast concrete panels also have been used, but to a much lesser extent than timber.

London Transport has successfully utilized a prefabricated decking structure, termed a traffic umbrella, for carrying street traffic over open excavations. The traffic deck is a segmental steel structure which is prefabricated, shop-assembled for inspection, and then dismantled and reerected at the construction site in a limited time period. The installation sequence for the traffic umbrella is shown in Figures 33, 34 and 35. This technique has been used successfully, while not necessarily economically, to limit surface disruption by permitting rapid installation of the decking structure during weekend or evening hours, thereby limiting the impact on traffic and surface development.



Source: London Transport Executive

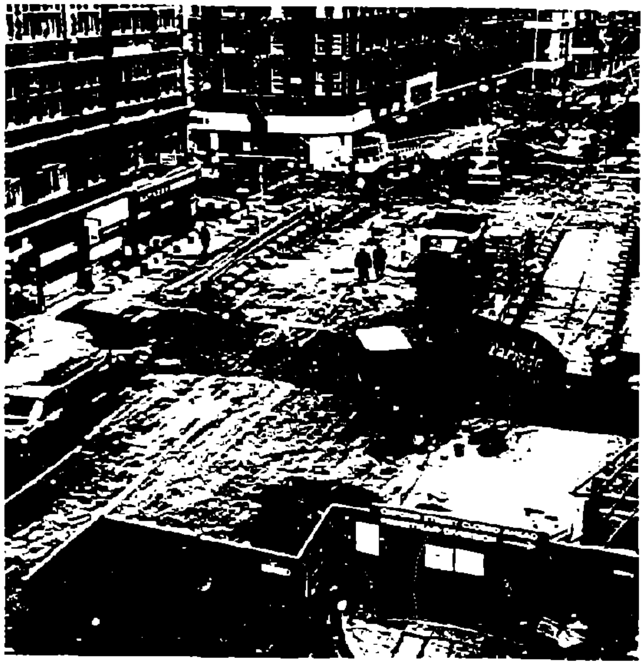
Figure 33

Prefabricated Traffic Umbrella Deck Support System

Source: London Transport Executive

Figure 34

Prefabricated Traffic Umbrella Deck Being Constructed



Source: London Transport Executive

Figure 35

Prefabricated Traffic Umbrella In Place

TUNNELED STATIONS

Tunneled stations are constructed from a mined underground heading or headings rather than from an open excavation. The decision to construct a station in mined tunnel rather than in excavation opened from the surface is based on the economics of the situation, the direct costs to the owner, and the impact upon the site.

Economics are decided by geotechnical conditions, prevailing labor practices, urban conditions, the general orientation of the station and the resulting depth of excavation, the direct impact on surface development, and the impact on subsurface development. Tunnel construction costs can vary extensively depending upon ground conditions and the ability to control groundwater. This type of construction is much more susceptible to variable or difficult ground, which might be unanticipated, than is open cut construction. Water or ground conditions which require the use of compressed air can have a staggering influence on construction time and cost.

In many situations, stations are tunneled to preclude an unacceptable impact on the urban area. Often where street patterns are irregular or existing utilities or surface development cannot be disturbed, station construction by tunnel becomes the only feasible alternative. While tunneled stations can minimize surface disruption, they do not preclude it. Construction access, construction of mezzanines and accessways, and surface settlement can cause serious disruption to the surface activity in the vicinity of a station constructed in tunnel. These potential disruptions can be easily overlooked during planning.

Tunneled stations can be defined by the configuration of the trainroom and for this report are termed multiple chamber or single chamber tunneled stations. These configurations are further classified as tunneled stations in earth or in rock.

Tunneled Stations in Earth

Tunneled stations in earth have been constructed in many cities, particularly in central areas where disruption to urban development or surface traffic was not considered acceptable. A prime example is the London subway, where most of the stations are constructed in tunnel. The street pattern in London is irregular, making it difficult to locate stations in public right-of-way. Rather than having an impact to the city of an unacceptable degree, it became standard practice to tunnel subway lines and to construct stations in tunnel.

During the course of this study, two techniques for constructing soft ground tunnels were observed by the Study Team in various cities: the tunnel enlargement technique and multiple drift technique.

Multiple Chamber Stations in Earth - The majority of stations tunneled in soft ground have been the multiple chamber type. They are constructed using standard diameter line tunnels driven through the station, enlarging the line tunnels to sufficient diameter to accommodate the station platforms and trains, and then connecting the two platform tunnels to a central access tunnel. The procedure typically followed for this type of station is:

1. The line or running tunnel is driven (Figure 36). It is standard procedure to drive a running track tunnel of the standard diameter through the station. Temporary lining is installed in the line tunnel.

2. The line tunnel is enlarged to accommodate a platform (Figure 37). This procedure is the most dangerous and costly step in the process. When a shield is used, it is constructed in a chamber at one end of the station platform and driven to the other end, where the shield skin plate is left in place.

3. An access or center concourse tunnel is constructed. This tunnel normally lies between the two platform tunnels and may or may not run the full station length.

4. Cross-passageways are constructed to link the two platform tunnels to the center tunnel.

5. Access to the surface escalator or stairways, mezzanines, and surface connections is constructed.

Of the systems inspected in this study, the London, Toronto, and Rome systems had constructed stations using this technique.

In London, all of the underground stations constructed in tunnel were constructed as multiple chamber stations in

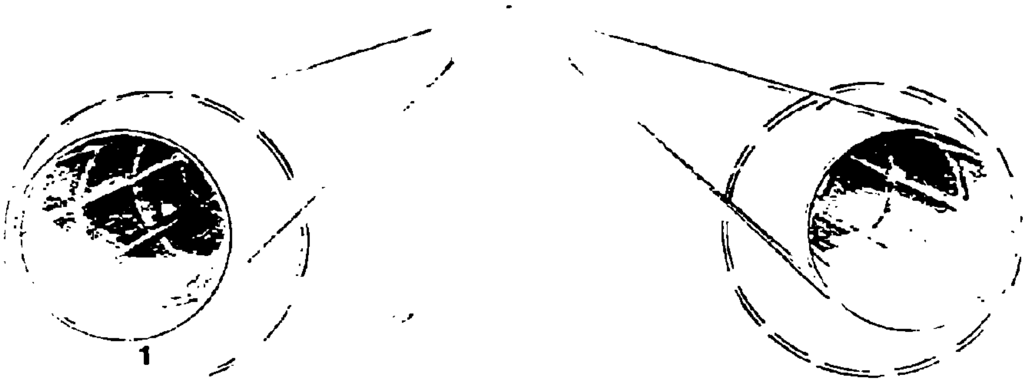


Figure 36
Tunnel Enlargement Technique
Line Tunnel in Place

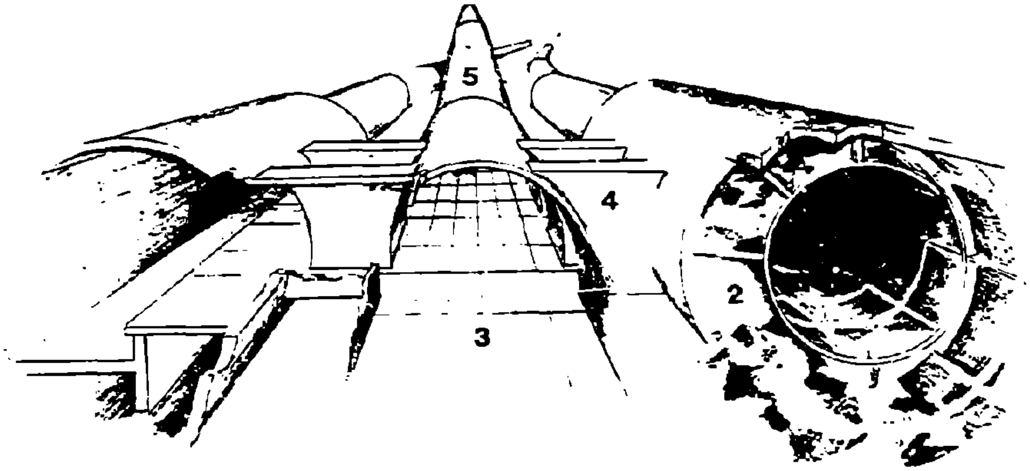


Figure 37
Tunnel Enlargement Construction Sequence

earth tunnel. Favorable ground, restrictive urban controls, and the availability of skilled tunnel workers have made this technique standard practice.

Toronto's system, which is basically a shallow cut-and-cover system, constructed two stations on the University line in multiple tunnels using the enlargement technique. This same technique is being used for stations on the new line in Rome.

Single Chamber Stations in Earth - While the majority of stations constructed in earth tunnels have been the multiple chamber type, there have been several recent examples of large, single chamber stations tunneled in earth. In all cases, these tunnels have been advanced using small chamber, multiple heading techniques, often with extensive ground improvement ahead of the tunnel face. As best as could be determined, the decision to proceed with this type of station in earth was never made on the basis of economics, but rather by the desire to minimize the impact on the urban area or on subsurface development. In fact in most cities, tunnel construction for this type of station is avoided because of the uncertainties that are involved in the construction process. In spite of these general attitudes, there are circumstances where large, single chamber stations tunneled in earth have been successfully implemented.

There are several single chamber earth tunnel stations in Paris on the new RER system. The RER is a high speed system which will traverse the city generally below the existing Paris Metro network. The RER stations are major transportation centers rather than merely subway stations. Several of the major stations were constructed in tunnel using multiple heading techniques. The resultant station structures, which are precast concrete lined, have clear-span, arched cross sections. Station sites required extensive ground improvement by grouting to make tunnel construction feasible. They are presented here as an example of the types of openings possible rather than as economical solutions.

In Milan, pressures to minimize urban disruption have led to the consideration of tunneled stations in earth. The recently constructed Moscova station was advanced in ground which had been stabilized prior to excavation by grouting. The earth was temporarily supported by shotcrete and steel ribs. A cast-in-place concrete lining was then installed.

This technique provided satisfactory control of ground movements and minimized surface disruption.

In Munich, one contractor was advancing a tunneled crossover structure in soft ground using a multiple drift technique (Figure 38) with shotcrete with steel ribs and mesh for initial support. This technique was termed the New Austrian Tunneling Method. The crossover structure was trainroom size in cross section or large enough to accommodate a station. The shotcrete/steel structure was designed as temporary support, and a cast-in-place concrete liner is constructed after excavation is completed. This procedure was proposed as an alternative by the construction contractor and accepted by the transit agency.

Figure 38
Munich Crossover Structure

Tunneled Stations in Rock

When geotechnical conditions are such that sound rock is reasonably close to the surface, distinct cost savings and reduced impact can be achieved by locating the transit system in rock tunnel. Most rapid transit stations are located relatively close to the earth surface, so those in rock are often in the upper, highly jointed and blocky zones where an arch is difficult to maintain. This type of rock can result in the need for extensive support and the use of many small drifts during the excavation phase, a time-consuming and costly operation. Increased depth of profile may be necessary to place a station in rock sound enough to excavate the cavity in a few large drifts and to support it with relatively light reinforcement. Planners have expressed concern that increased depth of profile will increase vertical travel time, having an adverse impact on ridership. However, deep mined tunnel stations have been constructed and operated successfully in many cities. Setting a proper vertical alignment for rock tunnel stations is often a matter of striving to gain just enough cover of relatively sound rock to permit safe and economical excavation while keeping the station as close to the surface as possible for ease of access.

Among the cities inspected in this study, three have recently constructed stations by rock tunneling methods. Tunneled stations in rock have been utilized extensively in Stockholm and Montreal, and to a lesser degree in Washington, D.C.

Stations in rock can be classified into two categories identical with those in earth: multiple chamber and single chamber. The multiple chamber stations are constructed using separate tunnels for each platform, for cross passages, and for accessways. The completed tunnel system then serves as the station. Single chamber stations have a large dimension, mined opening, usually arched and clear span, which encompasses either a center platform or two side platforms. In some cases, the mezzanine and trainroom are both located inside the same tunnel chamber.

Multiple Chamber Stations - Multiple chamber, rock tunnel stations are constructed using standard rock mining techniques and with the rock supported by various structural systems.

Multiple chamber stations have been used extensively in Stockholm. Stockholm has the advantage of having competent rock relatively close to the surface. The extensive amount of rock tunneling experience in Sweden is reflected in design and construction of the Stockholm rock stations. While stations in Stockholm have been constructed utilizing both the multiple chamber and single chamber configurations, the most recently constructed stations are multiple chamber designs. Separate tunnels are driven for each trainroom platform. These trainroom tunnels are advanced using traditional drill and blast methods. The rock is supported predominantly by rock bolts and shotcrete. Steel sets are not normally required due to the competency of the rock. The shotcrete structure is placed over an extensive drainage system to relieve pressure and to intercept groundwater behind the shotcrete (Figure 39).

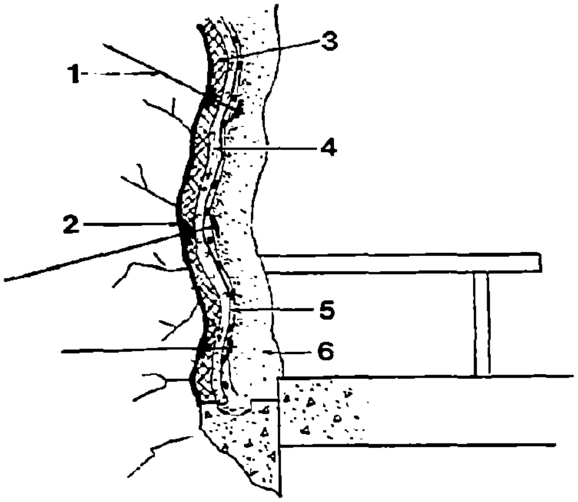


Figure 39

Stockholm Shotcrete Drainage System

The drainage system system consists of rockwool strips against the rock face, installed at intervals along the station axis and at locations of obvious leakage. Water is carried from the rockwool through perforated tubes to the track drainage system. This rock surface drain network is held in place by a combination of mesh reinforcement, reinforcing bar, plastic sheeting, shallow anchors, rock bolts, and applications of shotcrete selected individually for each site and varied for changing site conditions. One sequence for installing the system is as follows:

1. Rock bolts are installed for initial excavation support and may later be used as anchors for the placement combination of drainage materials.

2. Rock fissures are very carefully pressure grouted to reduce leakage to a minimum. A thin layer (¼ inch or less) of shotcrete may be applied to the entire rock surface. Time is allowed for leakage lines to manifest themselves as stains through the thin layer.

3. Rockwool strips (normally six inches, but up to 20 inches, wide and approximately two inches thick) are placed at leaking fissures and are usually spaced throughout the rock arch at regular intervals of three to seven inches.

4. Perforated drain tubes (usually plastic, 3/4-inch in diameter) are placed against each rockwool strip. The small tubes may be interconnected to a larger embedded conduit leading to a drainage sump.

5. Steel mesh reinforcement is placed over the rockwool, and tubes are held in place by shallow rock anchors. Reinforcing bars usually overlay these materials to integrate the drain network with the shotcrete support system.

6. Shotcrete is applied over the entire cross section for a minimum four-inch thickness.

7. After seasonal water pressure changes, the limited area of new leaks may receive a second overlaying drainage system. This spot coverage can be acceptable in the exposed shotcrete finish stations, because the surface assumes the irregular excavated contours where patchwork tends to be less noticeable.

The recently constructed Stockholm stations are distinguished by the use of exposed shotcrete as the station finish (Figure 40). After the shotcrete structure is completed, the surface is decorated by artists selected by the transit agency. The successful use of shotcrete as the finished surface is dependent upon the ability of the drainage system to relieve water pressures and control leakage.

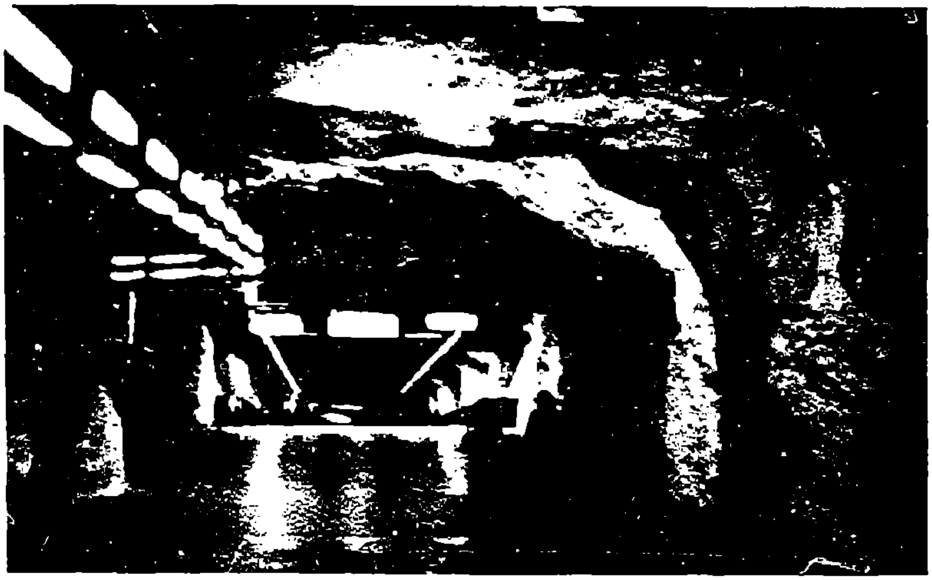


Figure 40

Stockholm Exposed Shotcrete Station Finish

Single Chamber Stations - Single chamber, rock tunnel stations are constructed using standard rock mining techniques, either full face or multiple drifts, depending on the rock quality. Rock tunnel stations which have the trainroom in a single opening have been constructed in Montreal and Washington, D.C.

Montreal has competent rock reasonably close to the surface. The Montreal stations constructed in rock have a single trainroom chamber excavated in rock. The tunnel for the station trainroom is normally mined through and enlarged as part of a line section tunnel contract. The trainroom lining, a conventional cast-in-place concrete structure, is placed by the running tunnel contractor except at the portion of the station trainroom which will be opened for mezzanine and station entrance construction. A separate contract is then awarded for the construction of the access to the surface. This work includes mezzanines, access to platforms, and access to the surface.

The rock tunnel stations in Washington, D.C., are constructed in rock less competent than that in Stockholm or Montreal. The Washington stations have a single trainroom chamber excavated in rock using a multiple drift technique. Running tunnels are driven through the station. A second contract is awarded to construct the station trainroom opening and the accessways to the surface. The trainroom itself is an extremely large underground space, approximately 60 feet wide, 45 feet high, and 700 feet long. Station service rooms are located at the ends of station platforms. The rock tunnel stations constructed in Washington are distinguished by the use of the structural lining as both initial and permanent support. The structural lining is constructed using rock bolts, three-stage application of shotcrete, and steel ribs (Figure 41). The sequence is as follows:

1. After the excavation is opened in short advances and multiple drifts, the first stage of shotcrete is applied.
2. The rock is then bolted.
3. Steel ribs are erected.
4. The second stage of shotcrete is then applied to fully block the rib against the rock.
5. After the tunnel is sufficiently advanced, a third stage of shotcrete with steel reinforcement is added.

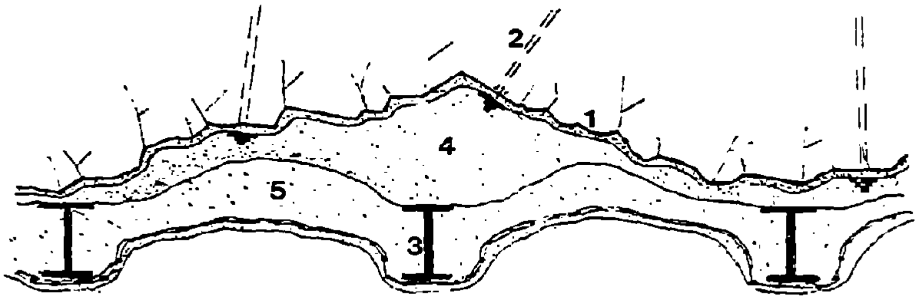


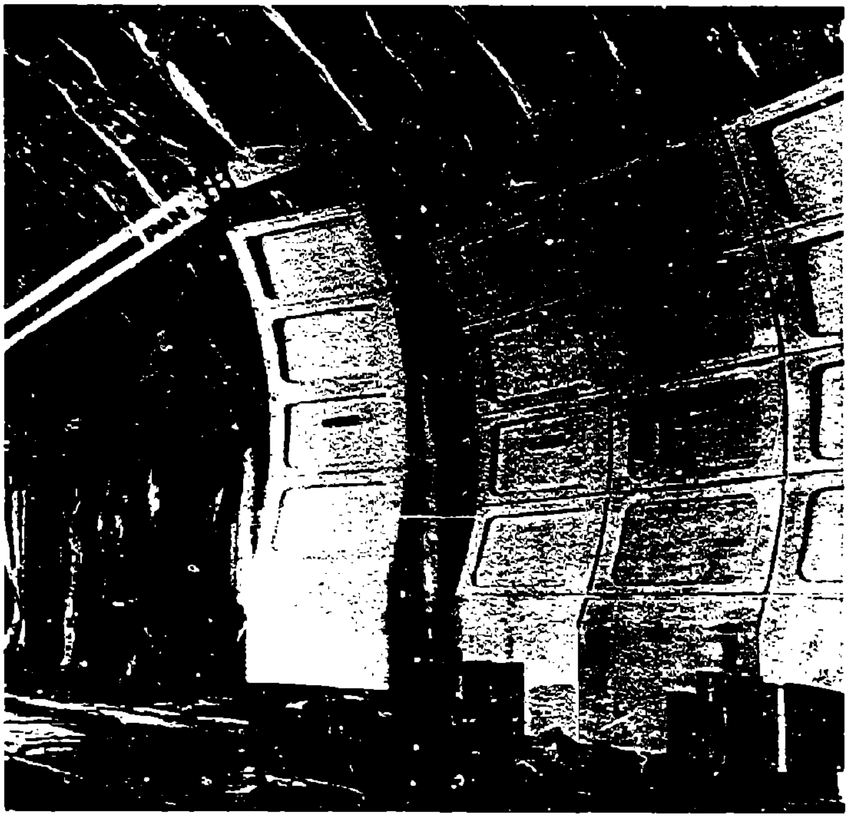
Figure 41
Washington, D. C., Rock Excavation Support System

A drainage system is provided to relieve the pressure of groundwater between the rock and the shotcrete lining. The station finish is a precast concrete structure erected in panels and standing free of the permanent lining. Two rock tunnel stations have been completed on the Washington system using this technique, and another eight are planned. The complete sequence is shown in Figures 42, 43 and 44.

Source: Washington Metropolitan Area Transit Authority

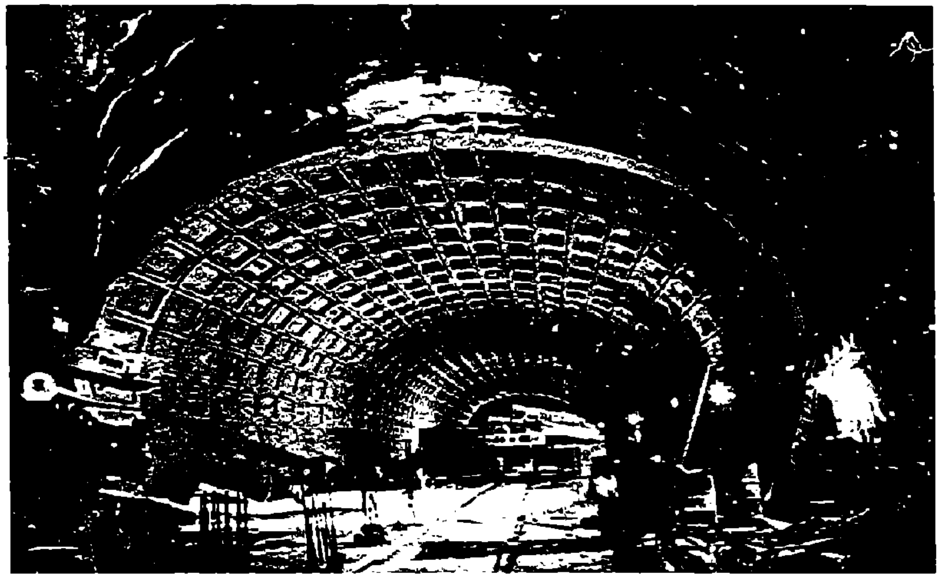
Figure 42

Dupont Circle Station Excavation Supported By Shotcrete, Rock Bolts, Ribs and Mesh



Source: Washington Metropolitan Area Transit Authority

Figure 43
Dupont Circle Station Precast Panels Being Erected



Source: Washington Metropolitan Area Transit Authority

Figure 44
Dupont Circle Station Interior Finish Shell in Place

GROUND IMPROVEMENT TECHNIQUES

The term ground improvement typically describes any technique used to modify the character of a particular soil to improve its strength and reduce its permeability and tendency to collapse. Such techniques are used under appropriate site-specific conditions to assist in the excavation support process, to minimize the need for direct underpinning, and to improve conditions for tunneling. Several ground improvement techniques are commonly accepted worldwide, including chemical grouting; cement grouting; and, to a very limited extent, freezing. The systems investigated for this report used no ground improvement techniques which have not been used by U.S. construction contractors. However, foundation grouting combined with a semi-rigid excavation support system seemed to be more commonly accepted in European cities as a substitute for direct underpinning, such as jacked piles or pit walls.

Grouting

Grouting is used to reduce the permeability and to strengthen a soil mass by filling the intergranular spaces with cement, bentonite, or chemical gel combinations. Coarsely granular, noncohesive soils are relatively easy to grout because of their large, interconnected pore spaces. At the other end of the scale, even the least viscous grout cannot penetrate the voids of a clay, and injection under pressure splits the formation, whereupon the grout occupies the newly formed fissures. Set-up time for the gels can theoretically be controlled by the amount of catalyst that is added prior to pumping the grout into the ground. In this way, the grout can be designed to be held in the desired area by having it harden before it escapes from the injection area. In practice, the chemistry of the groundwater often alters the gel time. Furthermore, all grouts enter pervious masses selectively and enter the most pervious first. Deposits consisting of lenses or layers of differing grain sizes must be grouted by successive injections, and the probability is high that some zones may be missed entirely. Since most any soil mass with the volume of a rapid transit station is a mixture of soil types, a typical grouting program would probably consist of two or three grout types injected under varying pressures.

The ideal grouted soil mass would have the strength and consistency of a lean concrete mixture or a soft sandstone, but in reality this rarely occurs. Nevertheless, grouted soils often slow the flow of groundwater and have a "stand-up" time that will permit the installation of support before the soil runs or slumps. While the use of grout has several advantageous aspects, there are also disadvantages. The flowing grout seeks the path of least resistance and may flow away through the most pervious stratum, leaving others untouched. The grout also may flow far from the job site and damage adjacent utilities or floor slabs.

Grouting has limited application in underpinning and cut-and-cover excavation support. Since the sides of a deep cut would still require support, grouting would be an unnecessary expense. The technique has its most useful application in tunneling, where it can increase the soils stand-up time just enough to permit the installation of support members.

Grouting has been used successfully in Paris and Milan for ground improvement at large stations constructed in earth tunnel. It has also been used in conjunction with semi-rigid excavation support systems to support light buildings in lieu of direct underpinning in Paris and Munich.

Freezing

Freezing of the ground is accomplished by placing a network of pipes in the ground and circulating a refrigerant through the pipe network. By freezing the pore water in the soil, the soil is turned into a cohesive, icy mass inside which excavation can be accomplished. The technique has been used in both fine-grained, cohesive soils and in coarse-grained, noncohesive soils. The soil must contain enough moisture to form the required icy mass. Hence, the technique will not work with coarse-grained soils high above the water table. In any geotechnical condition, freezing is expensive, because the earth must be kept frozen throughout the excavation period. For this reason, freezing is not considered a cost-saving technique.

Chapter 7
STATION TYPES

A range of subway station types was developed, based on typical urban and geotechnical conditions, to illustrate how different characteristic design requirements affect overall structure size, construction techniques, passenger capacity and convenience, and capital and operating costs. Seven station types were developed and evaluated. Typical variations on these types that illustrate other commonly used solutions to various urban and geotechnical conditions are found in Appendix A.

STATION PARAMETERS

Seven station types were developed to identify and compare differences in construction cost and the level of user convenience. The station types constitute a reasonable sample of the range of subway station designs in the world today, and accordingly, are used as a point of reference in this report to identify design-related cost implications.

The comparison is aimed at identifying each station type's principal elements, its physical and operational assets and liabilities, and the relevant construction cost implications that result from each design. It provides the station planner and designer a guide to make cost-effective design decisions in the design development process. The comparison identifies several station types that are likely to be economical to construct in generalized sets of urban and geotechnical conditions; however, these conclusions do not adequately account for the absolutely critical importance of site-specific conditions.

The development of station types involved a review of recent subway station design in North America and Europe and the subsequent selection of seven distinct station designs for detailed development and evaluation. The information gathered during visits to 13 North American and European cities, as well as prior research and experience in subway station design, was used to identify the major factors influencing station design. It was also the basis on which the seven illustrative station types were selected. Particular emphasis was placed on identifying those factors which have a major bearing on construction cost. For consistency, the review focused on simple line stations rather than the more complicated terminal or interchange stations.

Factors which most directly influence station design and cost, but which are virtually fixed at the station design phase and at site-specific locations, include geotechnical conditions (type of ground, presence of water), urban conditions (intensity and type of surface development, traffic, street patterns, right-of-way configuration and utilities and other subsurface development), systemwide considerations (system design capacity as it affects train length, station size), and community desires (minimum surface disruption, environmental issues, operational safety). Factors which are still subject to change or provide choice among available options during station design include method of station excavation, location of the station mezzanine, platform configuration, and type of passenger loading at the platforms.

Method of Station Excavation

There are two basic methods of excavation: cut-and-cover and mined. Cut-and-cover excavation, in its simplest form, is to open to the surface the full length, width, and depth of a station during construction. The excavation is sometimes covered with a deck to permit traffic to pass over the excavation while the structure is constructed. After the structural shell of the station is completed in the excavated space, it is covered and the surface area is restored. It is the most frequently used method of station excavation and is, of course, used extensively throughout the world.

Mined excavation occurs below the surface, typically horizontal to and without disruption to the surface except at shafts. Two general approaches to mined excavation are currently generally accepted. One involves the mining of a single, usually arched, space. The other involves the mining of twin tunnels that are enlarged in the station area to accommodate the platforms. This type of mined station has two trainrooms that are connected by a mined central concourse space running between and parallel to the two line tunnels.

Location of the Station Mezzanine

The station mezzanine is typically found in one of four locations: separate from the trainroom and at the street level, separate from the trainroom and above the platform level, separate from the trainroom and at the platform level, and within the trainroom and above the platform level. Each of these locations affects the station volume and procedures for excavation, thus affecting the station cost.

Platform Configuration

Station platforms have three possible configurations in a simple line station: side, center, and stacked one above the other. The first two arrangements are in common use. The vertically stacked platform configuration is a selectively used, dual trainroom station whose major assets are a narrow right-of-way requirement and certain operational benefits when used at the junction of two lines.

Type of Passenger Loading

Passenger loading refers to the location of access/egress points for passengers moving between the mezzanine and the platform. This loading may either be distributed evenly or unevenly along the platform from the mezzanine. Even distribution improves station circulation and safety. It increases user convenience by minimizing patron walking distances within the station and by reducing conflicting distribution movements on the platform.

STATION TYPE SELECTION

Following the review of current station design practices, seven station types were selected for detailed development and evaluation. The stations selected were among the most frequently encountered during visits to the various cities, and often typify the station design of a particular city. Each represents a different typical design approach and physical organization. For example, Station Type 1 is representative of an approach that minimizes the volume of excavation by keeping the trainroom shallow and locating the mezzanine at grade. Station Type 4, on the other hand, minimizes right-of-way width requirements. The seven stations are, of course, not the only types of stations being designed today, and accordingly, variations on these types are presented in Appendix A.

The seven stations are listed below and described in terms of three factors: method of excavation, location of station mezzanine, and platform configuration.

Station Type 1

Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and at Street Level
Side Platform

It is a shallow station that reduces construction cost by minimizing the volume of excavation. It is similar to stations in Mexico City.

Station Type 2

Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and at Platform Level
Side Platform

It is also shallow station minimizing the volume of excavation but maintaining proximity of the mezzanines and platforms for better station surveillance. It is representative of stations in Mexico City.

Station Type 3

Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and Above Platform Level
Side Platform

It is a shallow-to-moderate depth station that achieves operating economy through a central control point and reduces total station volume by separating the mezzanine from the trainroom.

Station Type 4

Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and Above Platform Levels
Side Platform, Stacked Platforms

It is a moderate-to-deep station that reduces right-of-way width requirements by stacking the trainroom platforms one above the other. Stations such as this one have been built in New York and Tokyo.

Station Type 5

Cut-and-Cover Box Structure
Mezzanine Within Trainroom and Above Platform Level
Center Platform

It is a moderate depth station in which the mezzanine and platform are located in a single two-story space, thus making the station more comprehensible to the user and improving the surveillance capability of the operator. It is representative of stations in Montreal and Washington, D.C.

Station Type 6

Mined Single Arch
Mezzanine Within Trainroom and Above Platform Level
Center Platform

It is a deep station that is similar to the last station in every respect but method of excavation. It is typical of stations in Washington, D.C., and Paris.

Station Type 7

Mined Twin Tubes
Mezzanine Separate from Trainrooms and Above Platform Level
Center Platform and Concourse

It is a deep station in which the volume of mined excavation is minimized to fit within constricted space or to reduce costs. Station alignment is not tied to an existing street network. It is representative of stations in London and Stockholm.

STATION TYPE DEVELOPMENT

The seven station designs have been simplified and made dimensionally similar to emphasize the key physical and operational features of each type. To most clearly compare the probable construction cost implications of each station type, the physical and operational standards and criteria and design features were made identical wherever possible.

Station Length

All stations were developed with a 550-foot platform length.

Station Capacity

Peak one-way station passenger "surge" capacity was set at 400 to 440 people per minute, the equivalent of roughly 72,000 daily passengers. This figure is typical of a large metropolitan station.

Each station type clearly has different design features that affect patron circulation and capacity. However, the circulation elements that typically limit station capacity are either the turnstile area or some element of the vertical circulation. The 550-foot platform can accommodate a far greater peak demand than 400 to 440 people per minute. Additional people could be handled by adding more vertical circulation elements, a larger turnstile area, and more dispersed entrances. However, for purposes of comparison, two station entrances have been shown for each type.

Platform Width

Platform widths were assumed to be 30 feet for center platforms and 16 feet for side platforms. The dimensions are typical of the more generous station standards in the United States. The twin tubes' side platforms were set at twelve feet, because this type of station typically has a central concourse to accommodate surge flows to and from the platform, and because the high cost of mining tends to restrict dimensions for these deep mined stations.

Ceiling Height

Ceiling heights were assumed to be twelve feet in the mezzanine area and ten feet in the platform area; the upper three feet in the mezzanine are provided for ventilation ducts and other mechanical equipment. Comparable ceiling height dimensions were assumed for the twin tubes and the vaulted station types, although the height naturally varied with the structure shape.

Queuing Space

A queuing space of 20 feet was provided on either side of turnstiles and at each end of all vertical circulation elements. This distance is based on typical passenger circulation standards used by transit operators in North America today.

Turnstile Capacity

Turnstiles were assumed to have a two-way surge capacity of 25 people per minute based on the same circulation standards. Twenty turnstiles are used in each station resulting in a turnstile capacity of 500 people per minute, which safely exceeds the assumed station capacity.

Vertical Circulation Elements

Vertical circulation elements included escalators located in combination with stairs for security reasons; elevators were provided for the handicapped. All three (escalators, stairs, and elevators) were provided between the street entrances and the mezzanine and from the mezzanine to the platforms of all station types except Station Types 1 and 2. There the mezzanines are at the same level as the street or the platform, respectively, and are connected by simple passageways.

Vertical Circulation Capacity

The vertical circulation element capacities were developed as follows, based on currently used passenger circulation standards.

Street-to-Mezzanine - This capacity is 220 people per minute per stair/escalator unit. The eight-foot stair has a two-way capacity of 120 people per minute, and the escalator capacity is 100 people per minute. The escalator running in the off-peak direction does not, of course, contribute to peak direction capacity. The elevators provide a negligible increase in capacity and have been considered only for their contribution to convenience for the handicapped.

Station Type 6, a deep, mined excavation, has three escalators rather than a stair and two escalators. With two escalators operating in the peak direction, the street-to-mezzanine capacity of the station is 200 people per minute per vertical circulation element, or 400 people per minute for the station.

Mezzanine-to-Platform - The capacity of the mezzanine-to-platform stair/escalator units varies with how they are operated. It has been calculated assuming that at least half of the escalator units will operate in the peak direction (the worst condition), with the likelihood that 75 percent of the units will operate in the peak direction.

Each stair/escalator unit's capacity is based on a six-foot wide stair having a capacity of 100 people per minute and one six-foot wide escalator having the same capacity, or 200 people per minute per stair/escalator pair. Thus, under the worst condition, the mezzanine-to-platform capacity in each station is a total of 400 people per minute.

Station Type 7, a deep, mined excavation, has the same vertical circulation capacity of 400 people per minute between the mezzanine and platform levels. However, the vertical circulation elements are comprised of three escalators and one included elevator. Two escalators operate in the peak direction to achieve a total capacity of 200 people per minute per vertical circulation element.

Total Station Capacity

Stations having stair/escalator units between the entrance and mezzanine with capacities of 220 persons per minute each have a total capacity of 440 persons per minute. This total capacity is the result of both entrances feeding equally into the mezzanine, which in turn feeds into the vertical circulation leading from the mezzanine to the platform.

Combining the two entrance capacities is not possible with Types 1 and 2, since each mezzanine serves only one side platform. The crossunder capacity, however, of 200 people per minute may be added to the entrance capacity. This gives a total one-way peak station capacity of 420 people per minute, the sum of the crossunder capacity and the one-way capacity of a street-to-platform level stair/escalator unit of 220 people per minute.

Types 6 and 7 have lower station capacities that are governed by the entrance-to-mezzanine and mezzanine-to-platform vertical circulation capacities, respectively. In both stations, two vertical circulation elements (each with two 100-passengers-per-minute escalators operating in the peak direction) produce a total station capacity of 400 people per minute.

In all but Station Type 7, the capacity limitation occurs in the entrance-to-mezzanine level circulation. Corridor, turnstile, vertical circulation, and platform capacity within the station exceed this limit. The design intent has been to emphasize internal station flexibility, convenience, and smooth distribution of passengers onto the station platforms. Thus, the design helps minimize congestion at the turnstile and at the mezzanine within the station; it reduces the likelihood of using the train platform for longitudinal distribution; it helps assure that the platforms are used primarily for train boarding and alighting; and it promotes the use of the mezzanine as the primary distributing circulation element.

Street Right-of-Way Width

The station types have been designed to fit within a 100-foot street right-of-way. This is a width typically found in more densely developed cities. While all of the stations do not work equally well within this right-of-way, the uniform width results in a fairer cost comparison of the types.

Types 4 and 7 are exceptions to the one hundred foot standard. Type 4 is designed to fit in a narrow right-of-way and is therefore shown with a 60 foot right-of-way width. Type 7 is a deep mined station whose alignment does not necessarily have to conform to existing street alignments or right-of-way widths. It is shown in an alignment that is skewed to the street pattern.

Location of Street Level Entrances

The two street level entrances are both located within the building line to reduce pedestrian circulation conflicts and congestion along the sidewalk. One entrance is shown in an easement within an existing building. This type of entrance is desirable, because it promotes the mixed uses of space and can increase the feeling of personal security in the station area. However, the easements can be difficult to negotiate and, if not coordinated well in advance of construction, can impede the rate of station construction. The second entrance is shown inside the building line, but on a separate transit property that contains the entrance shelter only.

Ancillary Space

Each station has roughly 7,000 square feet of ancillary space, which house electrical, mechanical and communications equipment; janitor and station agent facilities; and rest rooms. Approximately 1,200 square feet of space is provided adjacent to the mezzanine and about 5,800 square feet at the platform level. The amount of space provided is comparable to that being provided today in the new stations with extensive electrical and mechanical requirements, including air conditioning.

STATION TYPE DESCRIPTIONS

Each of the seven station types is described in terms of features that have a major effect on circulation, size and, accordingly, construction cost. The rationale for developing the station is discussed first. Then, the cost sensitive characteristics of the station and its relationship to the surrounding area are described.

Station Type 1

Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and at Street Level
Side Platform

Station Type 1 (Figure 45) has been developed to illustrate the potential and limitations of a shallow cut-and-cover station with mezzanines or fare collection facilities located at street level. Both features of the design reduce the volume and cost of excavation, but can also present utility relocation, passenger circulation, and economy of operation problems.

Station Relationship to Surrounding Area - The station could more easily be constructed in a right-of-way wider than 100 feet, but the overall width of the station would make its construction in a narrower right-of-way expensive, since the station would extend beyond the building lines, thereby dramatically increasing underpinning and support of excavation costs.

The station is shown with three feet of earth cover. This shallow condition minimizes excavation requirements, as is evident in the Mexico City stations. However, it can also cause street and utility relocation problems. Normally, this station would not be constructed at substantially greater depths due to the expensive excavation requirements imposed by its large plan.

Station Characteristics - The station has two primary entrances and two elevator entrances, one serving each platform. The primary entrances provide direct access to two mezzanines, each 40 by 60 feet and containing an attendant's booth, ten turnstiles, and related ancillary space. Their street level location reduces excavation requirements, and thus station construction cost.

However, the station's dual mezzanines have operational problems. Since there is an attendant's booth in each mezzanine, the station must be double manned for optimum operation. To cover each manned post 24 hours a day, seven days a week requires four people. At the present United States transit system salary scale, each person will cost about $15,000 per year. Thus, each manned post will cost roughly $60,000 per year, and double manning will cost around $120,000 per year. In addition, the isolation of the station attendants from passengers at the platform level can reduce the patron's feeling of personal security and safety.

The mezzanines may also have economic liabilities. Acquiring space for street level mezzanines can be prohibitively expensive in densely developed urban areas.

Movement between the platforms is more difficult with two mezzanines at grade separated by a street. During peak periods, large numbers of people may enter the station from the side opposite the direction they are going, thus creating major reverse traffic flows onto the opposite platform and through the crossunder.

The station trainroom, the area in which passengers board and alight from the trains, is an excavated volume of about 1.25 million cubic feet. Side platforms and platform-to-mezzanine circulation requirements produce a wide plan that is expanded an additional 40 feet in width for a distance of 150 feet on each side of the station's center axis to accommodate crossunder movements, ancillary space, and movement between the platform and the mezzanine. The side platforms have an unobstructed width of 16.5 feet, which is adequate space for distribution along the platform, as well as entering and leaving the trains.

Each platform is center loaded. That is, people arrive at and leave the platform from a central point. A major problem with center loading is that people are concentrated near the station center while the ends of the platforms could be underutilized. User walking distances at the platform level are also longer. To insure a free flow of traffic at the station center, the platform must be widened, and a generous amount of queuing space must be provided at the foot of the stair/escalator unit to the mezzanine. Both requirements increase the volume of excavation.

The trainroom is shown as a clear-span space. Since the span is nearly 60 feet, the structure costs would be quite high, but could be reduced dramatically through the use of center columns.

Ancillary space is located directly behind the platform. Since it is located in areas that are extensions of the expanded structural shell, the space is relatively easy to excavate and eliminates the cost of excavating beyond the ends of the platforms.

Two vertical circulation elements connect the mezzanine with the platforms. They each have one stair, an up escalator, and a down escalator. The capacity of each element is 220 people per minute.

The platforms are connected by a crossunder which has two vertical circulation elements. Each element has a capacity of 200 people per minute. The crossunder circulation pattern is U-shaped, which poses operational problems. Neither the operator nor the patron can maintain an active surveillance of the entire crossunder from the platform or mezzanine. In addition, people using the crossunder are faced with two blind corners, which reduce the sense of personal security.

Station Capacity - Station capacity, the maximum one-way flow of people to a center or side platform, is determined by the lowest capacity corridor or vertical circulation element in a station. In this station, the passenger handling capacity is 420 people per minute. The mezzanine-to-platform vertical circulation element carries 220 people per minute, and the crossunder from the opposite platform has a capacity of 200 people per minute.

Station Type 2

Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and at Platform Level
Side Platform

Station Type 2 (Figure 46) is similar to the first station. The major difference is the location of the mezzanine, which is at platform level in this station. This station has been developed to illustrate the advantages and disadvantages which a platform-level mezzanine brings to a shallow cut-and-cover station. The station type still poses utility relocation, passenger circulation, and manning problems, but it also tends to minimize excavation requirements and some operational problems.

Station Relationship to Surrounding Area - The station's relationship to the surrounding area is similar to that of Station Type 1. However, by locating the mezzanine at the platform level, the station plan is enlarged. This enlargement makes construction of the station at greater depths or in a narrower right-of-way even more costly than for Station Type 1.

Station Characteristics - The station has the same type of entrances as Station Type 1, but at 20 feet by 20 feet, requires much less street level space than the first station. Where street level space is expensive, as in densely developed urban areas, the reduction in size can result in a property acquisition cost savings.

The mezzanines and the station trainroom are located one level below the entrances. The mezzanines contain the same facilities and have the same passenger handling capacity as Type 1, but are slightly smaller.

This station's platform area and circulation are the same as the first station, but the expanded center of the station is extended an additional 40 feet on each side of the station's center axis. This extension provides queuing space in front of the mezzanine, but of course increases the volume and cost of excavation by comparison with the first station.

With the mezzanine located adjacent to the platform, the station agent can actively survey the platform. This improves the patron's sense of personal security in the station and tends to reduce vandalism. The station design does, however, have other operational problems like those of the first station. The two mezzanines still require double manning for optimum station circulation. The platform is center loading, which tends to concentrate rather than evenly distribute people.

Vertical circulation in this station is the same as that in the first station, both in location and capacity. Consequently, the crossunder poses the same personal security problems that result from a U-shaped circulation pattern. However, the attendant's booth is located where the agent in each booth can observe the stair/escalator units and discourage crime and vandalism in the crossunder.

Station Capacity - The passenger handling capacity of this station the same as the first station, 420 people per minute.

Station Type 3

Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and Above Platform Level
Side Platform

Station Type 3 (Figure 47) differs from the first two stations in the depth of excavation and location of the mezzanine. The station illustrates the assets and liabilities of a single mezzanine, separate from the trainroom and constructed at a depth which minimizes interference with existing street utilities. It also shows the potential and problems of achieving even passenger distribution at the platform in a side platform station.

Station Relationship to Surrounding Area - The station is illustrated with 20 feet of cover. The greater station depth reduces utility relocation problems and provides room for a separate mezzanine level below the street. It also increases excavation, support of excavation, and underpinning costs. While this station illustrates the costs of moderate depth cut-and-cover construction, it can also be constructed at shallower depths with a substantial cost savings.

Station Characteristics - The distinguishing feature of this station is the mezzanine. It is a single story space of more than six times the area of the mezzanines of either of the first two stations. This large area is determined by the width of the trainroom below it and by the location of the stair/escalator units that serve the platform. In systems with stations similar to this one, the mezzanine is generally shortened in length by locating the stair/escalator units closer to the center of the station, although this results in less even distribution of people to the platform by concentrating the access to the platform nearer the station midpoint.

A major asset of this mezzanine is that the control point is centralized on a separate level, thus allowing one manned post in the station. This can reduce operations costs by about $60,000 per year. Unlike the two-story trainrooms in which the mezzanine volume extends the full length of the platform, this mezzanine is shortened to economize in the volume of enclosed space. The reduced length also minimizes the barrier effect of the station structure below ground and simplifies the rerouting of utilities around the station.

In contrast with the previous station mezzanines, this design type improves passenger circulation to the platforms and between the platform. Four stair/escalator units serve each platform and distribute people evenly along the platform.

With the mezzanine separate from the trainroom, the station attendent again cannot observe the platform, thus reducing the user's sense of personal security on the platform.

The platform level has the same basic dimensions as the first two stations with one major exception. The station is 24 feet wider to accommodate twelve foot stair/escalator units at the side walls of each platform. The stair/escalator arrangement clearly has an impact on the cost of excavation, but contributes to the simplicity of the shape of the structural shell.

The width can be reduced twelve feet overall by separating the stair and escalator units, but the eight stair and escalator units will extend a greater distance along each platform, thus diminishing the otherwise even passenger distribution from the mezzanine to the platform. Another perhaps more important disadvantage of separating the stair and escalator units is that people using the stairs are no longer able to observe people using the escalator, and vice versa. As a result, the individual sense of personal security in the station is diminished.

To reach the units at the mezzanine, an already lengthy mezzanine must be extended, and accordingly, the cost of finishing and maintaining an enlarged station volume is increased. The platform level ancillary space is located between the stair/escalator units. These areas easily accommodate the typical ancillary space requirement with no additional excavation cost.

The stair/escalator units between the entrance and mezzanine are like those of the first two stations except that the run (the horizontal length of the units) is longer in this station. The longer run is the result of greater station depth, and increases both the capital and operating costs of the stair/escalator units.

The greater run of the entrance to mezzanine stair/escalator units and the eight stair/escalator units connecting the mezzanine and the platform, by contrast with the first two stations, represents the added vertical circulation requirements and costs that are the result of a separate mezzanine level and greater station depth. At the same time, the units eliminate the need for a crossunder and its associated user inconvenience.

Station Capacity - The capacity of the station is governed by the capacity of the two entrances to mezzanine vertical circulation elements having a capacity of 220 people per minute each, totalling 440 people per minute for the station.

Station Type 4

Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and Above Platform Levels
Side Platform

Station Type 4 (Figure 48) has been developed to illustrate the problems and potential of constructing a station in a narrow street right-of-way, which is often found in many older cities. In addition, this type of station is found where very high capacities are needed, or where a junction occurs for a branch line.

To achieve a narrow station width, the platforms are stacked, thus creating two trainrooms. Stacking also creates a deep station, with correspondingly high excavation costs, and possibly more groundwater and excavation support problems.

Station Relationship to Surrounding Area - The major difference in this station's relationship to the surrounding area is a narrower, 60-foot street right-of-way. For consistency, this station is illustrated with 20 feet of cover above the mezzanine roof. Since the station has three rather than two levels below grade, this amount of cover results in a deep and generally more expensive cut-and-cover station. However, the station can be constructed at shallower depths with a likely substantial savings in construction cost.

Station Characteristics - The station entrances are identical to those in Station Type 3. The mezzanine is about two-thirds the area of the Type 3 station mezzanine, but the area still exceeds that required for minimum efficient passenger circulation, because the mezzanine must extend to the farthest vertical circulation element that provides access to the platform near the station ends. Unlike the previous station, the mezzanine size cannot be reduced due to the number of stair/escalator units that must be located along one side of the station. Eight stair/escalator units alternate between the platforms, creating a fairly even distribution of people to the platforms and resulting in an efficient use of the area between the units as ancillary space, but requiring lengthy, mezzanine level access corridors to reach the units.

The distinguishing feature of this station is the vertically stacked, rather than horizontal, alignment of the trackways. This feature creates a narrow station, but also, under some alignment conditions, creates the need for complicated and costly transitions in the tunnel outside the station. The distribution of people on the platform and circulation at the platform is not substantially altered by the stacked platform from that of Station Type 3.

The mezzanine is visually separated from the platform, as are the platforms from each other. The isolation of station elements impairs surveillance and lessens the user's sense of security. In addition, movement between the platforms involves longer travel distances than in Station Type 3. Although not shown, stairs or another set of escalators could accommodate this cross platform movement if in the planning phase this were determined to be a major patron movement.

Vertical circulation between the mezzanine and platforms is the same in terms of the number and capacity of stair/escalator units as in Station Type 3. However, four of the vertical circulation elements have longer runs to the lower platform, which will increase capital and operating costs slightly. When compared with center platform Station Type 5, which is the most efficient in passenger circulation, both Type 3 with side platforms and Type 4 with stacked platforms require twice the number of mezzanine-to-platform vertical circulation units (eight). Further, Station Type 4 requires that four of those have twice the run, traveling through two full floors.

Station Capacity - The station capacity is the same as that of Station Type 3, 440 people per minute.

Station Type 5

Cut-and-Cover Box Structure
Mezzanine within Trainroom and Above Platform Level
Center Platform

Station Type 5 (Figure 49) illustrates several cost-reducing variations of the other cut-and-cover stations. It has a two-story trainroom that does not increase the volume of total excavation when compared with Types 3 and 4, but does reduce the volume of backfill one-half million cubic feet compared to Station Type 3. It also illustrates the potential of a center platform, which halves the number of vertical circulation elements, while providing excellent one-way capacity and optimum overall circulation and operation characteristics.

The principal disadvantage of this station type is that the full-height trainroom can become a profile control and greatly increase the overall depth of excavation throughout the system. Another disadvantage can occur due to the effect this type has on the geometry, excavation, and construction cost of the line sections at the station ends. The center platform requires that either a lengthy transition section, in the case of double box line structure, be provided to allow the track centers to expand from a typically narrow line section to spacing that accommodates the platform, or that the tracks be spaced far enough apart between stations so that they meet the station at the proper spacing. Either condition increases the line section costs substantially, and a series of transitions between stations reduces ride quality and increases equipment wear. If driven tunnels can join this cut-and-cover station, then large additional costs for line transitions are avoided.

Station Relationship to Surrounding Area - The station is located within the same right-of-way with the same depth of cover and the same entrance locations as Station Type 3.

Station Characteristics - The distinguishing characteristics of this station are the location of the mezzanine above the platform within the trainroom and the center platform layout.

Locating the mezzanine in the trainroom has both economic and functional advantages. Excavation requirements do not exceed those of Station Types 3 and 4, and backfill requirements are less than those of Station Type 3. Roof structure costs are also reduced as the backfill load diminishes.

The trainroom is shown in the drawings as a nearly 60-foot clear-span space. This structure would be extremely expensive, but could be reduced by reducing the span through the use of center columns.

By contrast with the last two station types in which the mezzanines were sized by the width of the trainroom and location of the stair/escalator units, this mezzanine is sized to comfortably handle the station's assumed passenger capacity. As a result, there are savings in structure, finishes, and long-term maintenance costs.

The single station control and even distribution of people to the platform are identical to Station Type 3 but unlike that station, the station attendant can observe virtually all of the station as a result of the open trainroom concept.

The center platform consolidates vertical circulation between the mezzanine and platform with a substantial savings in capital and operating costs. One-way capacity is the same as the other stations. Equal peak capacity in each direction, a requirement in only the most heavily used stations, is not achieved in this station. In addition, the center platform simplifies cross platform movements and facilitates movement of patrons from the mezzanine, because a directional decision is not required until the patron reaches the platform.

Ancillary space is located beyond the ends of the platform on two levels. The effect of this arangement is to enlarge the volume of excavation and increase costs. One method of reducing these costs is to locate the ancillary space a level above and at the ends of the platform within the trainroom space. This location would reduce excavation costs without impairing circulation on the platform.

Station Capacity - The capacity of this station is the same as the last two stations, 440 people per minute.

Station Type 6

Mined Single Arch
Mezzanine Within Trainroom and Above Platform Level
Center Platform

Station Type 6 (Figure 50) is identical to the last station in concept. It has been developed to illustrate the cost differences resulting from the use of different excavation methods. The total station volumes of the two stations are similar, but the cut-and-cover volume of excavation (which includes backfill material) exceeds this station's volume by more than one million cubic feet. The cost per cubic yard of mined excavation is, however, substantially higher than that of cut-and-cover excavation.

Station Relationship to Surrounding Area - The station is shown at much greater depth than the other station types. The platform is 100 feet below the street. Clearly, the station can be located at other depths, since the controlling influences are normally track geometry requirements, geotechnical conditions, and local policy. However, mining costs will not usually vary substantially with changes in depth. As always, site geotechnical conditions heavily influence the cost trade-offs to determine station depth.

The station is depicted within a street right-of-way, but a mined station would not necessarily have to be located within the existing street system, as the next station illustrates.

A major benefit of the mined station is the avoidance of utility relocation problems. This station will normally cause less disruption of the surface than the cut-and-cover station types. However, such conditions as a high water-table or unstable ground conditions can make mined excavation prohibitively expensive.

Station Characteristics - The major difference between Station Types 5 and 6 is the vertical circulation runs between the street and mezzanine levels. Since the station is much deeper, each vertical circulation element requires three escalators, two in the peak direction and one in the off-peak direction. This increases the capital as well as operating costs of these vertical circulation elements. In addition, user convenience diminishes as the travel distance from the entrance to the platform increases.

Station Capacity - The three escalator vertical circulation elements between the street and mezzanine level govern the capacity of this station. They each have a one-way peak capacity of 200 people per minute, or a slightly reduced total station capacity of 400 people per minute.

Station Type 7

Mined Twin Tubes
Mezzanine Separate from Trainroom and Above Platform Level
Center Platform and Concourse

Station Type 7 (Figure 51) is also a mined station, but the use of different excavation methods results in a different station organization. It illustrates the potential economies of small, separate trainrooms which reduce the volume (and somewhat the risks) of mined excavation, and of a separate mezzanine that is excavated using less expensive cut-and-cover methods.

Station Relationship to Surrounding Area - The major features of the station that influence, and are influenced by, surrounding conditions are the method and depth of excavation. The station trainrooms are expanded sections of the two line section tunnels and are shown 100 feet below the surface. This method and location free the station of existing street alignments and confining right-of-way widths. They also reduce surface disruption and interference with existing utilities, thus reducing site preparation and restoration costs.

However, mined excavation is substantially more expensive than cut-and-cover excavation. It does not eliminate construction disruption problems at the entrance locations. In addition, locating stations and tunnels outside the public right-of-way is complicated in the U.S. by unresolved legal issues concerning underground easements on private property.

Station Characteristics - The station mezzanines act as a transition between the street and station alignment. They are about one-half the size of the other mined station mezzanine and are excavated using cut-and-cover methods. This reduces costs by reducing the volume and unit cost of excavation.

The station has two mezzanines, thus requiring double manning and increasing operational costs. This adverse characteristic is balanced somewhat by greater service area provided by two mezzanines. In addition, the mezzanines are isolated from the trainrooms, which eliminates the possibility of active station surveillance by the station agents.

The platform level consists of two trainroom tubes and a central concourse area or tube. The volume of excavation in the trainrooms and concourse is one-quarter million cubic feet less than that of the other mined station, thus reducing excavation costs. The station platforms are twelve feet wide.

Passengers are distributed to the concourse from the mezzanine. Access between the concourse and platforms is provided at the quarter points of the platforms, thus providing even distribution to the platform and improved circulation on the platform.

The platform level ancillary space is located at the ends of the station under the stair/escalator units. Excavation beyond the ends of the platform is not required to provide sufficient ancillary space.

Vertical circulation in this station is similar to that of the last station. The major circulation elements connect the mezzanine and the concourse, and each consists of three escalators and an inclined elevator. These elements far exceed the cut-and-cover stair/escalator units in length and have correspondingly higher capital and operating costs.

Station Capacity - The station capacity is governed by the vertical circulation element capacity between the mezzanines and concourse, which is 400 people per minute.

SUMMARY COMPARISON OF THE STATION TYPES

Quantitative Differences

The first of several matrices which summarize the assets and liabilities of the seven station types (Table 4) shows quantitative difference among the stations. These differences include the station area, the station volumes, the volumes of excavation, and the travel distance from the entrance to the platform.

Station Types 1 and 2 are quantitatively the minimal stations. They have the least area and volume, the least volume of excavation and shortest patron walking distances. While these are important measures of cost and convenience, other factors have a major bearing on cost.

Table 4
Quantitative Station Characteristics

Station Characteristics	Station Types 1	2	3	4	5	6	7
Total station area ('000's of sq. ft.)	52.7	53.1	74.2	70.0	55.2	57.5	59.8
Total exterior station volume ('000's of cu. ft.)	1,227	1,257	1,798	1,785	1,783	1,529	1,404
Total volume of excavation ('000's of cu. ft.)	1,267	1,367	3,187	2,502	2,568	1,489	1,373
Travel distance from Entrance to platform (ft.)[1]	250	254	275	332[2] 312[3]	272	367	402

[1] The distance measured is patron walking distance from a station entrance to the nearest third point on the platform

[2] Distance to the upper level platform

[3] Distance to the lower level platform

The mined stations, Station Types 6 and 7, also have relatively small station areas and interior station volumes. Their volumes of mined excavation are particularly low by comparison with the moderate depth cut-and-cover stations, since backfill is not required. However, unit price of excavation and construction risk are substantially higher for mined excavation. Travel distance in these stations is especially long because of the station depth.

Station Types 3, 4 and 5 have essentially the same interior volumes. Type 3 has more station floor area due to the larger size of the mezzanine, and nearly 700,000 cubic feet of additional excavation due to the width of the station. On the other hand, the floor area of Station Type 5 is about two-thirds of Station Type 3 as a result of its center platform and substantially smaller mezzanine area. In contrast with Station Types 3 and 5, travel distances in Station Type 4 increase markedly as a result of the more complicated stacked platform circulation.

Capital Costs

The second matrix (Table 5) is a summary evaluation of the degree to which each station achieves certain design objectives related to capital cost savings.

Table 5
Capital Cost Savings

Station Design Objectives	Station Types						
Related to Capital Cost Savings	1	2	3	4	5	6	7
Minimize surface disruption during construction	○	○	○	◐	○	●	●
Minimize right-of-way width requirement	○	○	◐	●	◐	●	●
Minimize utility relocation	○	○	◐	◐	◐	●	●
Minimize disruption of high watertable	●	●	○	○	○	○	○
Minimize acquisition of street level space	○	●	●	●	●	●	●
Minimize volume of excavation by reducing depth of excavation	●	●	◐	○	○		
Minimize volume of excavation by reducing plan area of station	○	○	○	●	●	◐	●
Minimize structure costs by reducing roof load	●	●	○	○	●		
Minimize number of vertical circulation elements	●	●	○	○	●	●	●
Minimize requirement for specialized mining skills and equipment	●	●	●	●	●	○	○

● Maximum Achievement of Objective

◐ Moderate Achievement of Objective

○ Minimum Achievement of Objective

The mined stations, Types 6 and 7, are typically the least disruptive of existing surface conditions, and therefore can reduce the cost of site preparation, maintenance, and restoration. This particular attribute must, however, be balanced with the substantial additional costs of mined excavation.

Station Types 1, 2, and 5 most satisfactorily achieve the capital cost-reducing design goals among the cut-and-cover stations. They all minimize excavation, structure requirements and the number of vertical circulation elements. They also do not require mining skills which are difficult to find, and therefore are expensive.

Station Type 4 is a specialized form of station that serves two objectives (use of cut-and-cover excavation methods in a narrow right-of-way) especially well. Where these objectives are not important design considerations, other station types will produce greater cost savings.

Station Type 3 at many sites may not compare favorably with the other cut-and-cover stations, largely because its even distribution side platform characteristics require a greater station width (and thus, a greater station area and volume of excavation) and twice as much vertical circulation as an even distribution, center platform station.

Operating Costs

The third matrix (Table 6) is a summary of each station type's effect on operating costs.

Table 6

Operating Cost Savings

Station Design Objectives	Station Types						
Related to Operating Cost Savings	1	2	3	4	5	6	7
Minimize number of vertical circulation elements	●	●	○	○	◐	◐	●
Minimize run of vertical circulation	●	●	◐	◐	◐	○	○
Minimize station interior volume for lighting; ventilating purposes	●	●	○	○	○	○	◐
Minimize number of manned facilities	○	○	●	●	●	●	○

● Maximum Achievement of Objective

◐ Moderate Achievement of Objective

○ Minimum Achievement of Objective

The minimal area/volume characteristics of Station Types 1 and 2 make those stations attractive in terms of operating cost with one major exception: they require double manning for efficient operation. These additional personnel costs can easily erode operational cost savings in the other categories. Two mezzanines provide the opportunity for a larger station service area within the urban scene.

Station Type 5 compares most favorably among those stations with a central control point. The station's other operational savings are the result of its center platform which can reduce both the number and the run of the vertical circulation elements.

Patron Convenience

Finally, a fourth matrix (Table 7) summarizes the degree to which each station satisfies objectives related to user convenience.

Station Type 5 most satisfactorily achieves user convenience objectives. The center platform and even distribution from the mezzanine aid the user of this station. The open trainroom concept also increases the user's sense of personal security in the station.

The shallow cut-and-cover station with mezzanine at street level, Station Type 1, is the least satisfactory in achieving user convenience. Patrons are not evenly distributed to the platform in the center loading station, the station attendant is isolated from the platform area, and cross-platform movements require down-and-up circulation through a crossunder with blind corners.

Table 7

User Convenience

Station Design Objectives	Station Types						
Related to User Convenience	1	2	3	4	5	6	7
Maximize active surveillance potential of station	○	●	○	○	●	●	○
Minimize passenger concentrations on platform	○	○	●	◐	●	●	◐
Maximize ease of cross platform movement	◐	◐	◐	○	●	●	●
Minimize walking distance from entrance to platform	●	●	●	◐	●	○	○

● Maximum Achievement of Objective

◐ Moderate Achievement of Objective

○ Minimum Achievement of Objective

FLOOR PLANS
FOR
STATIONS 1 THRU 7

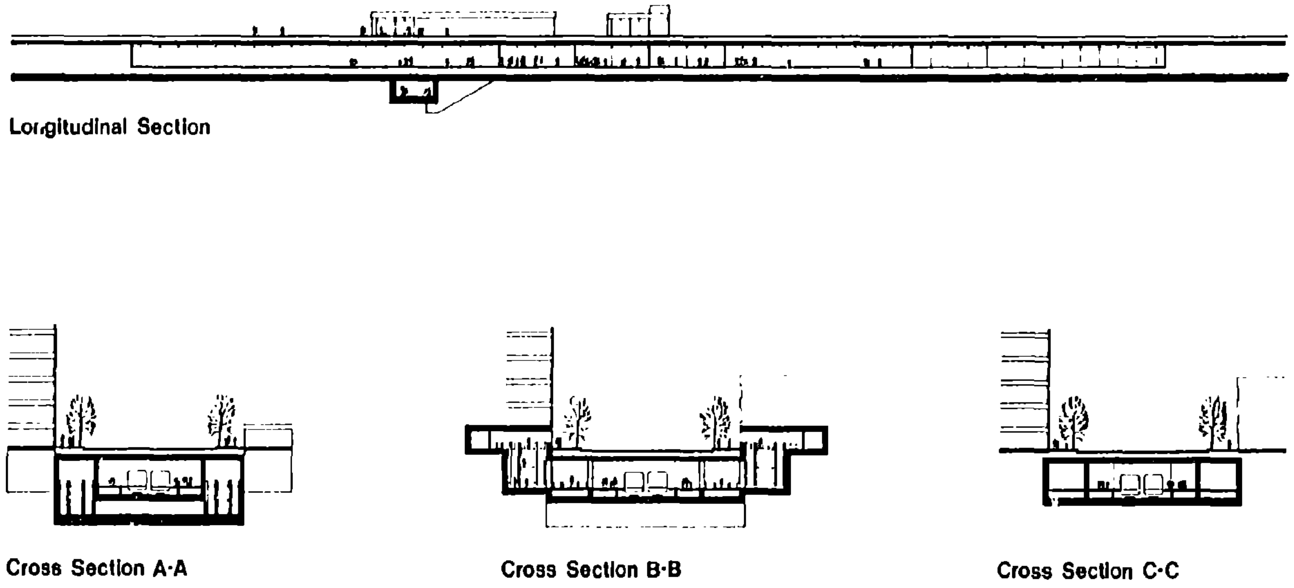


Figure 45

**Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and
At Street Level
Side Platform**

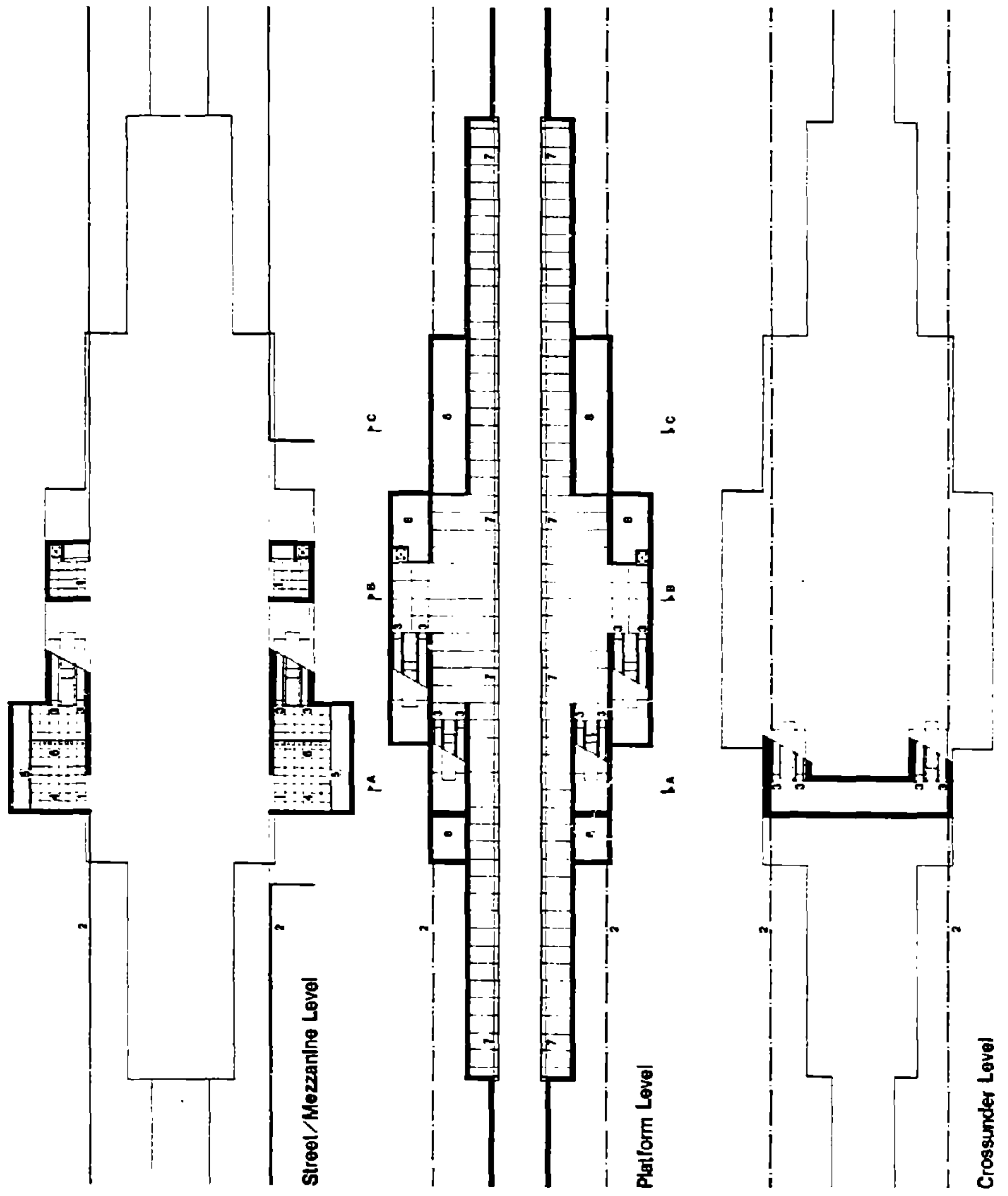
Station Type 1

Legend

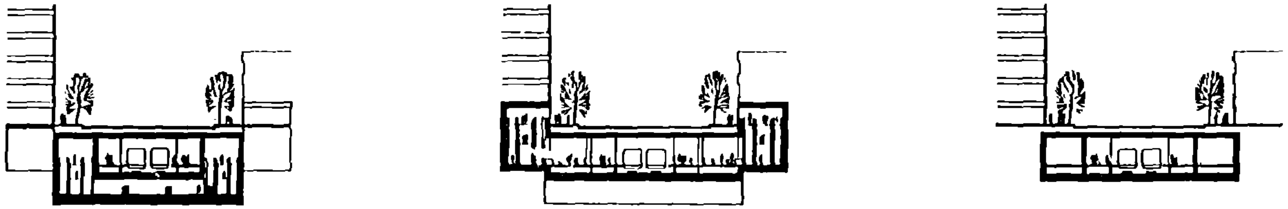
1 Street Entrance
2 ROW Line
3 Escalator
4 Mezzanine
5 Attendant's Booth
6 Turnstiles
7 Platform
8 Ancillary Room

20 10 0 20 40ft

De Leuw, Cather & Company
Skidmore, Owings & Merrill


Street/Mezzanine Level
Platform Level
Crossunder Level
A
B
C
2
3
6
7
8

Longitudinal Section



Cross Section A-A

Cross Section B-B

Cross Section C-C

Figure 46

Cut-and-Cover Box Structure

Mezzanine Separate from Trainroom and At Platform Level

Side Platform

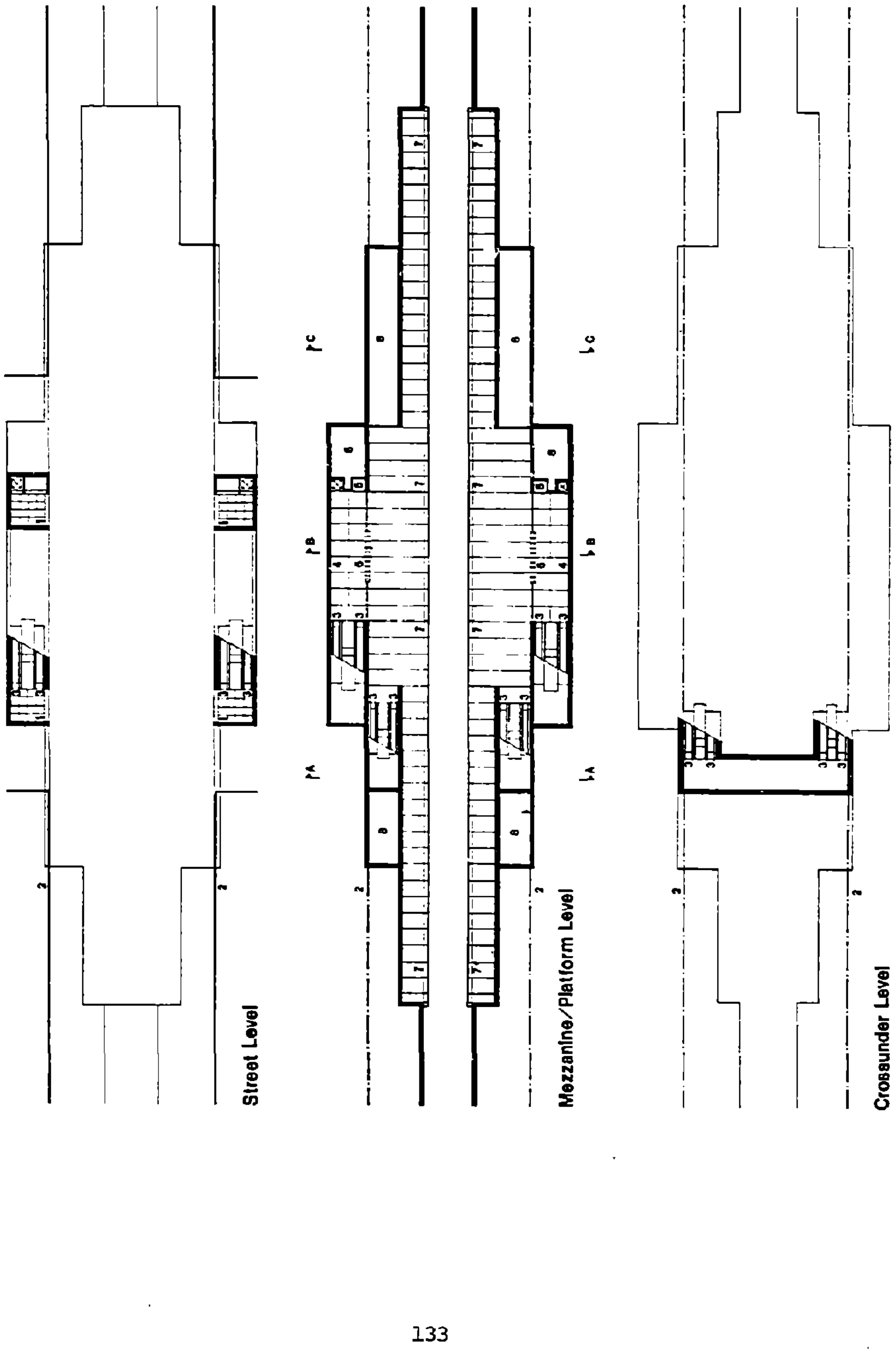
Station Type 2

Legend

1 Street Entrance
2 R.O.W. Line
3 Escalator
4 Mezzanine
5 Attendant's Booth
6 Turnstiles
7 Platform
8 Ancillary Room

20 10 0 20 40 ft

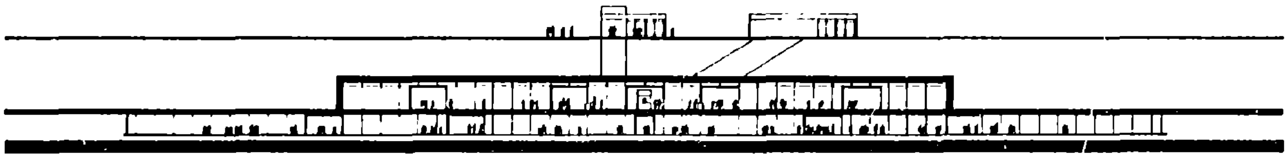
De Leuw, Cather & Company
Skidmore, Owings & Merrill



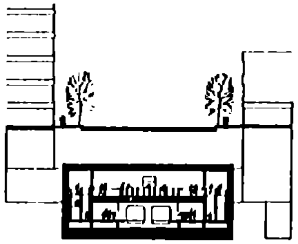
Street Level

Mezzanine/Platform Level

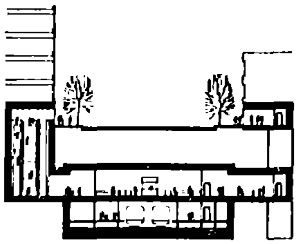
Crossunder Level



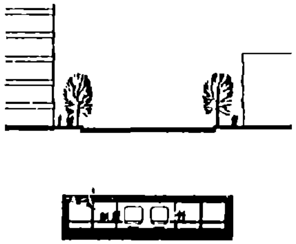
Longitudinal Section



Cross Section A-A



Cross Section B-B



Cross Section C-C

Figure 47

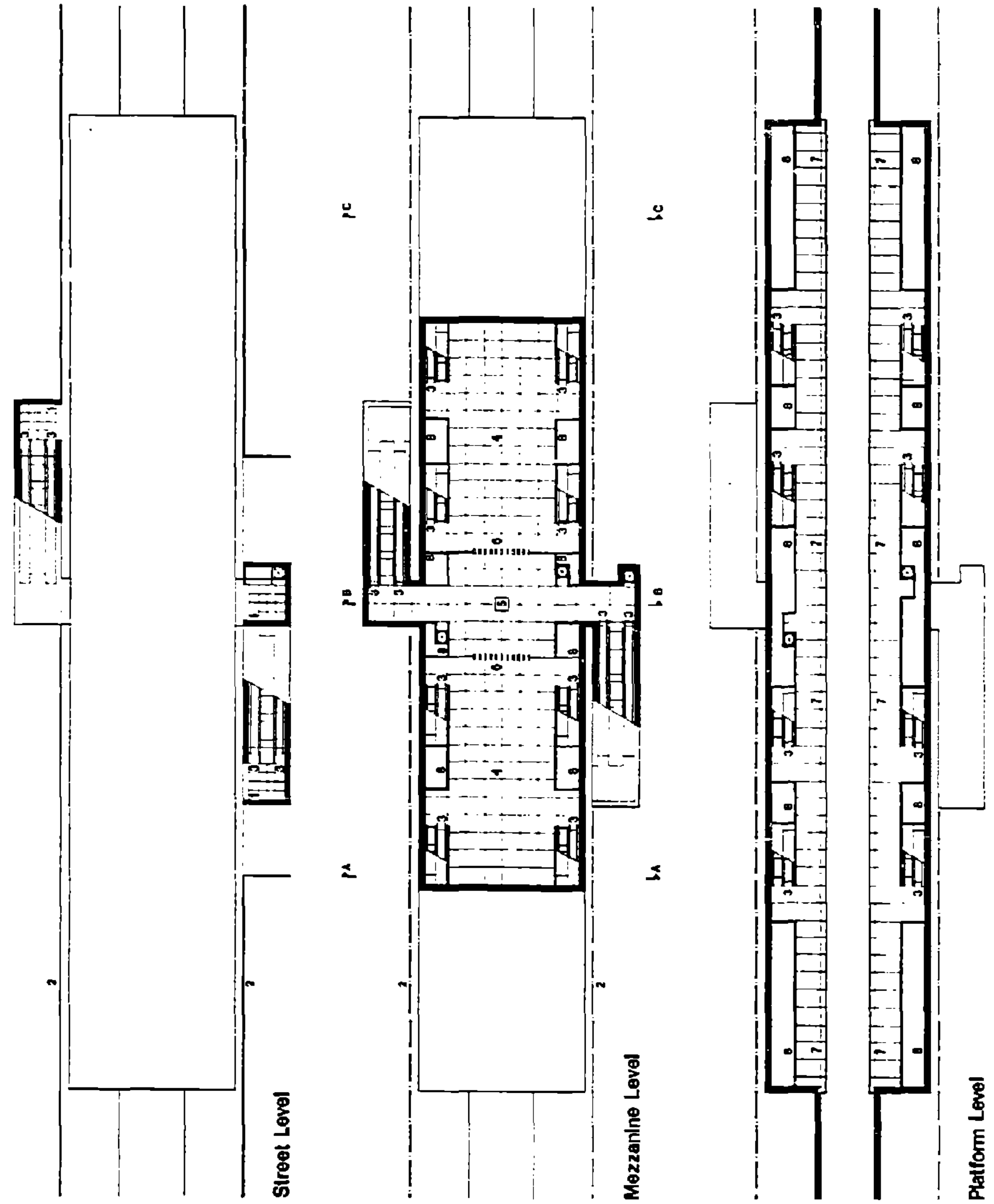
Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and Above Platform Level
Side Platform

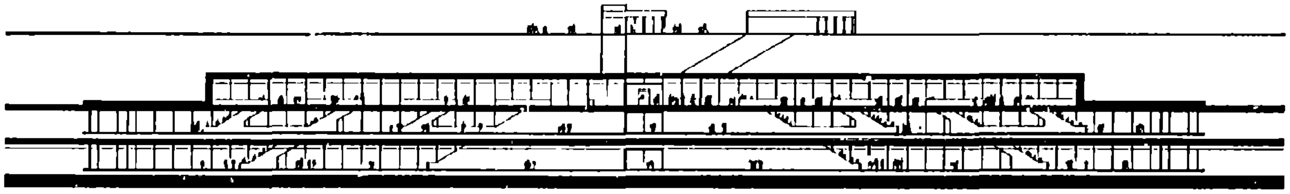
Station Type
3

Legend

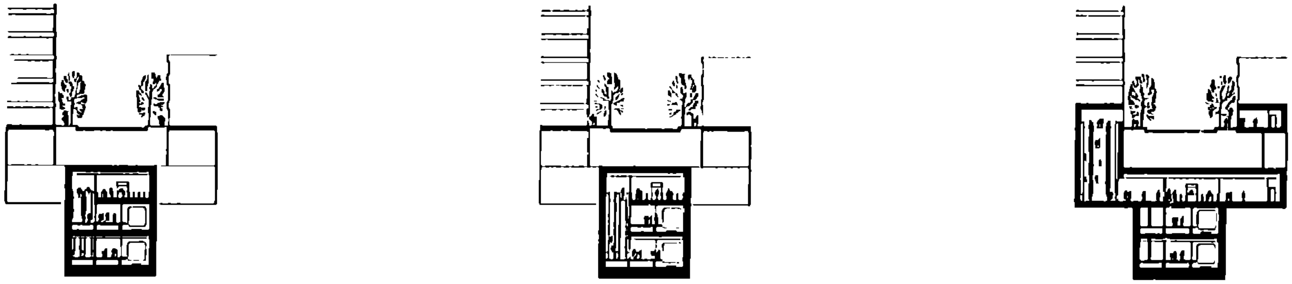
1 Street Entrance
2 R.O.W. Line
3 Escalator
4 Mezzanine
5 Attendant's Booth
6 Turnstiles
7 Platform
8 Ancillary Room

De Leuw, Cather & Company
Skidmore, Owings & Merrill


Street Level
Mezzanine Level
Platform Level
A
B
C
2
3
4
5
6
7
8



Longitudinal Section



Cross Section A-A

Cross Section B-B

Cross Section C-C

Figure 48

Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and Above Platform Levels
Stacked Platforms

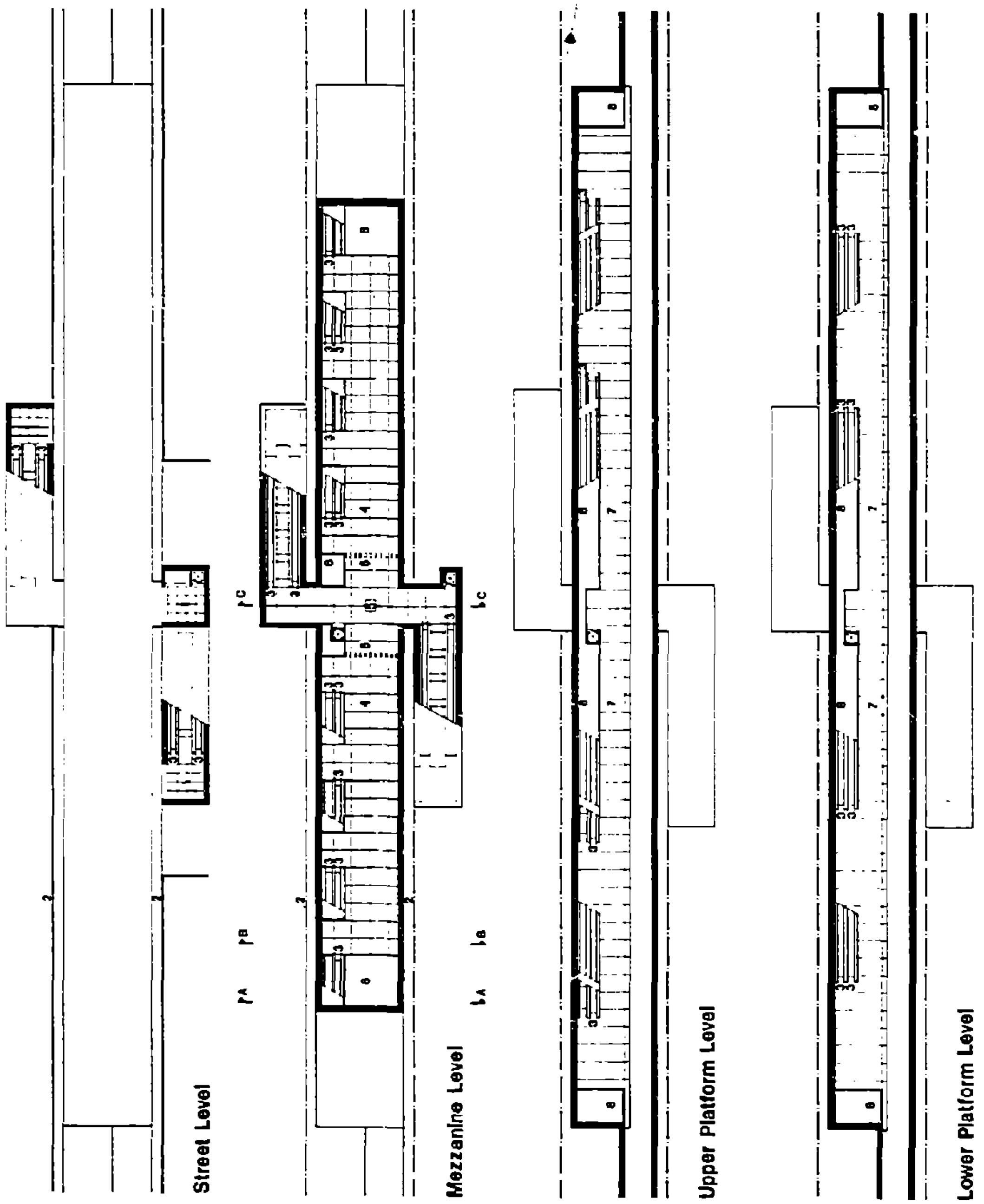
Station Type
4

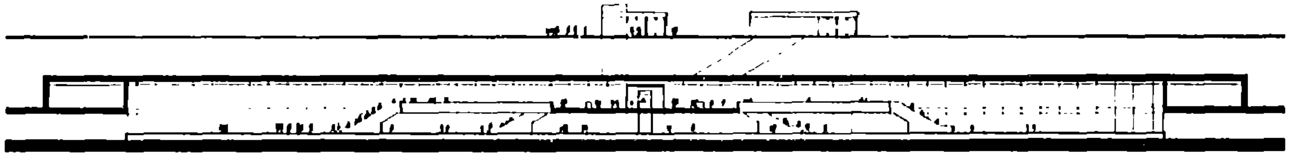
Legend

1 Street Entrance
2 R.O.W. Line
3 Escalator
4 Mezzanine
5 Attendant's Booth
6 Turnstiles
7 Platform
8 Ancillary Room

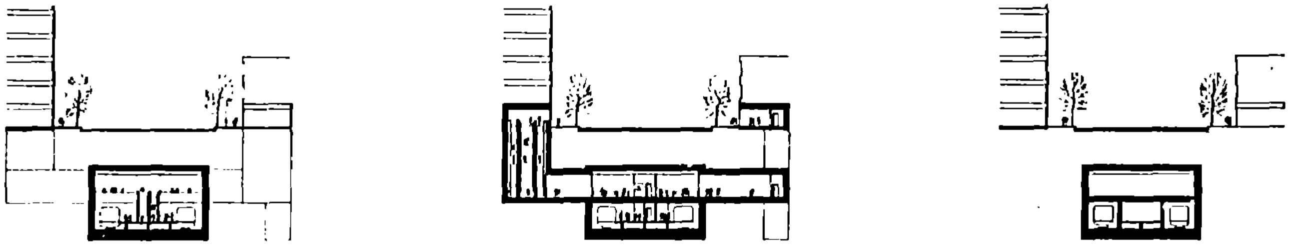
20 10 0 20 40 ft

DeLeuw, Cather & Company
Skidmore, Owings & Merrill


Street Level
Mezzanine Level
Upper Platform Level
Lower Platform Level
A
B
C
A
B
C



Longitudinal Section



Cross Section A-A

Cross Section B-B

Cross Section C-C

Figure 49

Cut-and-Cover Box Structure Mezzanine Within Trainroom and Above Platform Level Center Platform

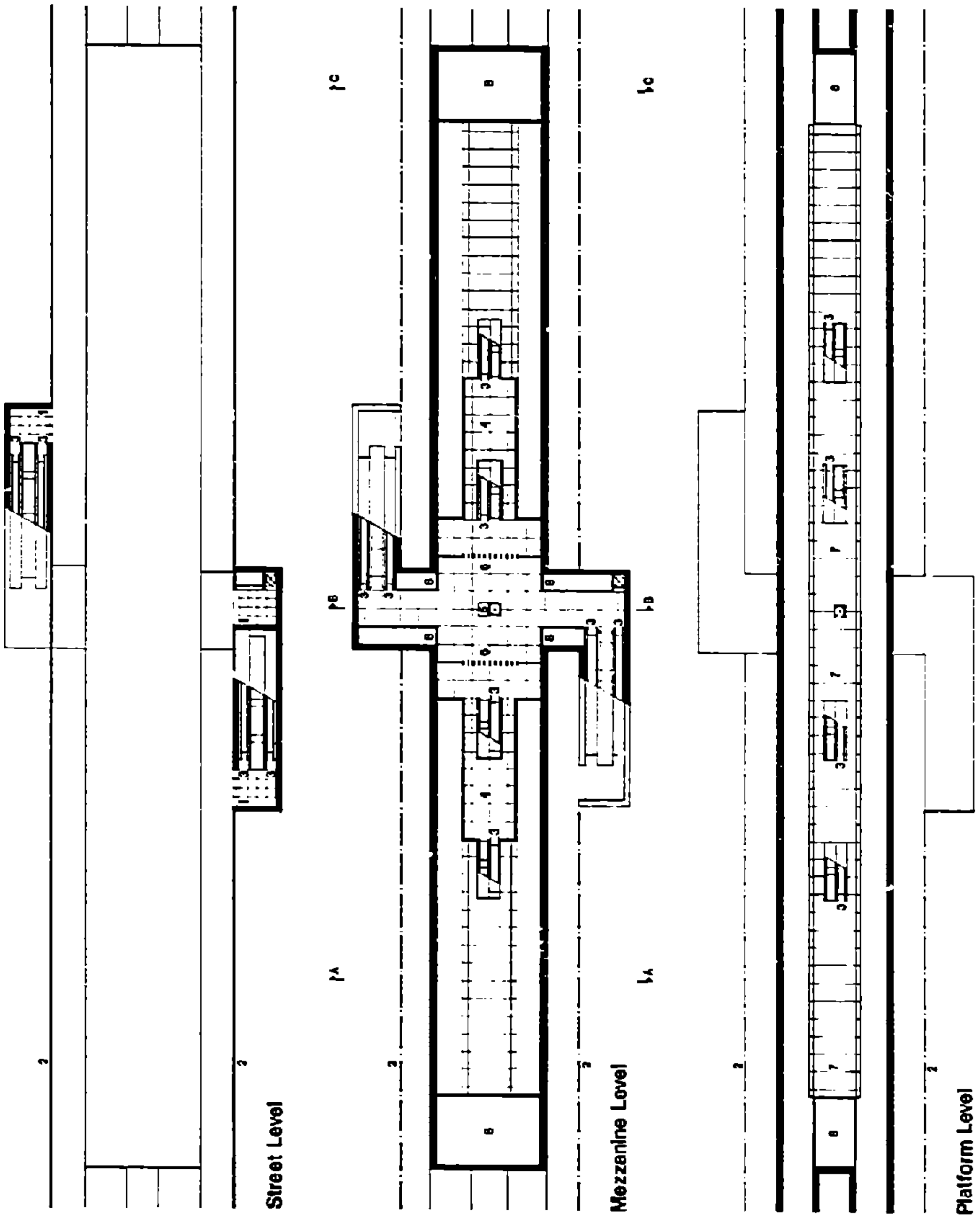
Station Type 5

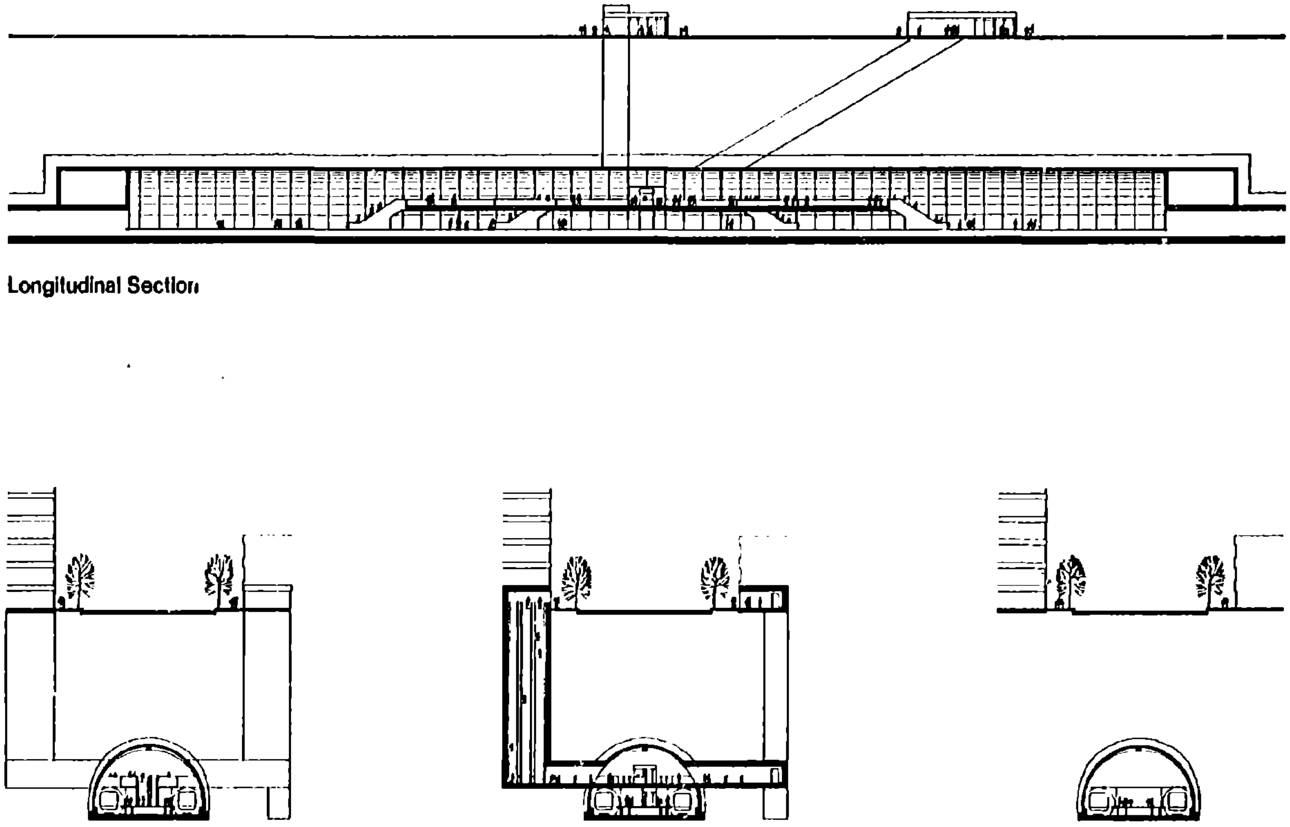
Legend

1 Street Entrance
2 R.O.W. Line
3 Escalator
4 Mezzanine
5 Attendant's Booth
6 Turnstiles
7 Platform
8 Ancillary Room

20 10 0 20 40ft

De Leuw, Cather & Company
Skidmore, Owings & Merrill


Street Level
Mezzanine Level
Platform Level
A
B
C
2
3
4
6
7
8



Longitudinal Section

Cross Section A-A

Cross Section B-B

Cross Section C-C

Figure 50

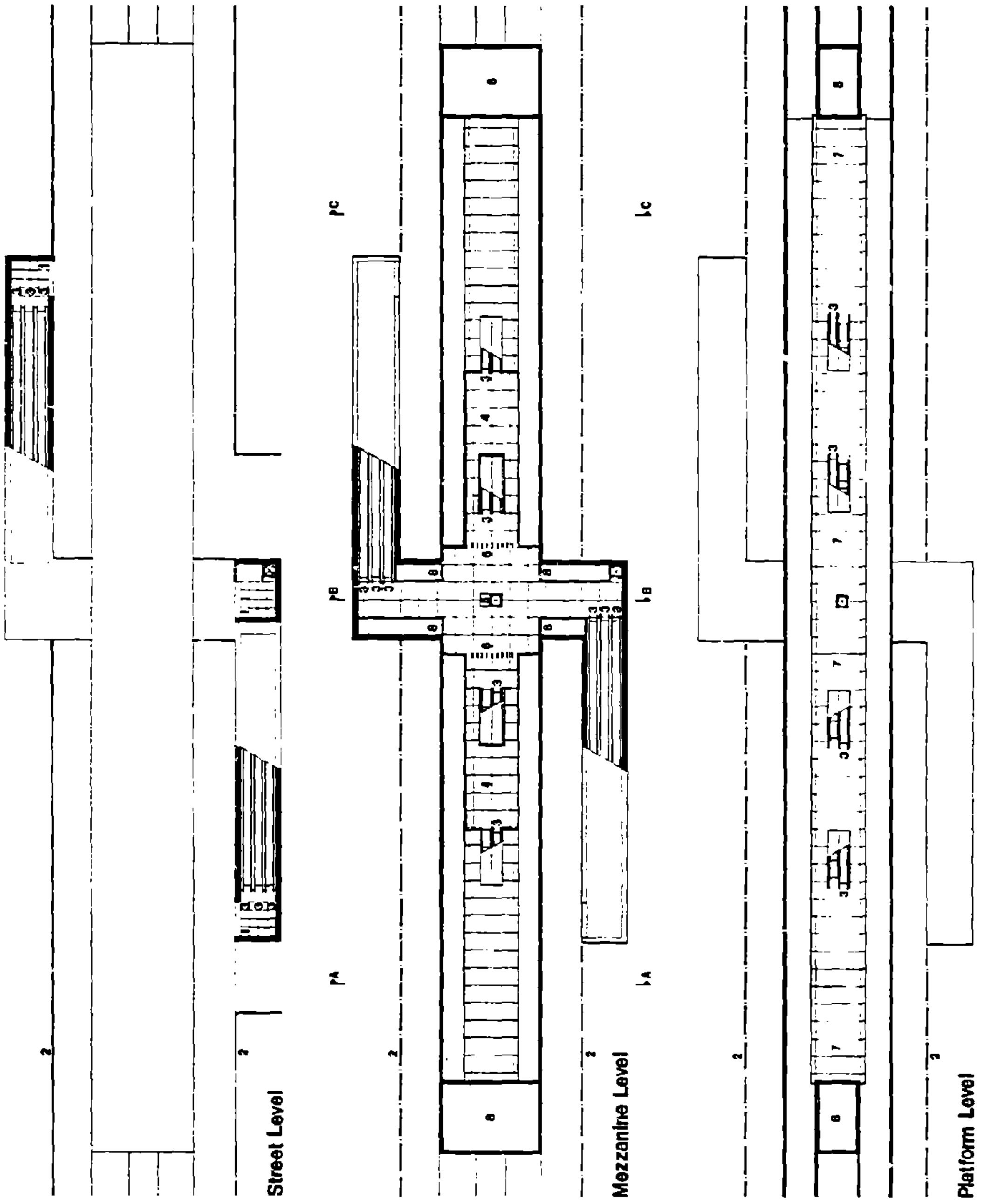
Mined Single Arch
Mezzanine Within Trainroom and Above Platform Level
Center Platform

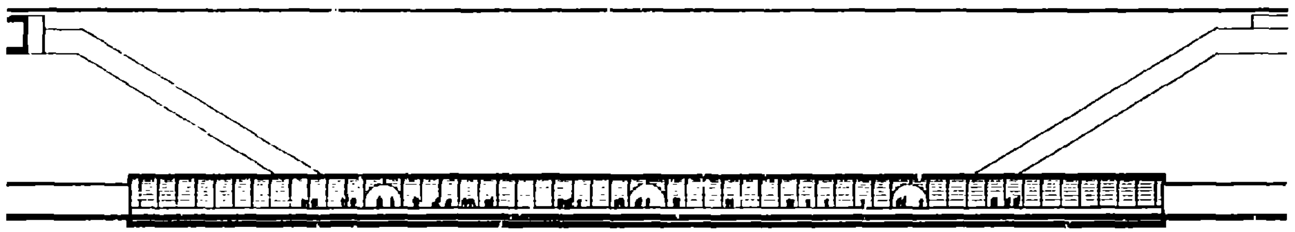
Station Type 6

Legend

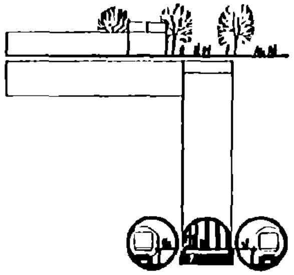
1 Street Entrance	5 Attendant's Booth
2 R.O.W. Line	6 Turnstiles
3 Escalator	7 Platform
4 Mezzanine	8 Ancillary Room

De Leuw, Cather & Company
Skidmore, Owings & Merrill

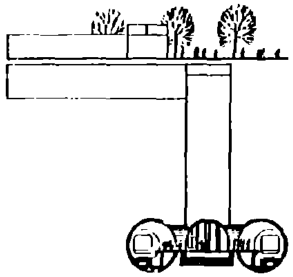

Street Level
Mezzanine Level
Platform Level
PA
PB
PC
A
B
C
2
3
4
6
7
8



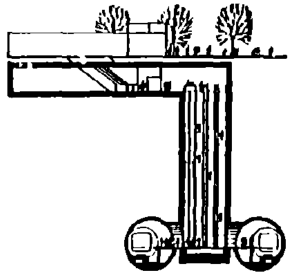
Longitudinal Section



Cross Section A-A



Cross Section B-B



Cross Section C-C

Figure 51

Mined Twin Tubes

Mezzanine Separate from Trainrooms and Above Platform Level

Center Platform & Concourse

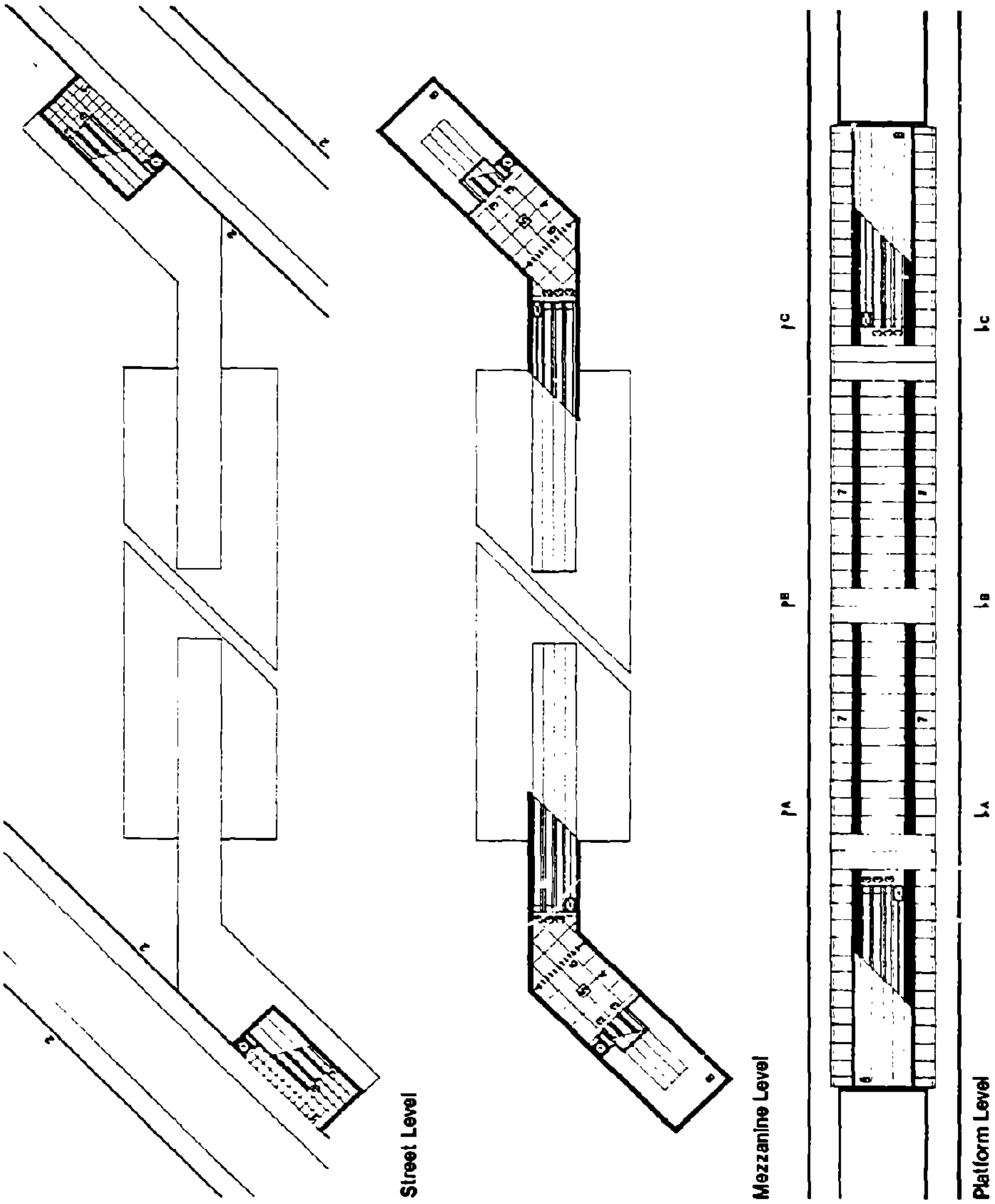
Station Type
7

Legend

1 Street Entrance	5 Attendant's Booth
2 R.O.W. Line	6 Turnstiles
3 Escalator	7 Platform
4 Mezzanine	8 Ancillary Room

20 10 0 20 40ft

De Leuw, Cather & Company
Skidmore, Owings & Merrill


Street Level
Mezzanine Level
Platform Level
A
B
C
7
7
7
7

Chapter 8
COST CONSIDERATIONS

The rapidly growing and almost prohibitive cost of urban underground rapid transit in the U.S. is the major reason for conducting this study. Station costs can become the major component of fixed facilities for rapid transit. A literature search and 13 on-site investigations were conducted to examine current activities to provide insight into the problems of rising cost and techniques being used to contain costs, particularly techniques which could reduce the cost of future U.S. underground stations. Investigating and identifying costs present two major problems: many of the elements of total cost are tied directly to the conditions characteristic of a specific city at the station site; and some of the most significant cost elements which lead to decisions on characteristics and location of a station are often the product of the complex interaction among social, institutional, and technical considerations.

One of the most influential factors determining station cost is the working environment under which planning, design, and construction are implemented. The economic environment determines the costs of labor, materials, and equipment. Attitudes toward public transit, physical characteristics such as geotechnical and urban conditions, and the availability of technical skills to perform a large scale transit project all determine this working environment.

Costs actually experienced in different cities (particularly in other countries) were applicable only to that city and could not be extrapolated for another city. For example, the prices of rock-mined stations in Stockholm cannot be compared with rock-mined stations in Washington, D.C. The dissimilarity in the competence of rock alone is reason enough to disqualify this comparison; however, when differences in contracting procedures, organizational framework, and design characteristics are added, any comparison is meaningless, and results mislead rather than inform.

Certainly lessons can be learned by observing transit construction in other parts of the world, but observations must be placed into context so that valid conclusions can be reached regarding the relationship of practices in other countries to those in the U.S. For this reason, every attempt has been made to avoid misleading cost conclusions.

During the interviews, transit officials were generally cautious about providing local prices to the Study Team, because extensive qualifications of the data would have been necessary. Those interviewed correctly anticipated that sets of qualifications would vary from city to city, negating the usefulness of absolute numbers. Typical responses by transit officials were that prices were not generally available in the categories which were of interest to the Study Team; prices would require extensive analysis to become compatible with other cities; costs are indigenous and not related to U.S. conditions; prices reflected the logical and expedient choice under the constraints faced at the time of construction; and prices were low due to fortunate circumstances at the time of construction. The end result was that very little statistical data was made available; thus, the Study Team concentrated on areas of cost concern rather than on detailed historical cost data.

Costs discussed and compared in this chapter are based on estimates of the seven station types developed in Chapter 6. The seven station configurations represent the majority of stations constructed within the past 15 years. The estimates also responded to concern for the cost significance of several station dimension variables: depth, width, and length.

Just as the station is a major cost component of the transit system, the station itself has several major components of cost. These components include all station capital costs. Items 1 through 7 are used in this chapter's estimates. Cost components 8 through 12 below are excluded from estimates in this chapter, because these elements were not subject to variations in design or construction methods.

1. Site work includes contractor mobilization, utilities handling, traffic maintenance and control, and underpinning or protection of adjacent facilities.

2. Earthwork includes all work associated with excavation, support of excavation, and backfill.

3. Station structure includes the basic structural shell, interior framing and partitions, and entrances.

4. <u>Station finish</u> includes architectural treatments and finishes for station surfaces, patron amenities, graphics, attendant booths, and acoustical treatment.

5. <u>Mechanical and electrical equipment</u> include all station operating equipment, such as escalators, elevators, ventilation, drainage, switchgear, lighting, and station utilities.

6. <u>Train control and communications</u> include all fixed facilities for trains to serve that particular station.

7. <u>Fare collection and miscellaneous operating facilities</u> include turnstiles, and vending and attendants' facilities. Automated (computer-controlled) fare collection systems are not considered in this estimate.

8. <u>Engineering</u> includes planning, preliminary and final design, architecture, construction inspection, and administration; customarily, the services are applicable to all of the above components of station costs.

9. <u>Right-of-way</u> includes cost of land acquisition, accesses, easements, dislocations, damages, administrative costs for negotiations, and property arrangements.

10. <u>Administration</u> includes costs incurred directly by the transit authority's staff for all activities associated with station implementation.

11. <u>Contingency</u> can be applied to all or selected components above.

12. <u>Excluded work and materials</u> refer to transit system items which are contained within the station envelope but would be installed through the station reach as part of the line structure if the station did not exist. Typical items are trackwork (exclusive of crossovers attributable to station operation), traction power, vibration control for adjacent facilities, and train control attributable to line operation.

Estimates were performed by standard construction estimating procedures; station quantities were not taken from bid documents but from drawings developed specifically for the study. Unit prices used in the estimates were developed considering labor, materials, and equipment units, current U.S. bid tabulations, price quotes from contractors and specialists, and the judgment of experienced estimators. Bid tabulations themselves can be misleading because of unbalancing which might be used to enhance early cash flow. Care was taken to ensure that all prices were within a reasonable 1976 national price range.

To examine costs, three series of estimates were performed: station types, significant dimensions, and construction method variations. Each estimate series was designed to obtain controlled conditions which are necessary to effectively illustrate the significance of dimensional variables and station elements.

1. For the station type estimates, the seven station types were compared assuming reasonable ground conditions and no unusually difficult site conditions. Major categories of cost of a typical transit station were examined.

2. For the station dimensions estimates, major dimensions (length, width, and depth) were examined to demonstrate that choices among seemingly minor dimensional variations can have an unusually large effect on total cost.

3. The construction method variations estimates were sample demonstrations of providing the construction contractor with designs which promote alternative construction methods. Variations in the application of slurry wall techniques and the use of columns versus no columns were used to examine the cost effects of providing major alternatives.

STATION TYPE ESTIMATES

There are seven station types and thirteen separate estimates in this series. Table 8 identifies the estimate with the station type and shows the depth of cover and excavation method for each estimate. The seven station types represent recently constructed stations which satisfy a variety of actual urban conditions. Each type represents the resulting compromise among pressures which shape the

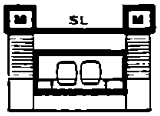
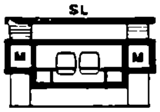
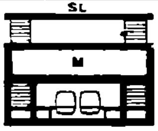
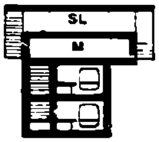
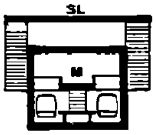
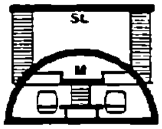
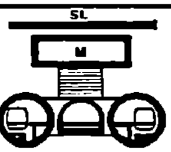
	Station Type	Estimate Number	Estimate Distinction	Excavation Method
Open Cut Excavation	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and at Street Level Side Platform **1** 	1	6 Ft. Cover	Open-Cut Earth
		1A	3 Ft. Cover	
	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and at Platform Level Side Platform **2** 	2	6 Ft. Cover	
	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and Above Platform Level Side Platform **3** 	3	6 Ft. Cover	
		3A	20 Ft. Cover	
	Cut-and-Cover Box Structure Mezzanine Separate from Trainroom and Above Platform Levels Stacked Platforms **4** 	4	6 Ft. Cover	
		4A	20 Ft. Cover	
	Cut-and-Cover Box Structure Mezzanine within Trainroom and Above Platform Level Center Platform **5** 	5	6 Ft. Cover	
		5A	20 Ft. Cover	
Mined Excavation	Mined Single Arch Mezzanine within Trainroom and Above Platform Level Center Platform **6** 	6	70 Ft. Overburden	Mined, Earth
		6A	70 Ft. Overburden	Mined, Rock
	Mined Twin Tubes Mezzanine Separate from Trainroom and Above Platform Level Center Platform and Concourse **7** 	7	85 Ft. Overburden	Mined, Earth
		7A	85 Ft. Overburden	Mined, Rock

Table 8

Station Type Estimate Series

configuration and characteristics of a station: design considerations, physical constraints, political and institutional influences, and available funds. These station configurations are representative solutions for conditions which can be expected in future U.S. construction.

The base estimate is for the reference station, Station Type 5 (Figure 52) with 20 feet of cover, assuming good ground conditions and no unusual site difficulties. To establish a sense of magnitude for the dollar value of proportional differences, Station Type 5 has a median estimated 1976 cost of $16.2 million. This figure includes major cost components 1 through 7 and a 20 percent construction-only contigency. Depending on site conditions and other variables, this station cost could be considerably greater than that for the base condition.

Station Type 5 has a center platform. Assuming that a double box line structure constructed by cut-and-cover methods would adjoin this station, a transition would be required to widen the double box to meet the center platform. The additional cost (the difference between typical box structure and special transition structure) brings the cost of Station Type 5 to $17.3 million. To avoid giving this station an advantage over other stations where special transitions are typically not attributed to the station configuration, the surcharge is included in estimates 5 and 5A. If mined line structures joined Station Type 5, this cost surcharge would not be applicable, since dual tunnels can be aligned with the platform without a transition structure. The $17.3 million total in estimate 5A is the basis for the 1.00 cost ratio, with other station costs being shown in proportion to the base figure.

Figure 53 summarizes the results of the station estimates. Estimated costs are presented as ratios relative to the reference Station Type 5 base of 1.00. For example, the estimated cost of Station Type 1 (estimate 1) is 74 percent of Station Type 5 (estimate 5A). This would imply that in a system where Station Type 5 would cost $20 million, Station Type 1 would cost $15 million if all site controls were equal. The estimates of the station types show that the most economical station is the station with the least amount of underground volume and the shallowest excavation. For example, Station Type 1 is estimated to cost about one-half that of the most costly station, Station Type 6, mined in soft ground. As expected, the cost of cut-and-cover station increases as depth of cover increases.

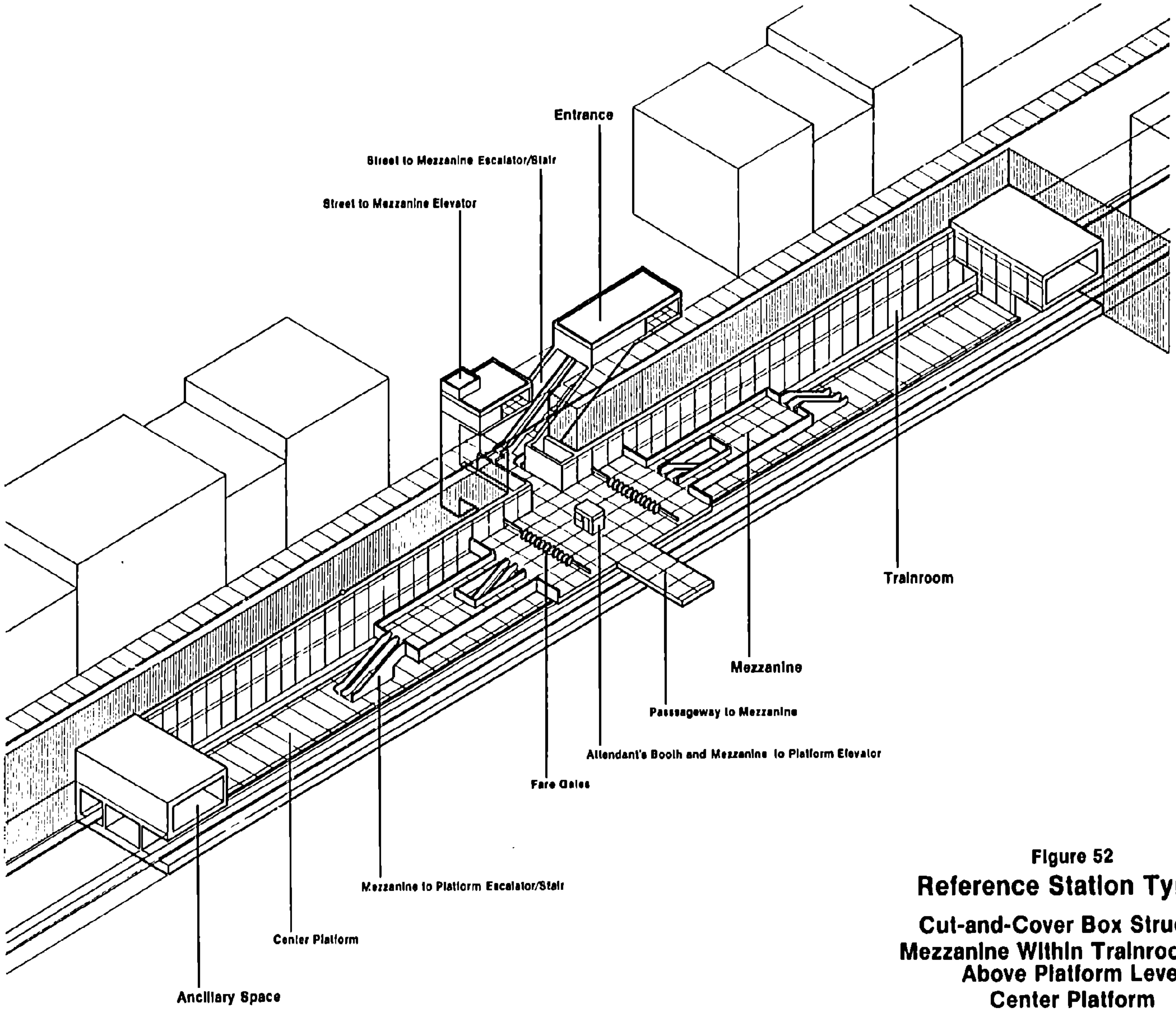


Figure 52

Reference Station Type 5

**Cut-and-Cover Box Structure
Mezzanine Within Trainroom and
Above Platform Level
Center Platform**

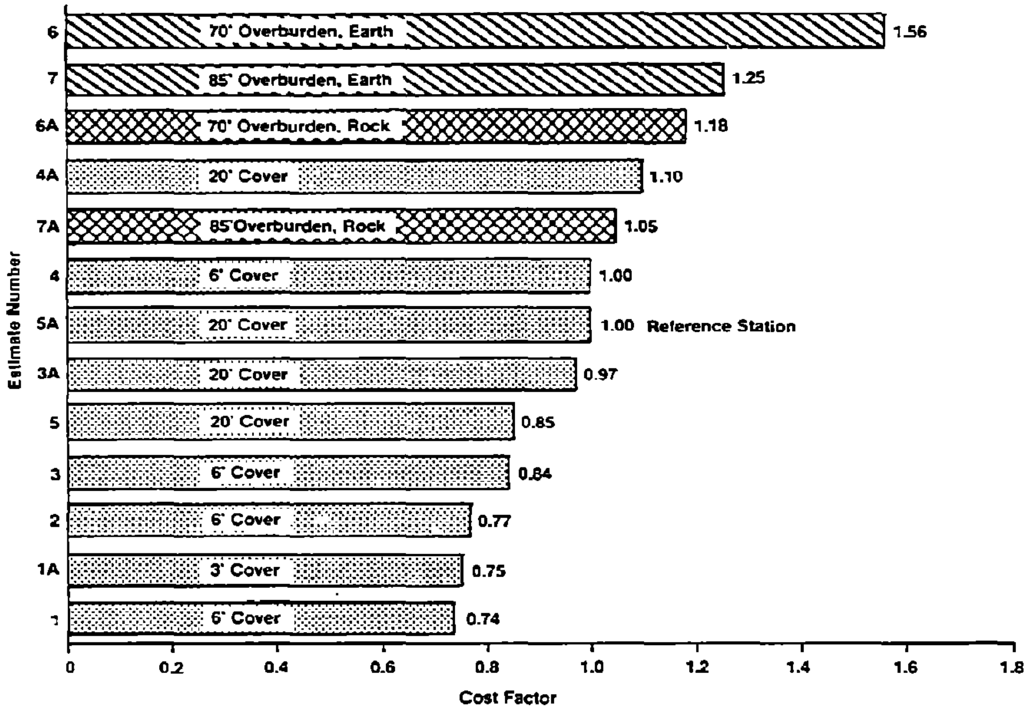


Figure 53
Comparison of Station Costs

The mined stations generally are more expensive than the cut-and-cover stations at the depths of cover established. The exception is Station Type 7 in rock, which is very close in cost to the reference station which is cut-and-cover with 20 feet of cover over the crown.

Figure 54 shows the major components of cost for each station type. Individual blocks within the horizontal bar for each estimate represent the major cost components.

This estimate series demonstrates cost relationships and should not be interpreted as assigning a price to these station types for future U.S. construction at specific sites.

The following assumptions and procedures were used to prepare the estimates:

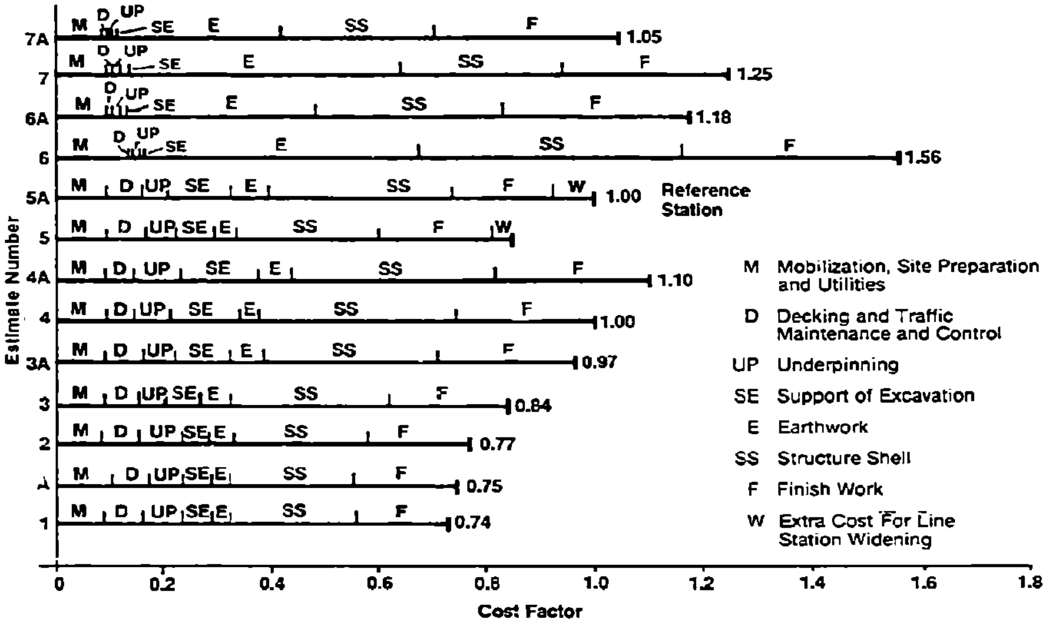


Figure 54

Breakdown of Cost Components

1. The quality of estimates is commensurate with the requirements of a concept study or a preliminary estimate for planning.

2. Estimating methods are consistent among all estimates for this series. Estimate 5A of Station Type 5 is used as the basis of estimate comparisons and ratios.

3. Estimates assume no unusually difficult or unmanageable ground or site conditions affecting price or progress rate.

4. All structures are assumed to be constructed using methods which are considered conventional in the U.S.

5. Quantities and cost elements were taken from station type drawings. All station types were developed to obtain the maximum degree of commonality in capacity and function.

6. Approximately 35 separate station cost elements were quantified and priced in each estimate. All estimates in the station type series represent stations ready for operation, except that line-related facilities, such as trackwork and traction power, are excluded.

7. The estimated cost of Station Type 5 (estimates 5 and 5A) includes the additional cost of line structure transition.

Station Components

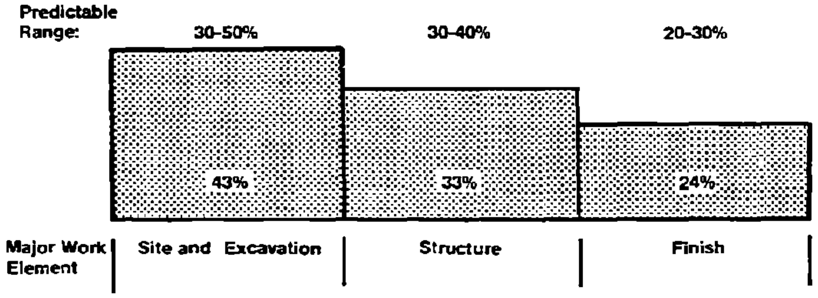
As a part of the study of the reference station estimate, the elements that make up the estimated cost of Station Type 5 were compared to determine their significance. Table 9 lists component percentages for the reference station. Actual percentages will vary from these listed, depending on the site conditions.

Table 9

Station Type 5 Cost Components

Major Work	Major Components	Component %	
Site and excavation	Support of excavation	12	
	Underpinning	9	
	Traffic	8	
	Earthwork	7	
	Utilities	7	
			43
Structure	Concrete, steel waterproofing, etc.		33
Finish	Station equipment	8	
	Mechanical, electrical, fare equipment	7	
	Architectural finish	6	
	Station and operations equipment	3	
			24
			100%

Cost saving efforts should focus on categories of highest potential, such as work which begins prior to the actual station structure. Figure 55 illustrates that the major portion of station cost is site and excavation work with descending cost percentages for structure and finish work. The actual cost of site and excavation work is heavily dependent on the character of the specific site. For example, support of excavation and earthwork costs make up about 20 percent of the total. Underpinning, traffic maintenance, and utility costs (25 percent), which are site-specific items, offer opportunities for savings if a station site selection can be made which gives their importance full consideration.



* Station Is Ready For Operation, Excluding Trackwork Traction Power, System Related Train Facilities

Figure 55

Relationship of Major Work Elements (Station 5A)*

Figure 56 identifies the cost components which are often capable of yielding substantial savings. If planning and design decisions consider these areas of savings potential, the opportunities for savings are increased. For example, in many transit systems, underpinning and support of excavation have been combined and largely incorporated into the cost of structure work by using slurry walls to perform multiple functions. In other cities, impact on traffic was minimized by locating the transit line and station off-street in exclusive transit right-of-way. Where stations must be cut-and-cover, shallow profiles greatly reduce the amount of excavation, simplify the excavation support system, reduce or eliminate underpinning, reduce structural requirements, minimize escalator lengths, and reduce accessway lengths and ventilation shaft depths.

One interesting feature in Figure 56 is that architectural finish is a relatively small percentage of total station cost. In the station used in the example, cutting back on architectural finish does not offer great potential for savings; however, added investment in this element, which is a small percentage of total station cost, has great leverage to enhance station appearance and the image of the system.

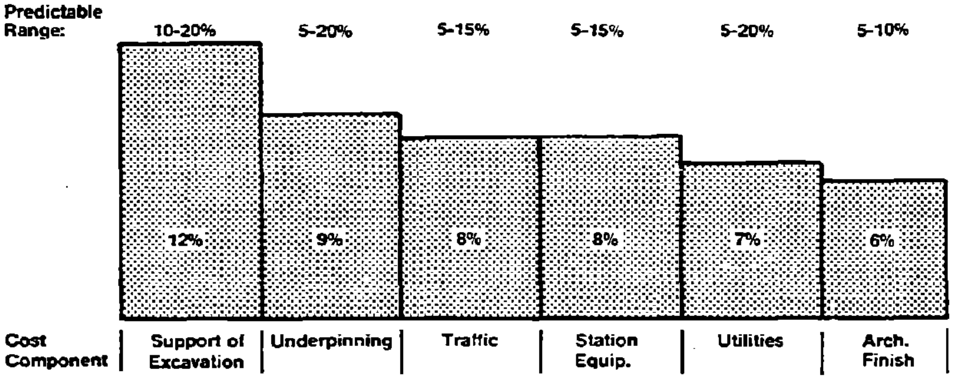


Figure 56
Comparison of Selected Cost Components (Station 5A)

STATION DIMENSIONS ESTIMATES

Deeper, wider, or longer underground facilities cost more money. In this series of estimates, design guidelines were developed by relating decisions on major station dimensions to their attendant costs. Increments of station length, width, and depth are associated with their resultant cost changes.

Recently constructed cut-and-cover stations having the general configurations of the stations types have lengths which differ by as much as 300 feet, widths by 25 feet, and open-cut depths by 60 feet. The station dimension estimate series demonstrates order-of-magnitude rate of change of cost related to decisions on these three cost-sensitive dimensions.

It is usually difficult to save large amounts by minimizing structure and finish work; however, these cost categories have historically received the most effort toward optimizing costs. The effort to optimize the final design and construction methods holds less potential for substantial savings when compared with the early opportunity to limit the costs of site work and excavation which are normally a larger percentage of total cost than structure work. Site work is directly related to volume of excavation, of which depth, width, and length are the component dimensions. Planning and early design decisions on platform width and length, top-of-rail profile, and architectural spatial relationships create design parameters which, in final design, determine overall station length, width, and depth. The cost impact of these early decisions often is not fully known at the time they are made. The station dimensions estimate series provides examples of the cost repercussions of these early decisions.

Station Type 5 was used as the reference station to develop cost trend lines resulting from length, width, and depth changes. The cross sections on the drawings in Chapter 6 represent the dimension and scale of assumed urban conditions, i.e., a fully developed CBD, heavy utilities and traffic, available widths as shown, and the requirement to maintain urban activity while minimizing disruption. Cost estimates were prepared for this station by varying one dimension while holding the other two constant.

Cost estimates were based on construction of a fully operational station with the exception of some line-related items. The rate of change of the cost of site and structure work was the feature being demonstrated. Length, width, or depth was varied through its reasonable range, and estimates were prepared at selected points on the range. Estimate results were plotted (Figures 57, 58, 59) to form three cost trend lines which display by ratio the expected cost change for the attendant dimension change.

The estimating methodology was consistent within this series. Unit prices or costs were assigned to the following cost elements for each estimate in this series: site preparation, traffic maintenance and staging, decking, support of excavation, dewatering, excavation, underpinning, utilities, concrete (invert slab, exterior walls, roof slab, platform, mezzanine), backfill, entrances, restoration and paving, station finish, and station equipment.

Depth of Structure

To establish the trend lines of Figure 57, depth of cover from street level to the top of the structure was varied from three feet to forty feet. The base estimate for ratio calculations was for 20 feet of cover over the crown.

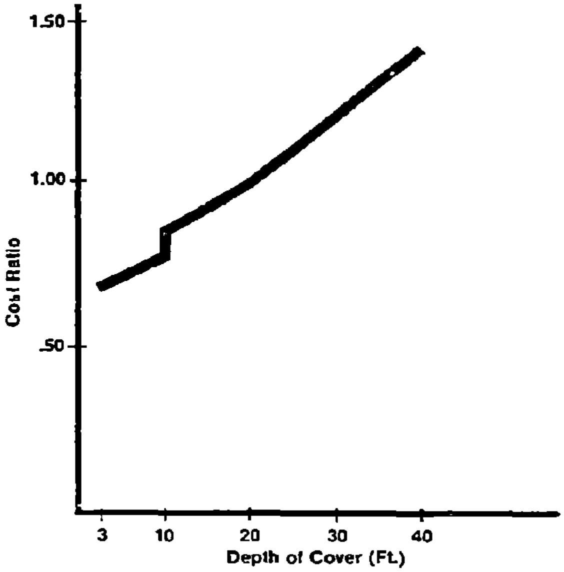


Figure 57
Depth Cost Trend

The significance of depth of cover on total cost is reflected in the cost ratio range as depth varies. For example, when depth of cover is reduced from 20 feet to ten feet, the cost is reduced to 85 percent of the base station cost. When depth is increased from 20 feet to 30 feet, cost increases by 20 percent to 120 percent of the reference station. Nearly all of the increase is caused by site work, such as underpinning, earthwork, and excavation support. A relatively small percentage is due to the thicker structural shell. Surface-related elements (decking, traffic maintenance, restoration, and paving) are independent of depth.

Estimate methodology assumed that underpinning was not required for depth of cover less than ten feet. This assumption is the reason for the stepped appearance of the trend line. When cover exceeds ten feet, the underpinning cost is substantial and heavily influences the shape of the curve for greater depths of cover.

Width of Platform

The center platform width for Station Type 5 was varied from 16 feet to 30 feet, and costs were estimated to show the relationship between station cost and width of station. Figure 58 presents the results graphically.

Similar to the effects of increasing depth, costs of site work components (excavation, backfill) are a substantial portion of the total as width is increased. As one would expect, structure costs do increase considerably as the station structure is being enlarged. Unlike the effect of increasing depth, the cost of surface-related components (decking, restoration and paving) increases proportionally as width is increased. Underpinning is also a cost factor as

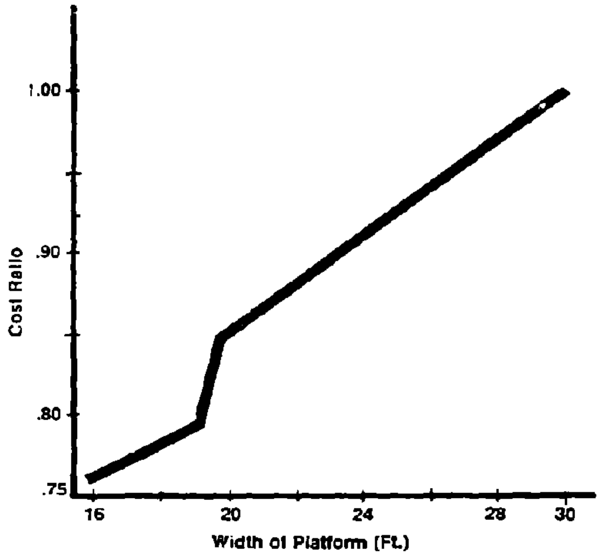


Figure 58
Width Cost Trend

width is increased; thus, there is a discontinuity in the cost ratio trend as initial underpinning costs are incurred. From this point, the cost ratio increases at an increasing rate as the platform is widened.

As an example, the cost ratio trend line in Figure 58 indicates that a ten-foot increase in width from 20 to 30 feet would result in an 18 percent increase in total cost, i.e., a cost ratio of 0.85 to a cost ratio of 1.0, or 18 percent change.

Length of Platform

The length of the platform was varied from 400 feet to 700 feet, with the reference length being 550 feet. Figure 59 presents the results of these estimates. The cost trend line is linear as length increases. All of the cost elements which compose the total cost are nearly linearly dependent

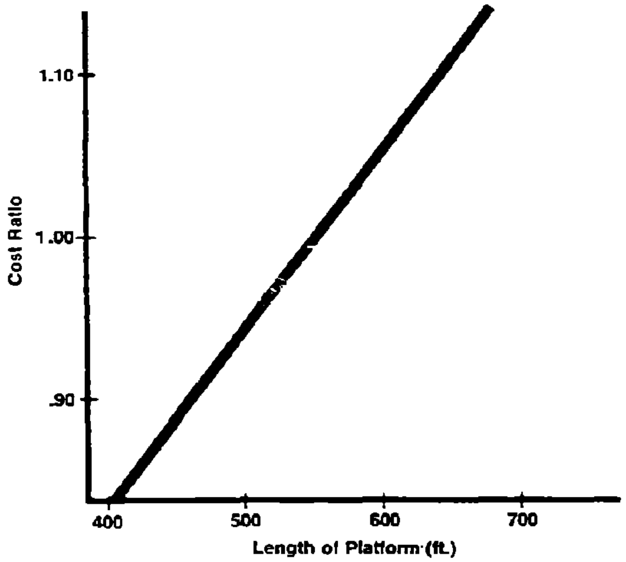


Figure 59

Length Cost Trend

on length of platform. Because surface and volume increase proportionally as length is increased, the cost of surface related elements, site work elements, and structure elements increase proportionally. In these estimates, the cost of increased length does not reflect a deduction for the line structure which the station would replace.

The cost effect on one foot of length change is hardly comparable to the effect of one foot of depth or width change; however, actual decisions on length dimensions are made in the 50- to 100-foot range rather than in the much smaller range of variation of depth and width dimensions. The standard length of Munich's U-Bahn platform is 394 feet. Recent stations in the United States have platforms as long as 700 feet. In Figure 59, an increase from a 400-foot platform length to 700 feet causes a price increase of approximately 70 percent in the station cost. Of course, station length is determined by train length, which is established to meet transit line capacity requirements and as such is not subject to variation in the design process to the extent of station width and depth.

CONSTRUCTION METHOD VARIATIONS ESTIMATES

Special Techniques

The on-site investigations indicated that slurry wall construction methods offer economies if a single wall can be used for two or more of the functions necessary for construction. These functions include providing support of excavation, minimizing direct support of adjacent structures, acting as a groundwater cutoff or control wall, and serving as the permanent structural wall of the station. Slurry wall methods in this estimate series include both tremie concrete in a slurry-filled trench or slot and precast concrete panels in a slurry-filled trench.

The construction of underground stations using slurry wall methods has received wide acceptance in other countries. However in the U.S., the majority of underground station construction is done by conventional methods, i.e., cast-in-place concrete using pre-fabricated form work. Two questions thus arise: can slurry wall construction methods be used economically in the U.S., and under what conditions can economies be achieved?

To test these questions, estimates were performed on two station types assuming conditions conducive to slurry wall construction. Construction costs for Station Types 1 and 5 were estimated for the two slurry wall methods and for conventional construction under the following assumptions:

1. The tremie concrete or precast panel walls perform the four functions listed above, which are characteristic of this method of construction.

2. By using walls constructed in a slurry trench, the costs of several conventional construction items are significantly reduced and occasionally eliminated. For practical considerations, the cost for conventional support of excavation was eliminated; the support function is accomplished by walls placed in slurry trenches. The precast panel and tremie concrete walls also serve as structural exterior station walls. In this estimate, costs were reduced, generally, by the proportions shown below:

Underpinning	10 percent of conventional cost
Dewatering	25 percent of conventional cost
Station end wall, conventionally formed structural concrete	10 percent quantity, hence cost
Mobilization	75 to 90 percent of conventional cost.

3. No unusually difficult ground conditions exist.

4. Station finish work was not included.

5. Station Types 1 and 5 have six feet of cover: otherwise, they are the same as the drawings in Chapter 6.

6. The unit prices of walls constructed in slurry trenches assume field conditions reasonably compatible with slurry trench methods. Prices are valid only within the range of conditions which applied to cost estimates for these two stations.

For the tremie concrete slurry wall method, the basic unit price developed through construction cost estimating procedures is $17 per square foot for the initial foot of wall thickness. The unit price for thicker walls increases at the rate of $1.42 per square foot for each additional inch of wall thickness. The unit price of the wall only, in place, is:

Station Type 1, 21-inch wall thickness - $30 per square foot

Station Type 5, 30-inch wall thickness - $42 per square foot.

For the precast concrete panel slurry wall method, unit prices were developed individually for the two estimate conditions, giving due consideration to the differences in depth of excavation and weight and height of panel to be lifted. The unit price of the wall only, in place, is:

Station Type 1, 12-inch wall thickness - $30 per square foot

Station Type 5, 24-inch wall thickness - $59 per square foot.

Under these assumptions, underpinning, dewatering, and mobilization costs are reduced considerably for slurry wall construction. Relative to conventional methods, large savings were realized by combining the support of excavation wall with the structural walls of the station. Thus, very little conventional cast-in-place concrete for exterior walls was necessary. The results of estimates for Station Types 1 and 5 using slurry wall methods compared to the conventional cast-in-place method are presented in Figure 60.

For Station Type 1, both the tremie concrete and precast methods were less expensive than the conventional cast-in-place method under the estimate assumptions. The tremie concrete method was less expensive than the conventional method for Station Type 5. However, the precast panel method was more expensive, mainly due to the added costs of handling the larger panels.

These estimates, although qualified and under controlled conditions, support consideration of slurry wall methods for future U.S. construction. When the tremie concrete precast panel walls can be used as part of the permanent structure or when they can satisfy a significant amount of the underpinning requirements, and geotechnical conditions present no insurmountable problems, slurry wall methods can be competitive and, in many cases, less expensive than conventional methods.

Another consideration is that 1976 prices and capabilities were basic to the estimates. It is not unreasonable to assume that the increased use of slurry wall methods in the U.S. would both increase the construction skills and ability to perform these methods and reduce the unit costs of these techniques.

To test the cost sensitivity of more favorable construction conditions and lower cost slurry walls, the assumptions used in developing Figure 60 were changed as follows:

Underpinning	none
Dewatering	10 percent of conventional cost
Unit price of wall in place	10 percent cost reductions as follows:

Tremie concrete slurry wall method

Station Type 1 - $27 per square foot
Station Type 5 - $38 per square foot

Precast concrete panel slurry wall

Station Type 1 - $27 per square foot
Station Type 5 - $53 per square foot.

All other assumptions are unchanged. The results of these more favorable construction conditions are presented graphically in Figure 61.

An additional ten percent reduction in exterior wall unit costs provides up to a three percent reduction in total station cost. It appears that the cost of slurry wall construction would have to decrease approximately 20 percent from estimated 1976 U.S. prices to produce a five percent reduction in total station cost. This figure again reinforces the study findings that decisions regarding length, width, and depth have more significant effects on total cost sensitivity.

Columns

The seven station types were all designed to be column free. In many circumstances, the additon of a row of center columns can offer an opportunity for savings. The center

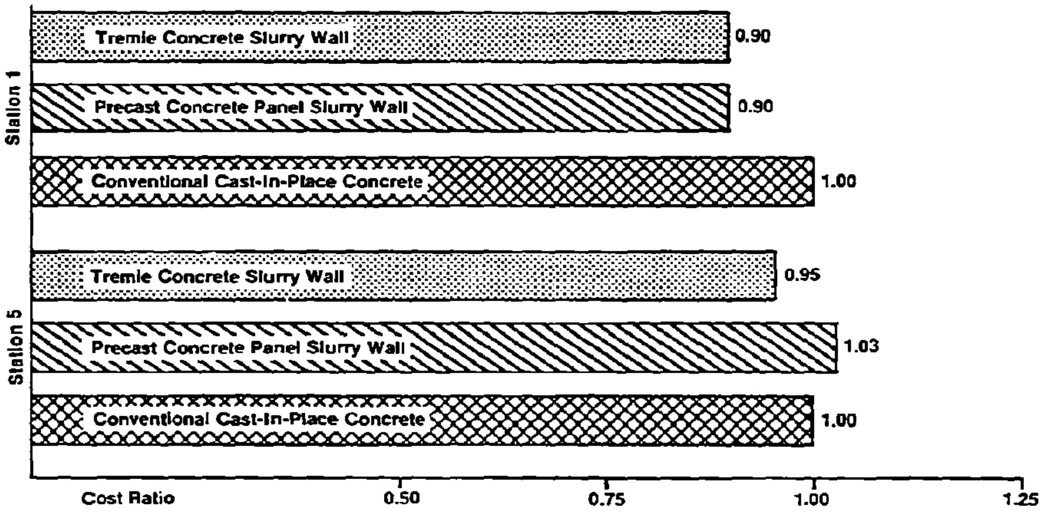


Figure 60

Cost Comparison With Standard Site Conditions
For Stations With Slurry Walls versus Conventional Walls

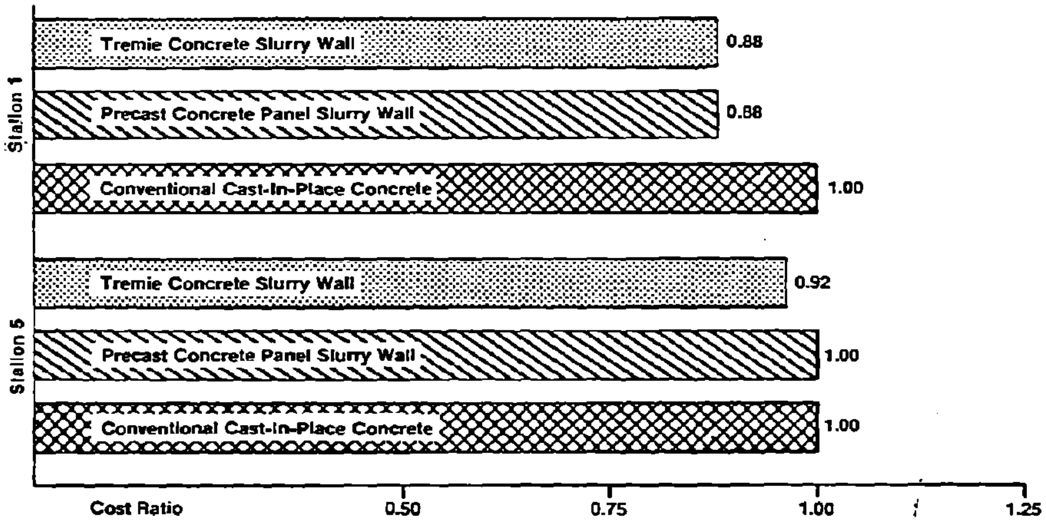


Figure 61

Cost Comparison With Optimized Site Conditions
For Stations With Slurry Walls versus Conventional Walls

columns permit a decrease in structural thickness of invert and roof. Usually, the decreased thickness is an opportunity to raise the elevation of the station and adjust the profile.

The estimate of the reference station, Station Type 5, was based on a column-free design. To determine the effect of center columns on cost, a row of center columns was added, structural members were reduced in thickness, and the profile was adjusted. The resulting cost decrease was seven percent of the base cost of Station Type 5 without columns.

Appendix A
STATION TYPE VARIATIONS

In addition to the station types illustrated in Chapter 7, a number of variations of these types either have been observed in visits to the thirteen cities or appear to have potential application under specific urban or geotechnical conditions. Some of these variations are stations commonly found in the world today, and each has the potential of reducing construction costs under certain circumstances. Consequently, these variations and their assets and liabilities are briefly examined.

The station type variations are derived from factors which defined the station types. The four factors that are subject to change during site-specific design (method of excavation, location of the mezzanine, platform type, and loading characteristics) are organized in a matrix (Table B-1) to systematically explore the range of station type variations.

The horizontal axis of the matrix portrays the basic methods of excavation: cut-and-cover and mined. The vertical axis of the matrix describes a sequence of station layout factors. First, four possible mezzanine locations are displayed on this axis. Then, within each category, three platform types are depicted. Finally, both end and center loaded stations are considered with each platform type for each mezzanine location.

The matrix can identify 72 potential station types. However, a review of the matrix reveals that many of the combinations are clearly impractical for reasons of cost or poor patron circulation. In addition, seven of the stations identified in the matrix are those examined in Chapter 7. They have been outlined in the matrix and identified by their station type number.

The matrix reveals 16 additional stations that are practical variations on the seven station types. Each of these variations is identified by two numbers. The first number refers to one of the seven station types of which this station is a variation. The second letter identifies which variation the station represents. Each of the variations is briefly described, diagrammed, and discussed in terms of its assets and liabilities.

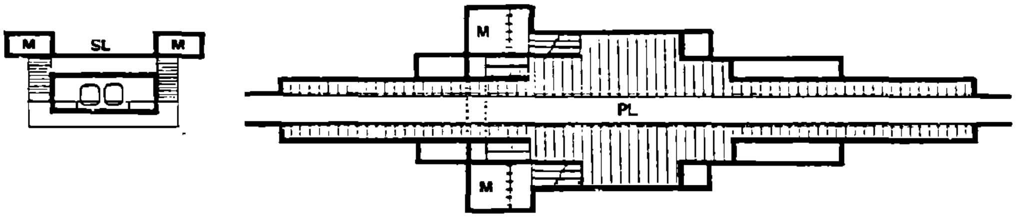
Table A-1
Station Type Variations

Station Layout Factors	Excavation Type Structure Type	Cut and Cover	Mined Excavation	
		Box Structure	Single Arch	Twin Tubes
Mezzanine Outside Trainroom and at Grade				
Side Platform	End Loading	1-1	6-1	▥
	Center Loading	1	╱	▥
Center Platform	End Loading	╱	6-2	▥
	Center Loading	╱	╱	7-1
Stacked Platforms	End Loading	╱	▥	▥
	Center Loading	╱	▥	▥
Mezzanine Outside Trainroom and at Platform Level				
Side Platform	End Loading	2-1	╱	▥
	Center Loading	2	▥	▥
Center Platform	End Loading	╱	╱	▥
	Center Loading	╱	▥	╱
Stacked Platforms	End Loading	▥	▥	▥
	Center Loading	▥	▥	▥
Mezzanine Outside Trainroom and Above Platform Level				
Side Platform	End Loading	3-1	╱	▥
	Center Loading	3	╱	▥
Center Platform	End Loading	3-2	6-3	▥
	Center Loading	3-3	╱	7
Stacked Platforms	End Loading	4-1	▥	▥
	Center Loading	4	▥	▥
Mezzanine Inside Trainroom and Above Platform Level				
Side Platform	End Loading	5-1	6-4	▥
	Center Loading	5-2	6-5	▥
Center Platform	End Loading	5-3	6-6	▥
	Center Loading	5	6	▥
Stacked Platforms	End Loading	▥	▥	▥
	Center Loading	▥	▥	▥

1	One of the station types	▥	Not applicable
1-1	Reasonable variation on the station type	╱	Undesirable for reasons of high construction cost, effects on structural integrity of the design, or poor patron circulation & distribution

STATION TYPE 1

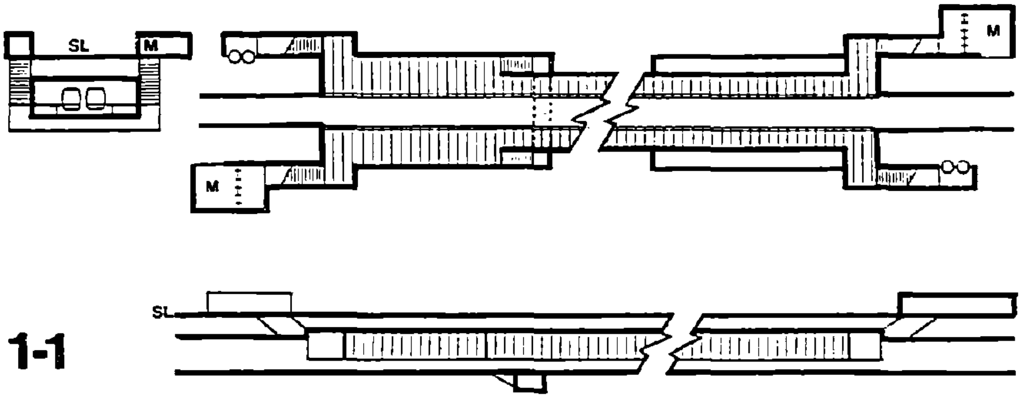
Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and at Street Level
Side Platform



1

Variation 1-1

This station is an end-loaded variation of Station Type 1. Vertical circulation to and from street level is located at the ends of the station. Mezzanine and fare collection functions remain at street level and separate from the trainroom located beyond each end of the platform. This variation would be compatible with situations where long distances between entrances are dictated by urban or other conditions.



1-1

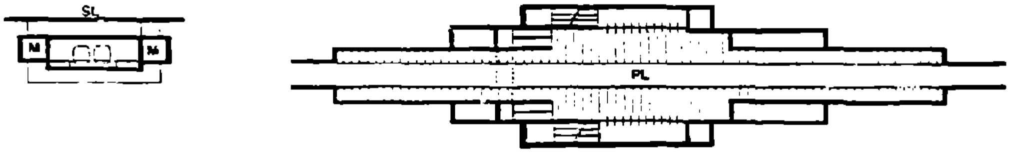
<u>Assets</u> - Street access from the station is improved due to the greater number and more varied locations of egress points.

Liabilities -

1. Platform distribution is poor due to the lengthened distance between ingress/egress and train boarding points.
2. Security and surveillance is poor at the unsupervised exits.
3. Increased vertical circulation adds to the construction cost.

STATION TYPE 2

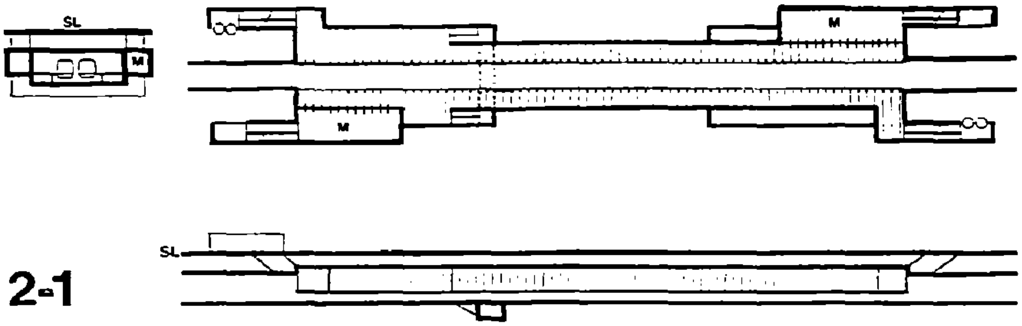
Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and At Platform Level
Side Platform



2

Variation 2-1

This station is an end-loaded variant of Station Type 2. Vertical circulation to and from street level occurs at either end of the station. Mezzanine and fare collection functions remain at platform level. As in the case of Variation 1-1, an end-loaded station would be compatible with situations in which long distances are desirable between street entrances.



2-1

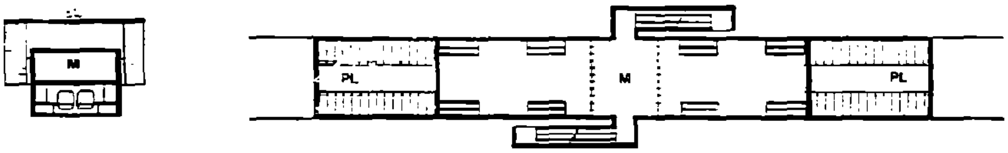
<u>Assets</u> - Street access from the station is improved due to the greater number and more varied locations of egress points.

Liabilities -

1. Platform distribution is unfavorable due to the lengthened distance between ingress/egress and train boarding points.
2. Security and surveillance is poor at unsupervised exits.
3. Increased vertical circulation adds to the cost of construction.

STATION TYPE 3

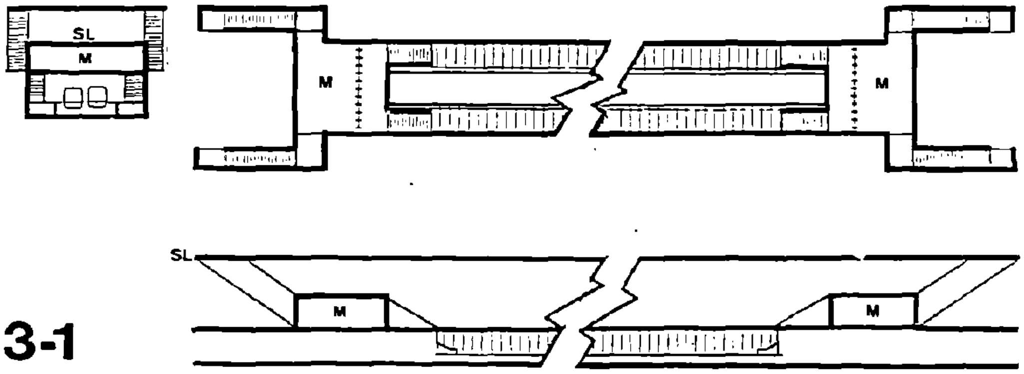
Cut-and-Cover Box Structure
Mezzanine Separate from Trainroom and Above Platform Level
Side Platform



3

Variation 3-1

The station is an end-loaded variant of Station Type 3. Vertical circulation to and from street level occurs at either end of the station. Mezzanine areas are separate from the trainroom.



3-1

Assets - Street and station access are improved due to the greater number and more varied locations of ingress and egress points.

Liabilities -

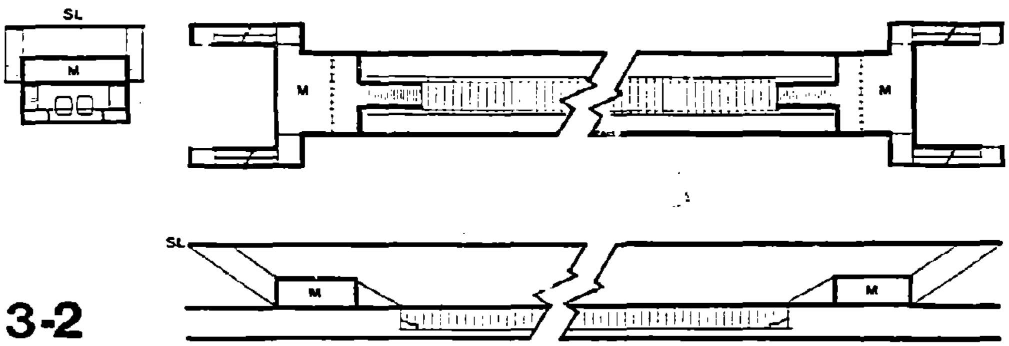
1. Platform distribution is unfavorable due to the lengthened distance between ingress/egress and train boarding points.

2. Two mezzanine areas increase operating costs due to double manning.

3. Increased vertical circulation from mezzanine to street level adds to the cost of construction.

Variation 3-2

This variation has the same mezzanine and end-loading as variation 3-1, but is modified by a center platform. Mezzanine areas are divided, separate from trainroom, and located at either end of the station.



3-2

Assets -

1. Street and station access is improved due to the greater number and more varied locations of ingress and egress points.

2. Cross platform circulation is improved with the center platform.

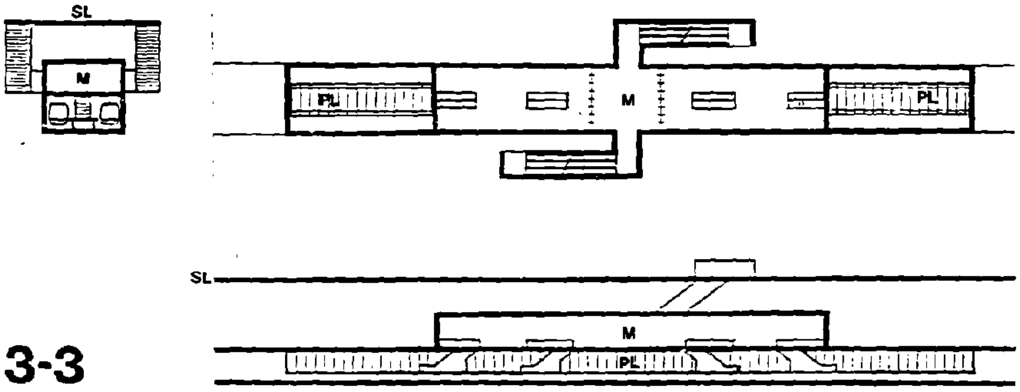
3. Mezzanine to center platform movement requires fewer stair/escalator units.

Liabilities -

1. Platform distribution is unfavorable due to the lengthened distance of travel between ingress/egress and train boarding points.
2. Two mezzanine areas increase operating costs due to double manning.
3. Increased vertical circulation from mezzanine to street level adds to the cost of construction.

Variation 3-3

This station is the center platform variation on Station Type 3. The mezzanine is separate from the trainroom and center loaded. Fare collection is centralized.



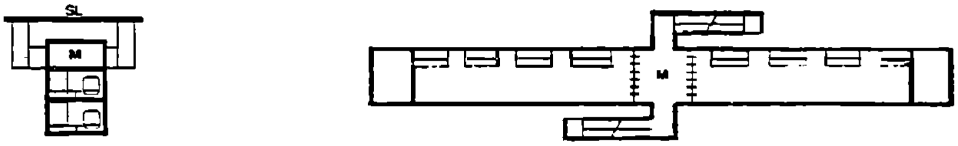
3-3

Assets - Center platform improves cross-platform circulation by eliminating the need for vertical travel.

Liabilities - The mezzanine area, which is determined by the size of the trainroom and the location of the stair/escalator units serving the platform, is larger than required for efficient patron circulation.

STATION TYPE 4

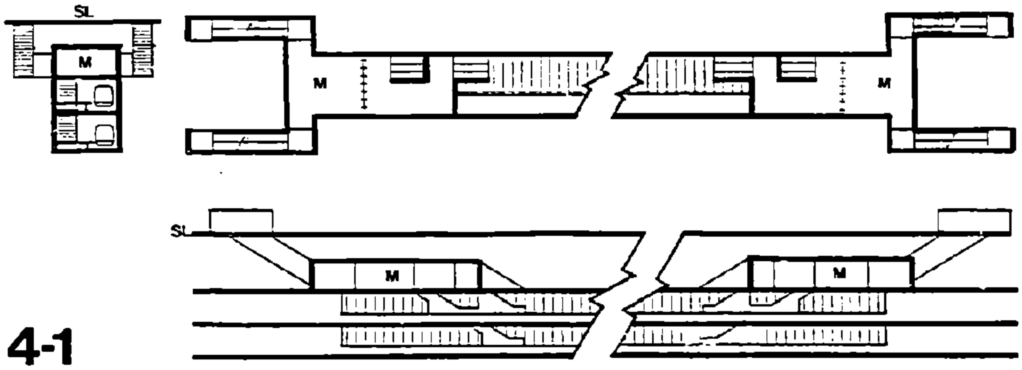
Cut-and-Cover Box Structure
Mezzanine Separate from Trainrooms and Above Platform Level
Stacked Platforms



4

Variation 4-1

This station is an end-loaded variation of Station Type 4. The platform remains the same. Access to the street level and mezzanines is located at both ends of the station.



4-1

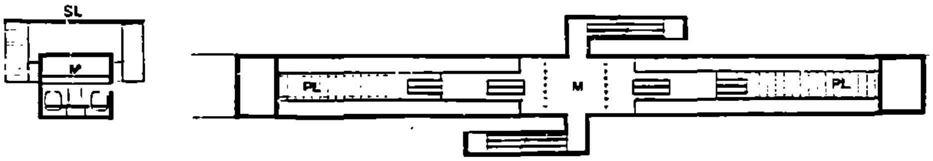
Assets - Street access and distribution are improved due to the greater number and more varied location of ingress and egress points.

Liabilities -

1. Dual mezzanines require double manning, thus increasing operating costs.
2. Increased vertical circulation from the mezzanine to street level adds to the cost of construction.

STATION TYPE 5

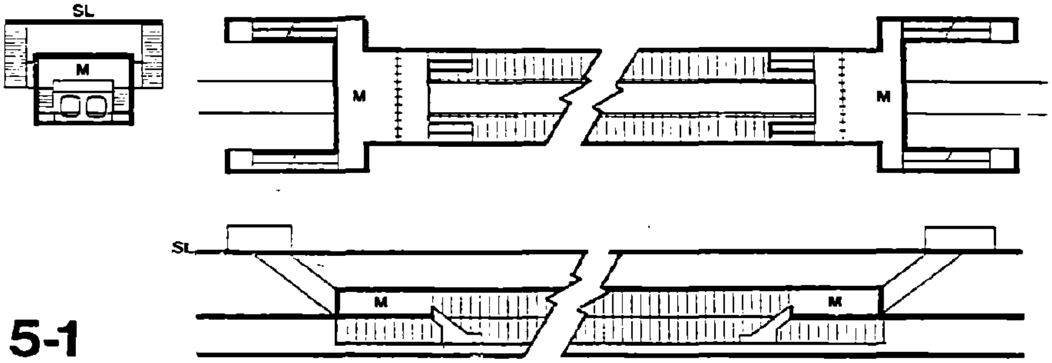
Cut-and-Cover Box Structure
Mezzanine Within Trainroom and Above Platform Level
Center Platform



5

Variation 5-1

Variation 5-1 modifies Station Type 5 through the use of side platforms. The mezzanine is divided into two areas located at either end of the station and within the trainroom.



5-1

Assets -

1. Street access and distribution are improved due to the greater number and more varied location of ingress and egress points.
2. Trainroom surveillance and security are improved due to the doubling of control points and increased visual contact between mezzanine and platform levels.

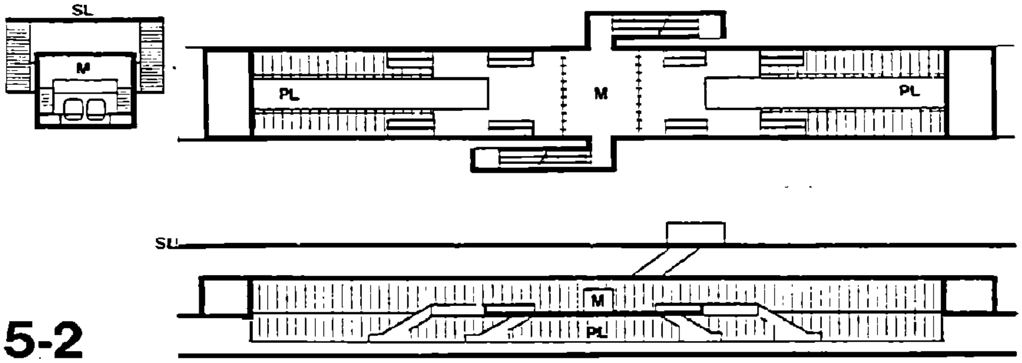
Liabilities -

1. Dual mezzanines require double manning for optimum operation and thus increase operating costs.

2. Increased vertical circulation from mezzanine to street level adds to the cost of construction.

Variation 5-2

This variation has the same loading and mezzanine conditions as Station Type 5, but has side platforms. The mezzanine is center loaded and located within the trainroom. Fare collection is centralized.



5-2

Assets - This design is useful when side platforms are dictated.

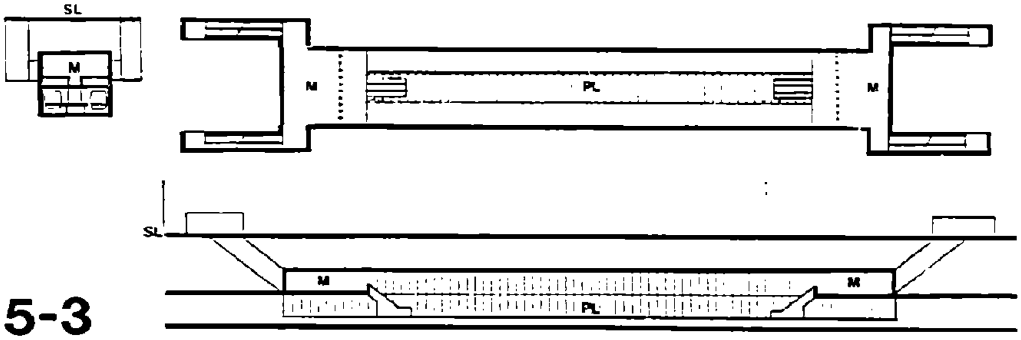
Liabilities -

1. Side platforms makes cross platform circulation more difficult than on a center platform.

2. Increased vertical circulation between mezzanine and platform levels adds to both the cost of construction and the cost of operation.

Variation 5-3

This variation has a center platform like Station Type 5, but has end-loading with the mezzanines and station entrances located beyond the ends of the station.



5-3

Assets -

1. Street level access to the station is improved due to the greater number and more varied location of ingress and egress points.

2. Trainroom surveillance and security are improved due to the doubling of control points and increased visual contact between mezzanine and platform levels.

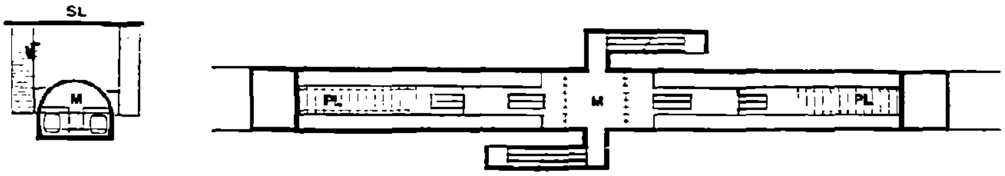
Liabilities -

1. Dual mezzanines require double manning and, therefore, increase operating costs.

2. Increased vertical circulation between mezzanine and street level adds to the cost of construction.

STATION TYPE 6

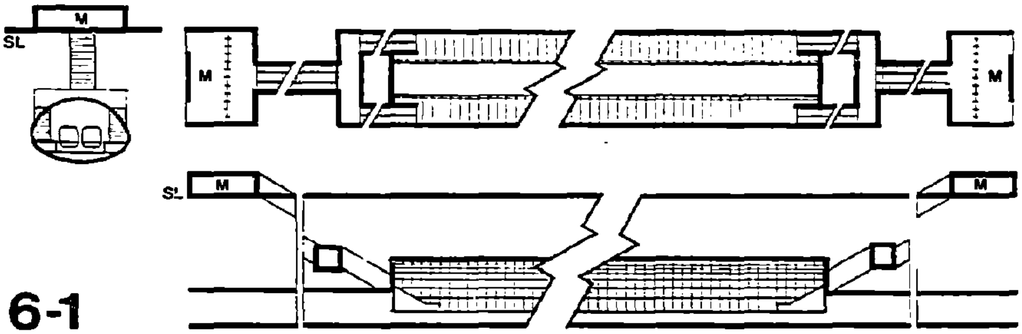
Mined Single Arch
Mezzanine Within Trainroom and Above Platform Level
Center Platform



6

Variation 6-1

This station is similar to Station Type 6 only in excavation technique. Mezzanine areas are separate from the trainroom and located at grade. The organization of the trainroom differs from Station Type 6 by being end-loaded to side platforms.



6-1

Assets -

1. Construction costs are reduced by eliminating the need for either a separate mezzanine excavation or for added trainroom excavation to accommodate a second mezzanine level.

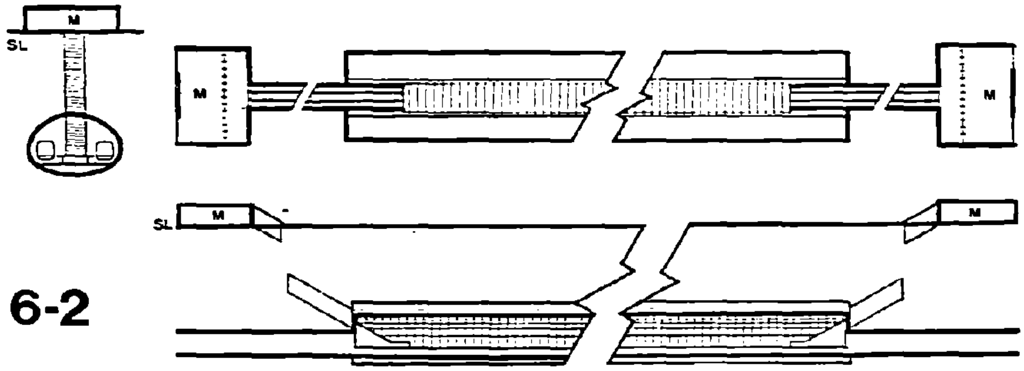
2. Separate mezzanines allow greater freedom of ingress/egress location at street level, resulting in potentially improved street access and distribution.

Liabilities -

1. Location of the mezzanine at street level requires a greater area of frequently expensive street level space.
2. Side platforms necessitate expensive crossover excavation.
3. Dual mezzanines require double manning that increases operating costs.
4. Side platforms make cross platform movement less convenient for the user.
5. Mezzanines outside of trainroom reduce security and trainroom surveillance.

Variation 6-2

This variation resembles 6-1 in excavation technique, mezzanine location, and loading condition. It differs by having a center platform trainroom. Mezzanine areas are separate from the trainroom and located at grade.



6-2

Assets -

1. Construction costs are reduced by eliminating the need for either a separate mezzanine excavation or additional trainroom excavation to accommodate a second mezzanine level.

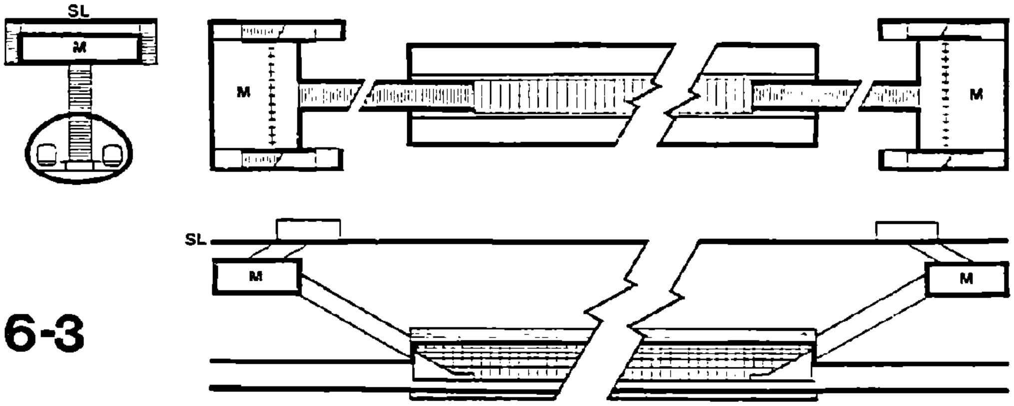
2. The separate mezzanine allows greater flexibility in locating the station entrances at street level, resulting in potentially improved street access and distribution.

Liabilities -

1. Location of the mezzanine at street level requires additional, frequently expensive street level space.
2. Dual mezzanines require double manning, and thus increase operating costs.
3. Separation of the mezzanine from the trainroom reduces the station agent's ability to provide surveillance of that trainroom.

Variation 6-3

This station variation is based on the same excavation technique and platform organization as Station Type 6. The modifications occur in mezzanine location and loading condition. As in 6-1 and 6-2, the mezzanine is separate from the trainroom, and located below grade. The trainroom is end-loaded with a center platform.



6-3

Assets -

1. The separate, below-grade mezzanines allow greater flexibility in the location of ingress/egress points at street level, resulting in improved street access and distribution.

2. Cut-and-Cover excavation of the mezzanine is normally less expensive than mined excavation of the trainroom and of a similar mezzanine volume within the trainroom and above the platform.

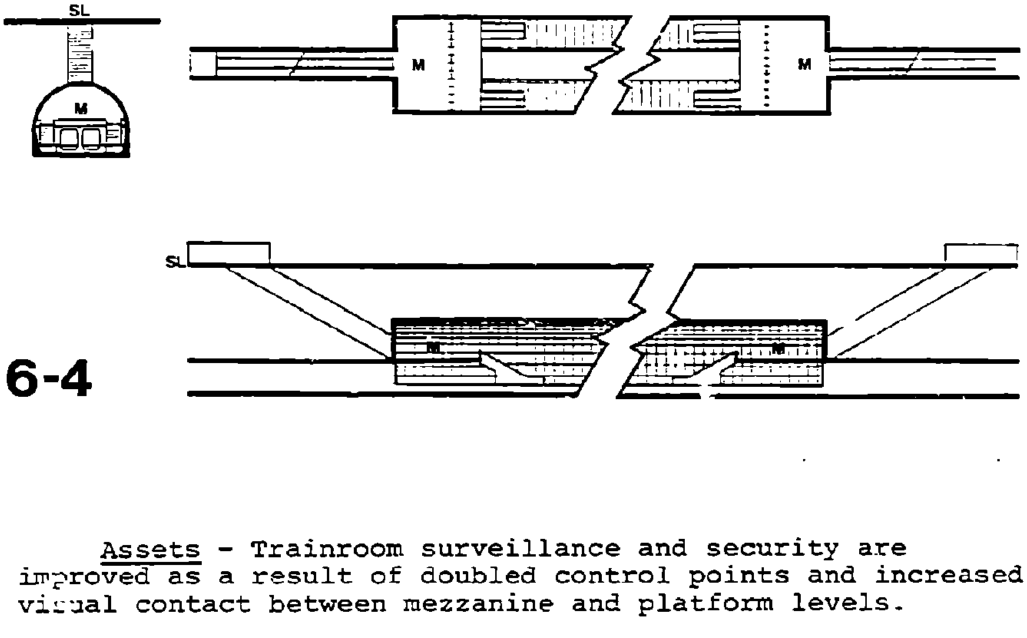
Liabilities -

1. Dual mezzanines require double manning and thus increase operating costs.

2. Separation of the mezzanine from the trainroom reduces surveillance potential and thus reduces the user's sense of personal security in the trainroom.

Variation 6-4

This station is an end-loaded, side platform variation on Station Type 6. Mezzanine areas are located within the trainroom at each end of the station, above platform level.



6-4

Assets - Trainroom surveillance and security are improved as a result of doubled control points and increased visual contact between mezzanine and platform levels.

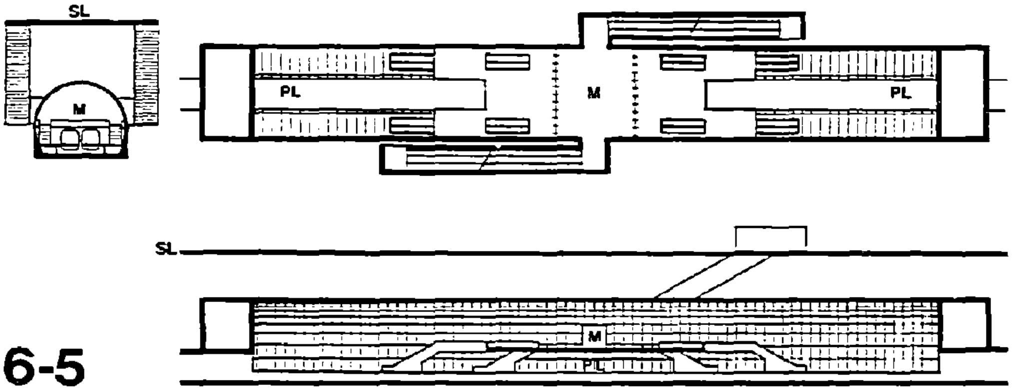
Liabilities -

1. Dual mezzanines require double manning and thus increase operating costs.

2. Side platforms require twice the vertical circulation elements of the center platform variation and also make cross platform movement more difficult.

Variation 6-5

This variation differs from Station Type 6 only in that it has side platforms. The mezzanine is located within the trainroom. The station is center loaded and has centralized fare collection facilities.



6-5

Assets - Platform distribution is improved due to decreased loading at points of vertical circulation from mezzanine to platform.

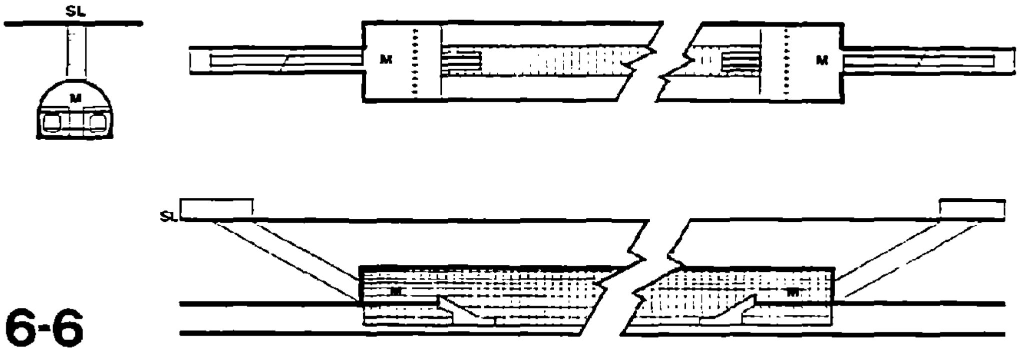
Liabilities -

1. Increased vertical circulation between mezzanine and platform levels adds to both the cost of construction and the cost of operation.

2. Cross platform movement is more difficult in a side platform station than center platform station.

Variation 6-6

This variation has a center platform like Station Type 6, but is end-loaded with vertical access to street level and mezzanines at each end of the trainroom.



6-6

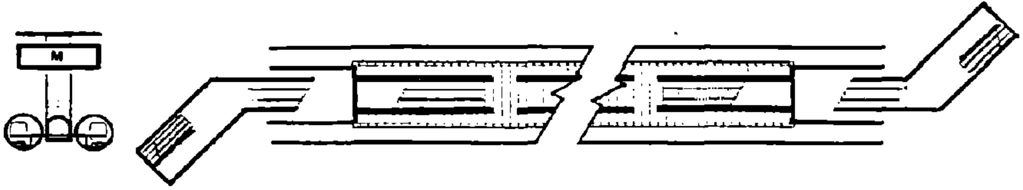
Assets -

1. An end-loading station has better access characteristics at street level than the center loaded station.
2. Trainroom surveillance and security are improved as a result of doubled control points and increased visual contact between mezzanine and platform levels.

Liabilities - Dual mezzanines require double manning and thus increase operating costs.

STATION TYPE 7

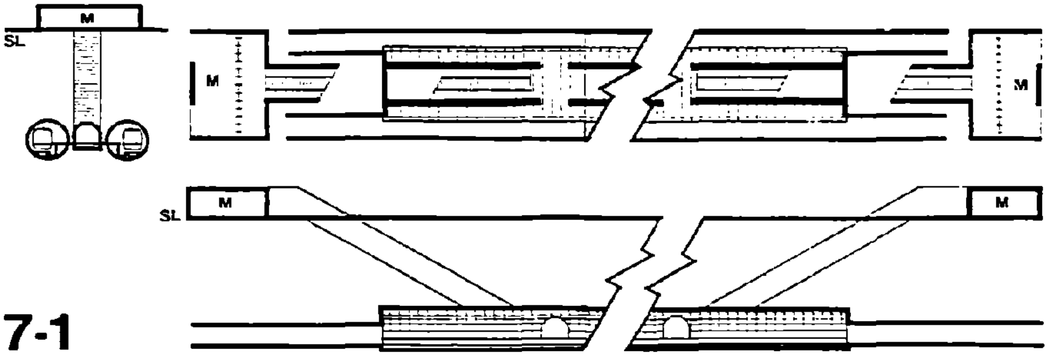
Mined Twin Tubes
Mezzanine Separate From Trainrooms and Above Platform Level
Center Platform and Concourse



7

Variation 7-1

7-1 differs from Station Type 7 only in mezzanine location. The mezzanine is located at grade and separate from the trainroom loading; the platform and concourse remain the same.



7-1

Assets -

1. Construction costs are reduced by eliminating the need for separate mezzanine excavation.

2. Street to platform distribution is simplified by eliminating the interruption in vertical travel between the street and platform levels.

Liabilities - Location of the mezzanine at street level requires additional street level space that is frequently very expensive.

Appendix B
TRANSIT AUTHORITIES VISITED

Listed below are the transit authorities visited by the Study Team and the representatives of the authorities who authorized or made provisions for the on-site investigations. The short title or popular name of the transit system is given first, with the address shown under it. The acronym for the transit authority is given in parentheses. Mr. Andre J. Jacobs, Secretary General, International Union of Public Transport (UITP) introduced by letter the Study Team and study objectives to the European authorities who were visited.

London Underground

London Transport Executive (LTE)
55 Broadway
London, S.W. 1
Mr. D. G. Jobling,
Construction Manager, Works Division

Paris Metro

Regie Autonome des Transports Parisiens (RATP)
53ter Quai des Grands-Augustins
75006 Paris
Mr. Louis Guieysse,
Directeur General Adjoint

Brussels Metro

Societe des Transports Intercommunaux de Bruelles (STIB)
Rue de Stassart 34
1050 Bruxelles
Mr. P. Hustin,
Underground Works Manager

Munich U-Bahn

Stadtwerke Munchen and U-Bahn-Referat (UBR)
Einsteinstrasse 28
8 Munchen 80
Mr. P. Engelbrecht,
Werkdirektor

Stockholm T-Bana

AB Storstockholms Lokaltrafik (SL)
Box 6301 - Tegnergatan 2A
113 81 Stockholm
Mr. Ingemar Backstrom,
General Manager

Metro Milan

Metropolitana Milanese S.P.A. (MM)
Via Vecchio Politecnico, 8-M1
20121 Milano
Dr. Augusto Clerici,
Secretary General

Rome Metropolitana

Societa Tramvie e Ferrovie Elettriche di Roma (STEFER)
Piazzale Ostiense, 6
Roma
Dr. Lorenzo Rosati,
Vice Director

Montreal Metro

Bureau de Transport Metropolitain (BTM)
Communaute Urbaine de Montreal
1701 Rue du Havre
Montreal, Quebec
Mr. Gerard Gascon, Director
and
Mr. G. L. Blain,
Director, Transportation Department
Montreal Urban Community Transit Commission (MUCTC)

Toronto Subway

Toronto Transit Commission (TTC)
1900 Yonge Street
Toronto, Ontario M45 1Z2
Mr. S. T. Lawrence,
Manager of Engineering

Mexico City Metro

Sistema de Transporte Colectivo (STC)
Delicias 67
Mexico City, 1, D.F.
Mr. Antonio Alegria S.,
Subdirector General

CTA

Chicago Transit Authority (CTA)
P.O. Box 3555 - Merchandise Mart Plaza
Chicago, Illinois 60654
Mr. George Krambles,
General Operations Manager

BART

Bay Area Rapid Transit District (BARTD)
300 Madison Street
Oakland, California 94607
Mr. Wilmot R. McCutchen,
Manager, Installations - Engineering

Washington, D.C. Metro

Washington Metropolitan Area Transit Authority (WMATA)
600 5th Street, N.W.
Washington, D.C. 20001
Mr. Warren Quenstedt,
Acting General Manager

Appendix C
RECOMMENDATIONS FOR FURTHER RESEARCH

Several research and development projects are recommended to demonstrate the applicability of the conclusions of the report and to open new avenues for U.S. system developers.

1. Establish a group to review contracting requirements and study the feasibility of implementing the recommendations of the U.S. National Committee on Tunneling Technology.

Standing Subcommittee No. 4, Contracting Practices, of the U.S. National Committee on Tunneling Technology in its 1974 report, Better Contracting for Underground Construction, made 17 specific recommendations to improve U.S. contracting practices. A program to assimilate these findings into U.S. practice should be established. The first step would be to identify those practices which have the best possibility of immediate acceptance, and design specific measures to implement them. A list of priorities should be established for other committee report recommendations and a long-range strategy devised to gain general acceptance of any practice which holds the potential for future construction savings.

Persons with specialities in separate disciplines (legal, construction, design) could spend six months in investigation and assimilation of information and three months preparing the implementation program. Total cost is estimated to be $170,000.

2. Gather U.S. experience in constructing rapid transit stations.

Current practical experience under various underground station conditions is serving as a proving ground to test the value of design approaches, construction techniques, and construction materials. By nearly every measure, full scale projects offer a more dependable test of effectiveness than limited development or demonstration. The effects of scale and size are particularly important in underground work. Extrapolation of information from small to large scale is usually less precise than the designer can be comfortable with. These points were often made by transit officials in cities visited by the Study Team.

Periodic reports on items of major cost significance could be prepared in consistent format and disseminated. This process would identify various design approaches, methods of construction, and steps leading to major or cost-sensitive decisions so that planners and designers are aware of the location of events that could contribute to their current work, specifically, cost efficient practices for underground stations. Transit authorities seldom have funds available to formally report or analyze work in progress for the benefit of the industry at large. The amount of detail that could be obtained would be commensurate with industry needs. An industry-wide R & D program would furnish data to describe the conditions under which a practice was successful, the realistic degree of success, and the pitfalls of its application. The range of applications for major practices at the time they are occurring would offer a perspective for trials at additional sites.

Funding for this project depends on the selected level of effort. The range of initial costs to define a specific program, designate cooperative sources, and establish information collection and dissemination processes would start at approximately $30,000 for information which is already being generated by the industry and needs only to be structured and disseminated. $10,000 per year may sustain the information program.

3. Consolidate and disseminate existing information directly applicable to savings for underground stations.

A multitude of technical studies are now available, in progress, and planned by private groups and government agencies having common interests in underground construction. Most of the studies have something to contribute to the subject of cost effectiveness for stations. Specific information from many technical studies can be consolidated and focused on practical cost-savings applications to serve future station design. This effort does not overlook the importance of continuing research programs but emphasizes immediate applications.

Persons with specialities in soil and rock mechanics, structural engineering, mining and underground construction, construction estimating and data management may spend six months consolidating data into usable report form. A procedure to update data focused on limiting construction costs should be established. The study group should be supported by a technical writer, economist and engineering graphics artist. Total cost may be limited to $110,000.

4. For a U.S. system presently under construction, design and solicit construction bids on a station where slurry walls perform multiple functions.

Findings of this study indicate that under certain design and field conditions, multi-function slurry wall construction can be competitive with conventional construction methods. Experience in other countries strongly indicates that when geotechnical and urban conditions permit, wide application of the slurry wall (or secant pile) technique has cost advantages.

The slurry wall station design would be bid as an alternative design in the contract documents. It could be constructed if it is the low bid or close to the low bid. Complete cost analysis would be conducted on its progress. Recommendations to improve the slurry wall process would be based on this experience.

Most of the cost of design would be absorbed by requirements normally attached to the design process. The surcharge for resolving unfamiliar technical matters should not exceed $50,000. The additional cost for selecting the site, negotiations, coordinating the demonstration through construction, and reporting results may reach $100,000, bringing the overall project to $160,000.

5. For a U.S. system presently under construction, develop a station to be constructed by earth mining.

Investigations for this study demonstrate that transit systems in other countries frequently find it necessary to mine stations in earth. Although more expensive than cut-and-cover construction in most circumstances, mining has benefits, such as increasing location options and lessening disruption of urban activity. By choosing sites with suitable geotechnical conditions, the same benefits would be expected for U.S. construction.

The demonstration project would require a station (preferably a multiple chamber design) to be earth mined, provide alternative designs for bidding, and invite alternative designs by the bidding contractors. The design development would concentrate on earth stabilization prior to mining, prevention of surface settlements, excavation support techniques, and construction safety. Contractor cooperation with analysis of construction progress and cost would be among the items in a competitive contract.

A considerable amount of design investigation will be necessary to insure that contract requirements will be compatible with skills and equipment currently available. The design surcharge, relative to cut-and-cover, could reach $150,000.

6. Study the application and costs of grouting under foundations versus direct underpinning.

Investigations for this study showed that European underground construction utilizes chemical and cement grouting under structures in conjunction with excavation support systems (both mined and open cut) to a considerably greater extent than in U.S. practice. One reason for these practices is the disparity in local customs regarding liability.

The economics of wider use of combining grouting and excavation support to avoid the expense of direct underpinning in the U.S. would be investigated. Urban and geotechnical conditions would be linked to various combinations of grouting and excavation support to demonstrate applicability.

Expertise in geotechnical engineering and in underpinning, grouting and support of excavation techniques is required for this project. Twelve months and $100,000 would be needed to make estimates and consolidate technology into report form.

7. Investigate all underpinning methods useful to transit construction.

Underpinning requires contractors' skill and comprehension of site conditions to achieve success. Techniques and equipment tend to proprietary; therefore, some methods are not detailed for wide dissemination.

Current underpinning technology and a description of skills would be consolidated in report form. Usable technical information could be made widely available. Representative physical site conditions would be detailed and matched with the most cost effective underpinning technique, which would also be detailed. The study would not be limited to conventional physical underpinning but would cover the range of jacked piles, pit piers, grade and needle beams, root piles, slurry walls, pile walls and grouting and combinations of techniques.

This project would require interviews with a number of specialized contractors and construction estimates on various methods under specific representative conditions. Design and construction disciplines would be required for a study duration of ten months at $150,000.

8. Establish optimum platform widths.

The selection of platform width is the critical determinant of station width which, in turn, exerts a major influence on total station cost. The current tendency is to use empirical methods and judgment to select platform width. One of the influential factors on width selection is simplified design and construction by repeated use of this major dimension. Establishing the relationships among platform width, station capacity, and train operation would provide useful guidelines for planners and designers. The objective would be to minimize station width to gain economy without jeopardizing the quality of transit service. Patterns of circulation throughout the station, crowd management plans, patron safety, and walk area obstructions would be necessary considerations.

Project researchers pursuing these objectives should work closely with other groups having interest in industry standards, such as A.P.T.A. in the U.S. and U.I.T.P. in Europe. Expertise in planning, architecture, design, and station and system operations should be included in a study team. A wide variety of station configurations and patron loadings should be analyzed under various methods of train operation. The project may require 12 months and cost $100,000.

9. Investigate station finish materials to facilitate installation, improve maintainability and durability, and accommodate aesthetics.

Underground transit stations may gain public acceptance through an image of cleanliness and visual attractiveness. This study indicates that the cost of finish work is low relative to total station cost. Furthermore, the astute choice of durable, maintainable, and attractive materials and the installation technique does not appreciably increase total cost.

The project would analyze the products which are currently available and their methods of installation to methodically grade their value for durability and maintainability in the operating underground station environment. Materials for acoustical treatment combined with finish materials would be included in the analysis. The objective is to combine materials, installation techniques, and station configurations for the lowest life cycle cost and greatest degree of attractiveness.

Report guidelines would begin with currently successful installations. The study would require 12 months and up to $80,000 to make sufficient contacts with operators, manufacturers and finish contractors and devise guidelines. The need for research or development of new materials is not indicated, but the project would describe areas where manufacturers may provide improvements.

10. Develop temporary decking for improved traffic safety and better economy in materials and installation.

Temporary decking to carry heavy traffic in the urban environment will continue to be a major feature of cut-and-cover construction. It draws attention, and often adverse reaction, from the public.

The current problems with timber and concrete panels are well known. A study would attempt to improve panel installation and grade adjustment techniques. With adequate requirements placed on timber decking for traction and public safety under all weather conditions, a study would determine the conditions for economic use of the timber system. An improved design of the concrete deck panel system and panel handling techniques may become a product of this study.

The study would describe workable combinations of controls on the contractor, materials, deck system designs, procedures for materials and system maintenance, and public safety measures. General improvement of current conditions at decked job sites without major total cost increases is the overall objective. Expertise in structural design, construction materials and handling, traffic engineering and safety and legal involvements would be required to complete a study of approximately 14 months for up to $300,000.

11. Study the methods available to develop coordinated utility and traffic plans.

Two of the most variable and potentially large cost categories in station construction are utility handling and traffic maintenance. Study investigations indicate that the true cost of these items to the contractor is not reflected by bid tabulation prices. The owner experiences costs and progress delays directly attributable to these items but not usually classified as direct costs to traffic and utilities.

A study to contain cost in this area would identify the patterns of successful practice with physical and institutional conditions to which the cost saving patterns may be applied with reasonable confidence. It would define the range of characteristics of transit organizations which are best able to affect interagency cooperation. It would also define the effective combination of responsibilities and liabilities among the many parties affected while dealing with these major categories of station cost.

A study team with expertise in utility and traffic handling, construction estimating, and agency administration may spend six months and $60,000 to organize information and present the useful patterns of practice as construction guidelines. Interviews to include a large cross section of personnel with current experience would supplement the team's background knowledge.

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Report of Inventions

After a diligent review of the work performed under this contract, it was determined that no innovation or invention was discovered.

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