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16. Abstract

This study describes rapid transit system implementation, design, and construction procedures. The relationships and responsibilities of governmental, private, and public groups involved in planning and implementing an urban rapid transit system are discussed. In this report, techniques and processes of cut-and-cover and tunnel construction are discussed in detail. Environmental impacts of this construction as well as safety and insurance aspects are presented. Physical and institutional controls (sensitivities) on construction are identified. Physical controls include such factors as utility density, traffic conditions, maintaining existing structure integrity, ground conditions, and weather. Institutional controls include the project schedule, right-of-way acquisition, material and equipment supply, and labor agreement and productivity.

Three San Francisco Bay Area Rapid Transit (BART) projects and two Washington Metropolitan Area Transit Authority (WMATA) projects are analyzed herein with respect to time schedules, costs, and sensitivity to physical and institutional controls. These data are utilized in developing generalized models of four specific types of underground construction: cut-and-cover station, cut-and-cover line, free-air-driven tunnel, and compressed-air-driven tunnel. The models presented herein are a planning tool for evaluation of the alternative types of underground construction in a transit system with respect to local costs and physical and institutional controls. Possible future tunneling cost-reduction techniques and recommendations for further research are made.

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SYSTEMS ANALYSIS OF RAPID TRANSIT UNDERGROUND CONSTRUCTION

Volume I: Sections 1-5

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DECEMBER 1974

FINAL REPORT

Prepared for
U.S. DEPARTMENT OF TRANSPORTATION
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PREFACE

Rapid transit systems play a vital role in the solution of urban transportation problems and the maintenance or refurbishing of the social and economic fabric of the central business district and the surrounding suburban complex of a metropolitan area. Town, regional, and state planners, many city fathers, engineers, architects, sociologists, and much of the general public are intimately involved with planning and evaluating rapid transit systems; others are concerned with the implementation of these systems. All these efforts receive considerable comment and, often, unfortunate criticism from the news media.

A great deal of the deliberations of implementers of potential or ongoing rapid transit systems is concerned with the imponderables relating to construction cost and time. This is due in part to a lack of historic records and in part to the complexities of the work involved. It was in appreciation of this fact that the U.S. Department of Transportation initiated this study. The authors believe that the products of the study will be of considerable value to all concerned in rapid transit planning and construction.

The generalized models described in this report are a powerful tool for identifying the sensitivities to cost and time of the major elements of rapid transit construction and subsequently in optimizing the implementation process. The studies presented here of the technological, institutional, and environmental factors that lead to recommendations for changed approaches in the implementation process provide major base inputs for optimizing planning and implementation.

The work plan was as follows:

- Determine the constraining factors (controls), in terms of time and cost, on the principal construction events of an underground rapid transit structure in typical downtown city areas. To this end, select and analyze representative, already constructed, underground projects.
- Develop the interaction models to demonstrate the sensitivity of the construction events to variations of the constraining factors. For this objective, undertake a detailed study of the technological, institutional, and environmental factors — all of which are of interest in the planning, design, and construction of rapid transit structures.
- Develop generalized models for determining inefficient areas in the implementation processes. This permits alternative or new contractual procedures that can reduce or eliminate inefficiencies to be identified and evaluated. Output from the detailed studies on the technological, institutional, and environmental aspects can provide a major base for optimizing the planning, design, and construction process.
- Make recommendations for economically beneficial technological changes in the rapid transit structure implementation process. Prepare a plan to demonstrate the effectiveness of such changes.

The cosponsors of the study were:

- The U.S. Department of Transportation, Office of the Assistant Secretary for Systems Development and Technology
- The Urban Mass Transportation Administration, Office of Research and Development, Rail Programs Branch

The contract technical monitor was Dr. George Kovatch of the Transportation Systems Center, Urban Rail Supporting Technology Program.

The authors wish to thank the study cosponsors and the technical monitor for the personal assistance and constructive advice they provided during all phases of the report. In addition, the authors are grateful to the staffs of the Bay Area Rapid Transit District and the Washington Metropolitan Area Transit Authority for the many helpful suggestions they made in the course of reviewing the draft report.

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Section 1

SUMMARY

This study describes rapid transit system implementation, design, and construction procedures. Included in the study is a general discussion of environment and safety. Selected BART and WMATA projects are analyzed, and from the analysis generalized sensitivity models for cut-and-cover and tunnel construction are developed. A summary of the study is given below.

SECTION 2 – TRANSIT SYSTEM IMPLEMENTATION AND ORGANIZATIONS

The general procedural steps needed to plan, engineer, and construct a rapid transit system are delineated in this section. This process is complex and involves many organizations in addition to the technical and construction disciplines.

The three stages of rapid transit system implementation are:

> Stage 1 – "Planning through Financial Approval" describes the development of conceptual and preliminary plans, lists data requirements and sources of planning and technical data, and discusses the preparation of environmental and financial statements.
>
> Stage 2 – "System Engineering Design Through Selection of Contractor" is concerned with the purely technical design of the system. Included are discussions relative to standards and design criteria, design decisions, route location, engineering phases, schedules and cost estimates, and contract bidding procedures.

> Stage 3 — "Construction" discusses construction management and supervision, work certification, cost controls, C.P.M. scheduling, and procurement. Also discussed are change orders and liquidated damages.

Typical owner-engineer-contractor organizations, their functions, and their interrelationships are described and compared. Current cut-and-cover and tunnel construction contracts and specifications are described, and the unsatisfactory areas are identified.

SECTION 3 — CUT-AND-COVER AND TUNNELING TECHNOLOGY

In this section, the specific interactions between the engineering design, the structures, and the resulting construction process are dealt with in detail. The selection of a structural system (i.e., either cut-and-cover or tunnel) and the specifics and methods of construction require a decision-making process that primarily involves the physical controls.

Important fundamental technological decisions made by the owner-engineer and management are discussed, along with the impact of these decisions upon the design and construction of the principal work events. Present-day construction technology applied to each work event for cut-and-cover and for tunnel construction is described, and recent advances in such technology are reviewed with reference to experience gained in some areas of the BART project.

SECTION 4 — ENVIRONMENT, SAFETY, AND INSURANCE

There are two major environmental impacts of underground transit construction.

The first is the effects upon businesses, vehicular and pedestrian traffic, and buildings in the locality of the construction. Most of these effects are detrimental to traffic movements and businesses, but are of short duration. Cut-and-cover construction is more disruptive than tunneling.

Long-term effects of the implemented transit system appear to improve both surface traffic and business. The second environmental impact is that of the construction site conditions as they affect the safety and health of the workmen and the general public integrity of the property fronting the construction.

An investigation was made of the BART and WMATA construction approaches to environmental impact, insurance policies, and safety programs. The insurance policies of both systems are summarized, the pros and cons of system-wide insurance are discussed, and the safety programs and the methods of monitoring and reporting on their effectiveness are described.

Accident claim settlement records were obtained for the three BART study projects, and the claim payments were plotted against the construction schedules to attempt to identify construction work operations with the property damage, bodily injury (third-party), and workmen's compensation settlement claims. In this respect, the data available were not in sufficient detail to permit anything but the following two general conclusions: (1) that cut-and-cover construction is more costly than tunnel in terms of public liability; (2) that tunnel construction is more hazardous to the workmen than is cut-and-cover.

SECTION 5 — SENSITIVITY PARAMETERS

The construction cost of rapid transit systems is extremely sensitive to the physical environment and the institutional framework in which each project is carried out. The cost and time sensitivities were derived from four study projects described in Section 6 and from cost estimates made for the generalized models outlined in Section 7. The development of these sections proceeded concurrently with this section.

Physical control sensitivities are the measures of the physical constraints on the performance of a work event in a project. Institutional control sensitivities are the measures of the contractual or financial constraints upon the time/cost of construction as a whole.

The physical controls were identified as:

- Utility density
- Traffic conditions
- Existing structures
- Ground conditions
- Architectural requirements
- Weather
- Fill demand

The interaction of each one of these upon the work events is discussed.

The institutional controls were identified as items within four main groups, the groups being defined according to their influence upon the time/cost of the system as a whole. These groups were:

- Schedule time
- Direct cost
- Productivity of labor
- Financial

The several specific institutional controls in each group are described, and trend influences upon the project are discussed.

SECTION 6 – STUDY PROJECTS

To obtain base data for system modeling of rapid transit station and line sections in urban areas, representative contracts of two rapid transit systems were studied – the San Francisco Bay Area Rapid Transit System (BART) and the Washington, D.C., Metropolitan Area Transit Authority System (WMATA). The following criteria were used in selecting the contracts from the two systems:

- Station structures in cut-and-cover, line structures in cut-and-cover, and tunnels had to reflect current planning, design, and construction concepts.
- Structures had to represent the planning, design, and construction approaches of two separate systems in different geographic areas.
- The structures had to be located in areas where average downtown conditions prevailed; i.e., the ground conditions and the patronage, traffic, utilities, and existing structures had to be average.
- Historic records of the structures had to be available to define the bid and actual costs and to provide schedules and construction reports, including accident and insurance reports.

Bay Area Rapid Transit (BART)

The Bay Area Rapid Transit (San Francisco Bay, California) was considered eminently suitable for the purposes of this study, and the three BART projects chosen generally complied with the above criteria. The three projects were: a cut-and-cover station structure with short sections of three contiguous line tunnels, a cut-and-cover line structure, and a tunnel line structure.

Washington Metropolitan Area Transit Authority (WMATA)

As examples of rapid transit construction with different ownership in another geographic area, two projects were chosen from the Washington, D.C., Metropolitan Area Transit Authority System. Since the system is at a fairly early stage of completion, both the choice of project and the availability of historic data were limited, but useful data were still obtainable to provide the desired basis of comparison with the

BART projects. The projects were: a cut-and-cover station and line structure, and a soft-ground tunneled line section within a project containing a considerable length of rock tunneling.

The data obtained for the five selected projects included:

- The drawings and specifications
- The bid records, including the itemized and total costs quoted by the bidders
- The construction cost (including change orders)
- The construction schedules in the form of the contractors' bar graphs
- Insurance procedures, settlement claims, accident records and reports, and medical facilities for the compressed air project

Work Approach

Determination of Work Events. A project consists of a number of construction work events which were determined for each of the projects studied. Representative project costs were obtained by applying prices to the work events using the average of the three low contractor bids. The costs for all the projects were then escalated to account for inflation to January 1974.

Construction Schedules. The project contract documents for both systems required the work to be started and completed by specified dates. For general progress monitoring, the contractors developed the major work-event bar charts that are reproduced in this report.

The schedules identified two classes of delay: those that could be attributed to the owner-engineer; and those that were the responsibility of the contractor.

Determination of Physical Controls. These factors apply direct constraints on the construction and consequently affect the cost/time elements of the work events. From a study of the selected projects, the control factors were identified and evaluated. Influence coefficent matrices were compiled to determined the quantification to be made of each control with respect to the work events and the sensitivities.

Determination of Institutional Controls. Generally, these controls relate to owner-generated contractual and financial policies and have a direct influence upon the cost/time of the project as a whole. Also included under this heading is productivity, as affected by geographic locality, and actions by regulatory authorities that have a bearing on project implementation.

The contract documents of both the BART and WMATA systems provided most of this basic information. The institutional controls for the two systems were different. Controls were identical for the projects within each system, but the data available did not permit a meaningful quantitative comparative evaluation of the systems to be made.

Through the use of the contract information, supplemented by discussions with managerial and other personnel involved, the institution controls were identified. This provided the basis for evaluating the controls for the generalized models.

Study Project Sensitivities

The sensitivity of the study projects to the physical controls is demonstrated in matrix form, with the starting point in the matrix being the tabulation of the escalated costs per system foot for each work event. Each control element's influence is then applied to the work events, and by subtraction, a basic cost for each event is developed. The total of the individual basic costs is the cost of the project if the control influences did not exist. The results are discussed.

The study approach in this matter included interviews with the construction managers, resident engineers, and cost engineers concerned with the work, and in some cases, the contractor's staff. In addition, historical records, when available, were studied. Comparison of the cost of the same work events in different projects was enlightening and helped to confirm the data.

The physical control influence values adopted must necessarily be based on experience and judgment rather than a precise analysis; therefore they should be used for trend indications rather than for actual cost derivations.

The methodology of evaluating the influences of institutional controls for the two transit systems studied was established in the same manner as was the methodology for the physical controls. Input was obtained from schedulers, cost engineers, purchasing managers, construction managers, engineers, and also from a study of contract documents. Owing to the system-wide nature of these influences, it was not meaningful to apply them to the individual study projects which were already constructed. A separate study was undertaken to establish the background material for evaluating the sensitivities relating to environmental requirements, safety, and insurance programs. The results of the study project sensitivities formed the springboard for developing the sensitivities for the generalized models.

Model Matrices and Structures

With the physical and institutional controls defined, model parameters and the format for the model matrices were determined. It was desirable that these model structures should be applicable to transit systems that might be implemented anywhere in the United States and should not merely reflect those used in BART and WMATA. However, since the models are based on the five study projects outlined, they must be used with caution. Use of the models for other projects will most certainly require adjustment or revision.

After review of the study projects and other projects in the BART system for which data were available, four model structures were developed.

SECTION 7 – GENERALIZED TUNNEL MODELS

Generalized models were developed for four kinds of underground structures that are typical of rapid transit construction in downtown areas. The structures chosen are applicable to transit systems that might be implemented anywhere in the United States. They are:

- A cut-and-cover station 838 ft long, with a 700-ft-long center platform and a booking mezzanine
- A cut-and-cover line structure 3225 ft long. This structure has single boxes (to interface with a center-platform station on one end) that merge into a twin box by means of a transition structure
- A twin tunnel trackway 3000 ft long constructed in soft ground by means of a movable shield and with segmented steel liners. A workshaft is constructed at one end of the tunnel and work is completed in free air
- A similar tunnel trackway constructed under compressed air

Work Events

The work events selected for the generalized models are the same as those defined for the study projects with one additional work event – muck disposal. Muck disposal cost and environmental aspects are becoming a problem of concern and are therefore included as a model work event.

Basic Costs

Work event costs for use in the model were developed from similar structure costs in the BART and WMATA systems. Study project unit costs were selected from unit prices of the three lowest contract bids for each type of structure.

Controls

Physical and institutional controls were determined from a study of appropriate structures in both the BART and WMATA systems. Representative averages were developed for each control.

Description of Model

The models accept as input the basic measures of project size, descriptions of the site-related physical characteristics of the project, and the nature of the relationship (the institutional controls) between the owner, engineer, and project contractor. Costs can be adjusted for geographically related productivity of labor and for time-dependent escalation of labor and material costs.

These models were designed to be operable with a minimum of specification related to technical design, site characteristics, and institutional arrangements. The models, therefore, show only trend effects of the tunneling technology and of the physical and institutional controls, rather than the actual specific costs.

The generalized models consist of three major parts:

- The first part gives the basic costs of each work event in the project for average physical conditions and optimal institutional controls.
- The second part deals with the effects on project cost of physical controls.

- The third part deals with the effect on project cost of institutional controls.

The generalized tunnel models can be used for:

- Studying the relative cost of segments in an urban rapid transit system.
- Determining the "soft" areas of tunneling in which changes in technology or institutional controls influence project costs and/or reduce the time for construction.
- Evaluating new tunneling technologies to determine savings in overall project costs and construction time.

When the models are used, new costs for work events and sensitivities must be developed for each application to reflect the difference in time and place of a future system under consideration. The costs presented in this report relate only to the BART and WMATA study projects. Guidance is provided on the approaches that may be used to generate applicable work event costs. The generalized tunnel models are computerized for rapid analysis of possible construction situations.

Generalized Model Sensitivities

In the determination of sensitivities for the four selected models, the structures represented two standardized cut-and-cover structures (i.e., one station and one line structure), one tunnel structure constructed in free air, and one in compressed air. Average physical conditions and optimal institutional conditions were assumed. The physical control sensitivities (influence coefficients) were adjusted to an average basis, and to evaluate limiting conditions, maximum and minimum high and low values of each physical sensitivity were established. In addition, the study considered changes of work scope related to maximum and minimum values of the three important peripheral physical controls: utility density, traffic conditions, and existing structures.

The institutional control sensitivities were evaluated by developing added costs for the factors involved when optimum institutional controls are absent and either a moderate or a major influence is present because of nonoptimal institutional controls.

The institutional cost controls include several factors within the following:

- Contractors' fixed costs with respect to schedule changes
- Direct costs related to owner-purchased materials and insurance
- Labor costs with respect to productivity
- Interest rates in connection with owner-related financing

The evaluation of the institutional sensitivities required an in-depth analysis of historical costs and other data, including construction, insurance safety statistics, and insurance records.

The sensitivity values for the physical and institutional controls were applied against the base costs of the structures to provide a comparative evaluation of the control effects upon the cost of construction. The cost effect of conservative changes in technology are presented for each work event.

Model Utilization

Guidelines are given for using the models to determine relative costs of segments of a rapid transit system. Required essential elements include preliminary design drawings and quantities for the proposed system, together with the estimate cost units for the work events. Items discussed are escalation, bidding climate and productivity, and estimation of basic cost data. The selection of model "values" for individual physical controls and the evaluation of institutional controls are described.

SECTION 8 – POTENTIAL COST REDUCTION TECHNIQUES AND NEW TECHNOLOGIES

As the study developed, certain areas of possible future improvement emerged. These include changes in the O-E-C relationship, improvements to existing technology, and new cut-and-cover and tunneling techniques.

Improved Contractual Procedures

Possible approaches to changing the owner-engineer-contractor relationship to improve the soft areas are explored. Suggestions are presented for contractural changes, more comprehensive site investigation, and more thorough site testings. The potential benefits are outlined and include: improved information to the contractor during bidding; more opportunities for the contractor to develop innovative construction approaches; the optimization of institutional factors; and suggestions for publishing the potential benefits for those concerned with implementing rapid transit construction.

The implementing procedures and organizations for both the BART and WMATA systems formed the basis for the delineation and discussion of these approaches. The contract documents for the study projects as well as others in the BART system, together with material generated from the sensitivity studies, identified some of the present deficiencies in defining the construction work and the method of obtaining bids.

Areas of possible changes to the contractual procedures were fairly easy to identify since this subject has been an ongoing topic of interest for years among engineers and contractors concerned with heavy underground construction. However, owing to the legal and technical complexities involved in the numerous and varied contracts peculiar to rapid transit construction, and to the fact that the owner is a public agency, it was not possible to recommend significant changes in the contractual procedures. Rather, emphasis has been placed on improving the information process during the bidding stage and on implementing sound institutional planning.

Improved and New Technology

Probable impacts are discussed, in terms of cost and time, of modifying existing cut-and-cover station concepts in order to orient the construction concept towards more tunneling construction. This would establish a climate for the use of more innovative tunneling techniques, more flexible and economical station planning, and less impact on the street environment – all of which would diminish the time/cost of the construction.

An examination of the sensitivities and the construction work event costs in the study projects (Sections 5 and 6) indicates the areas of work that would benefit from improved technological approaches. The improvements suggested have all been demonstrated as efficient techniques, both in the BART system and in other systems in the United States and overseas.

To determine the areas that would benefit substantially from new technological approaches, a study was made of the construction cost and schedules in the five study projects and other similar projects. The sensitivity material that was being developed concurrently was also studied. The following facts were readily apparent: the cut-and-cover station construction met utilities, traffic, and existing structures "head on," and its construction was expensive and time-consuming;

tunneling lengths were too short to allow optimization of construction methods; and construction schedules might be improved considerably through a design that permits the tunnel to be constructed ahead of the stations.

The approaches suggested for modifying the existing concepts of station planning and the construction techniques of breaking into previously driven trackway tunnels are not particularly new. In some form or another they have been used for a number of years in England, Russia, and Canada. Some of the techniques leading to the adoption of continuous tunneling, however, have not been used or fully developed and will require research and development.

Research and development on functional station concepts and promising tunneling methods and equipment are recommended, as is the establishment of geology/soils information banks where rapid transit systems are being planned.

SECTION 9 — CONCLUSIONS AND RECOMMENDATIONS

On the basis of this study, conclusions were formulated in four major areas.

Conclusions

System Modeling. Definition of work events, physical controls, and institutional controls and analyses of time and cost relationships in the five rapid transit study projects served as the basis for the development of system models. With the input of local parameter values, the models should be adaptable to projects anywhere in the United States and should function as a guide in evaluating alternative underground transit segments. The model sensitivities to variations in controls yield a cost index for comparison of alternative construction methods in downtown urban areas. In the use of the model, local costs must be developed and revisions in some sensitivities may be required.

Contracts. There are numerous instances in which project construction can be optimized through better owner-engineer-contractor arrangements.

Two principal elements of this optimization are: 1) consultant contractor input in the design stage; and 2) the acquisition of more detail on utilities, traffic, underpinning, and soil conditions prior to contractor bidding, thus avoiding some of the contractor's cost markups for unknowns.

Technical Considerations. In many busy downtown areas where traffic is heavy and utilities are usually dense, station design can be oriented towards tunnel design and can thus effect savings in time and cost. Such designs would permit the construction of track tunnels in more economic lengths.

Environment (Impacts and Safety). Underground construction has both short-term and long-term environmental impacts upon the traffic and businesses in the streets contiguous to the construction. In order to evaluate the effects, systematic gathering and processing of historical data are required.

Investigation of accident and injury records for the BART and WMATA study projects revealed that safety can be appreciably improved by comprehensive and complete accident reporting. Only through this approach can the accident record be improved in the future. Safer construction processes will yield savings to the public (owner of the system) and to the contractors through lower insurance costs and reduction of time or schedule delays.

Recommendations

Investigations in this study indicated that research and development should result in improved construction efficiency and reduced cost of implementing future rapid transit systems. The subjects of the recommendations for the research presented are:

- Optimizing rapid transit station design
- Lining systems for optimizing the tunneling process
- Geology/soils information bank
- Environmental impacts of underground construction
- Improved accident reporting and statistical analyses

Section 2

TRANSIT SYSTEM IMPLEMENTATION AND ORGANIZATIONS

INTRODUCTION

There are several reasons why the planning, design, and construction of a rapid transit system is highly complex:

- The total system must be designed, at least to a preliminary engineering stage, before bonding can be obtained and any construction can be started.
- Preliminary planning involves discussions, tacit agreements, and input from many third-party authorities or agencies.
- Transit routes generally cut across two or more metropolitan regions, the number of which can substantially increase the number of authorities to be satisfied and interests to be served.
- Engineering decisions are complicated by the poor ground conditions normally encountered in metropolitan areas, by important existing structures, by complex utilities, by heavy traffic, and by the restricted working areas that may exist along most of the transit route. All this must be taken into account when selecting the various types of structures.
- The actual construction, particularly in the downtown areas, is beset with the same difficulties mentioned above (i.e., poor ground conditions, existing structures, complex utilities, heavy traffic, restricted working areas). In addition, below the street surface, the actual location and type of utilities and existing structure foundations are often undetermined until actually exposed, and the ground, during actual excavation, can behave in a dramatically different manner from what may be predicted from the soils investigations.

The many steps and procedures that lead to the completion of an underground portion of a rapid transit system are the subject of the discussion that follows. As can be seen in the Implementation Flow Diagrams (Figures 2-1, 2-2, and 2-3), there are three major subdivisions, or stages. The completion of the work in each stage represents a major advance in the implementation of the system, and upon the completion of a stage, decisions as to how the next stage should proceed must be made.

STAGE 1 OF IMPLEMENTATION – PLANNING THROUGH FINANCIAL APPROVAL (See Figure 2-1.)

Introduction

The idea of rapid transit in an urban area usually takes root when it becomes apparent that the central business district and the contiguous areas are being gradually strangled by surface motor traffic. The consequent constriction of business development and the ever-increasing travel time and cost to the traveling public cause municipal authorities and businessmen to seriously consider the possibility of public rapid transit. To advance such a consideration, a Transit Authority is formed and empowered to plan, implement, and operate a rapid transit system for the public benefit. It is outside the scope of this study to discuss the actual formation and mandate of such an authority, except to describe what it may accomplish during the planning and implementation stage.

Conceptual Plans

Conceptual plans consisting of possible route and station locations must be developed. This task requires knowledge of the existing and probable future travel patterns within the urban area likely to be served by the proposed system. Some engineering input may be required to define the possible structural and geometric configurations (underground, aerial, and surface) along the route, and to establish the location of yards and shops, for storage, repair, and maintenance of the transit vehicle when the latter is not in service.

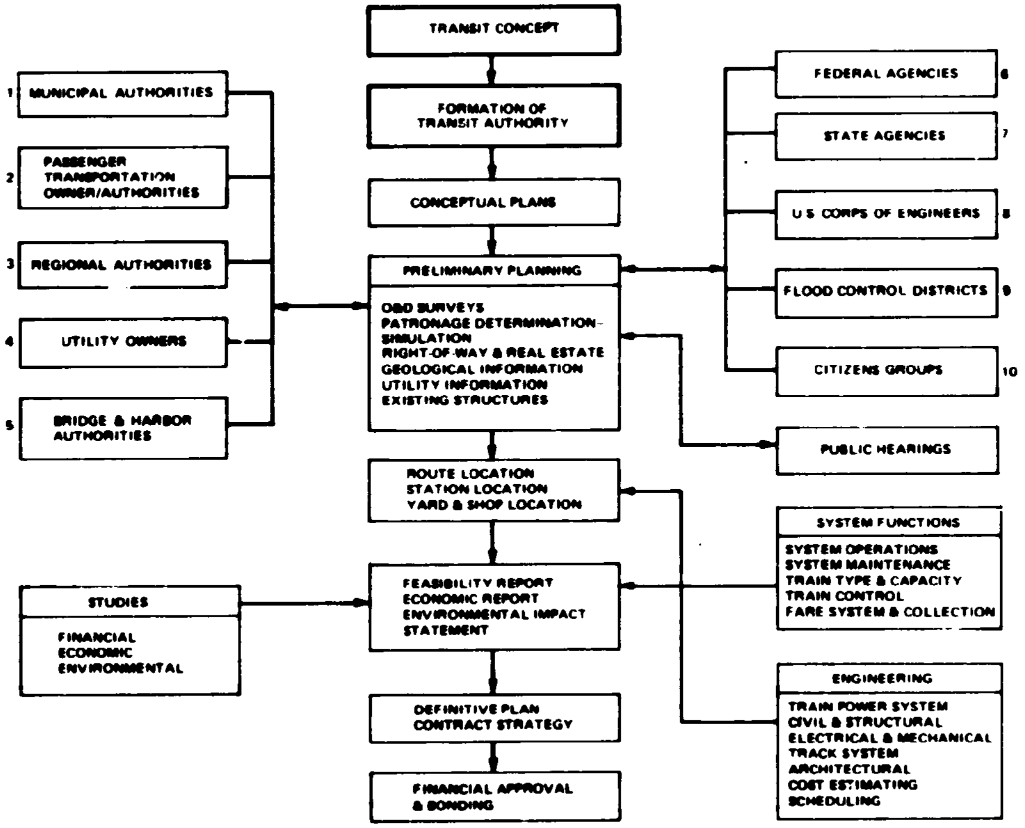


Figure 2-1. Rapid Transit System Implementation Flow Diagram, Stage 1 – Planning Through Financial Approval

Preliminary Layout Plans

A preliminary layout plan (or plans) can be developed after the resolution of a number of varied tasks which test and modify the conceptual plans.

Origin and destination (O&D) studies form one important basis for determining both the general transit route and the location and capacity of the stations. The studies must be conducted in sufficient depth over a fully representative time and season period to define existing and desired trips by the traveling public. The data obtained are processed to yield minimum, average, and peak volumes on a daily, weekly, and seasonal basis and must be reiterative to ensure compatability with vehicle systems, operations, route, and station location studies normally being done concurrently.

Most, or all, of the organizations designated "1" through "9" in Figure 2-1 provide technical or other inputs into the preliminary plan, and many hold approval authority with respect to the project facilities. Town planning and rapid transit planning are integrated processes (one being largely dependent upon the other), and at all stages of firming up the preliminary route planning, close attention must be given to the present and future concepts of the municipal planning departments and to the wishes of the public. Input from these sources largely determines the future growth and travel patterns, modifies the conclusions from the O&D studies, and influences the location of stations and station entrances.

The impact of the rapid transit system upon the traffic patterns and the consequent modification of streets, sidewalks, and parking facilities must all be considered in the preliminary plan. The determination of station parking lots and the effect on the surrounding neighborhood, street, and traffic patterns must also be included.

Data Sources

Passenger Transportation Owners and Authorities. The rapid transit system will strongly affect existing passenger transportation systems and will probably produce drastic changes in the existing system's operating patterns. At the same time, the rapid transit system may be very dependent upon surface passenger transportation for patronage at many of the stations. Stations may be advantageously planned to accept feeder transportation vehicles in restricted areas and to operate in conjunction with an integrated fare system.

Regional Authorities. These are responsible for both planning and operating functions. With respect to planning, an authority may integrate or modify local municipality plans to conform with the aims of established overall regional development plans. Planning functions include land use, zoning, and various modes of transportation, such as rail, road, and airports. Operating functions include owner trunk utility services, which serve the common needs of the municipalities, such as water supply, sewage disposal, roads, and passenger transportation.

Utility Owners. As discussed elsewhere in the study, conflict with the utilities along the construction route results in a major cost item in the construction of the underground portions of a rapid transit system. During the firming up of the preliminary planning, consideration must be given to the probable impacts on cost and schedule arising from such conflicts. To this end, the initial preliminary plans are "tested" against the major existing utilities. Discussions with the various owners determine possible policies, provide an indication of the cost of undertaking the utilities modifications necessary to the construction work, and reveal any plans the owners may have for upgrading their utilities in the future.

Of a somewhat different nature are the discussions with the Electric Power Authorities in connection with the supply of the traction power. In these discussions, power supply characteristics, rate structure, and location of substations are of particular interest during the preliminary planning.

Bridge and Harbor Authorities. Where the transit route is planned to cross under or over rivers or harbors, common interests must be discussed and conflicts resolved with the Bridge and Harbor Authorities. For example, the transit system may reduce bridge patronage, or the transit structure may need to be incorporated with that of an existing bridge. Where the transit route is planned to cross navigable water, agreement in principle must be obtained with the harbor or river authorities on matters of right-of-way and installation procedures.

Federal Agencies. The relationships of federal agencies with rapid transit systems are important in the areas of funding (of research and development programs) and system financing. Federal agencies also serve as clearing houses for information relative to technical developments in many aspects of rapid transit system implementation.

State Agencies. State agencies may be important in the areas of funding, regulating, and operations. During the planning stage, the State Highway Agency may be involved closely in the resolution of common right-of-way and structural facilities. Funding and regulating agencies will be consulted on the possible contributions and controls that may affect the preliminary design.

U.S. Corps of Engineers and Flood Control Districts. Both the U.S. Corps of Engineers and Flood Control Districts may affect the engineering aspects of the preliminary design.

Citizens Groups. The generation of citizen support is essential to the success of a program of this kind. This effort should start with the program planning and carry through into the program design. It should include meetings with local, representative groups in the private domain, such as taxpayer associations, Chambers of Commerce, neighborhood groups, environmental organizations, etc. These groups should be kept informed about planning and engineering considerations and given the opportunity to make comments and recommendations. The normal public hearings cannot take the place of this effort, since by the time these hearings are held, the project and decisions are presented virtually on a "take-it-or-leave-it" basis: and the public is likely to be resentful if it has not been allowed to participate in the decisions.

Gathering Data for Route Location

To translate the conceptual plans into a preliminary route plan, right-of-way studies and related real estate investigations must be undertaken, and technical data relating to soils and geology, utilities, and existing buildings along the proposed routes need to be gathered.

Right-of-Way and Real Estate Studies and Investigations. The base data required for this task are obtained from street maps, topographical plots, and property maps. Where property acquisitions appear to be a requirement, information on valuations and title is required. If street and topographical maps do not contain enough detail, they may have to be supplemented by an instrument survey.

Soils and Geological Information. Soils engineers and foundation contractors who maintain soils and geological records or who have construction experience within the areas of the proposed transit route are valuable sources of information. Geological survey maps furnish a generalized picture of subsurface conditions. The Department of Highways, Bridges, and Harbors may be able to provide valuable data concerning records and experience in the areas of interest.

With the information from the above sources, preliminary route soils/geological profiles can be produced in the areas where there is sufficient definition. In areas for which information is inadequate and in which it appears that the transit structures will be underground or aerial, a geological boring program is necessary to produce route soils/geological profiles of reasonable dependability. Acquisition of these data is often critical to the design and should be started early to avoid delay and to make preliminary cost estimates more accurate.

Utilities Information. Most utility owners have the location of their utilities indicated on street or right-of-way plans. For the development of the preliminary plan, this information, when supplemented by discussion with the owners, should be sufficient to determine the magnitude of conflict, if any, between the proposed transit structures and the other structures.

Existing Structures. The underground sections of the transit structure may require excavations close to or under buildings, bridges, and other structures. The choice of transit structure and the selection of the general construction approach are dependent upon the likely sensitivity of the existing structures to disturbance from such excavation, as well as on the soil conditions encountered. As the design structure and the general construction approach are major design and cost factors, effort must be expended during the preliminary planning to obtain details on foundations and loads and to acquire structural information on all major structures that are likely to influence or be influenced by the proposed transit work.

Sources of such information will be the owners of these structures and the associated architects, engineers, and contractors. Building officials may provide an additional source. Subsurface testing should be undertaken where reasonably clean-cut and consistent information is not available.

Defining the Route Location

Following the analysis of the origin and destination studies, and after the discussions with the municipal, regional, and other authorities and agencies, the anchor points of the system, the stations, can be located. The task requires the interleaving and cooperative efforts of several disciplines. The structural and architectural engineers, drawing on inputs from soils and geological engineers and using utilities and existing structure information, can establish station layout and structure type and approximate track elevation. With these data, and with the input from the right-of-way and real estate studies, the civil (route location) engineer can define the horizontal and vertical alignment of the track. This work includes locating and laying out yards, maintenance shops, and other facilities, and requires close consultation with the operations, maintenance, and traction power engineers.

When the geometrics of the running tracks and yards have been established, the structural and civil engineers work together to define the structural type for the line structures, i.e., cut-and-cover, tunnel, at grade, and aerial. (These determinations, together with specific route alignment and station locations, are sensitive to environmental, social, and economic considerations, and citizen participation at this point may avert future conflicts.) Subsequently, right-of-way limits and property acquisition requirements can be defined.

Feasibility and Economic Study

The development of the preliminary alignment plans permits the feasibility and economic study to proceed in three steps. The first defines the system technically and specifies its cost; the second defines the system operationally; and the third covers the financial, economic, and environmental aspects.

Engineering. The civil/structural, electrical/mechanical, architectural, and track engineering groups provide definition of the transit system structures, trackage, all supporting facilities, right-of-way, and property acquisition requirements.

Operations. The train type and capacity are determined from the predicted passenger loading and the kind of service to be provided. Following this determination, the train control and power system, the fare system, and the collection system can be defined.

Financial and Environmental Statements. At this point, cost estimates of all the elements required to construct and equip the system can be undertaken (subject to refinements as engineering design progresses), and schedules for the implementation of the work are concurrently drawn up. Financial and economic statements are written using data produced by engineering and an environmental statement is produced from data obtained from financial, legal, economic, sociological, and other institutional sources.

Definitive Plan Document and Financial Approval

The definitive plan document is in the form of a composite report combining the conclusions of the feasibility and economic study with other material. The main sections of the report typically may include:

- The engineering plan
- The operations plan
- The financial plan
- The financial impact statement
- The economic analysis
- The systems benefits statement

Obtaining legal approvals and making the necessary financing arrangements for implementing a rapid transit system are normally the responsibility of the Transit Authority. The Definitive Plan Document will form the basis of this task. (Financing is deemed to be outside the scope of this study.)

STAGE 2 OF IMPLEMENTATION — SYSTEM ENGINEERING DESIGN THROUGH SELECTION OF CONTRACTOR (See Figure 2-2.)

Standards and Design Criteria

The following discussion on establishing standards and design criteria for a rapid transit system is restricted to those that pertain directly to the design of structure and related features. The establishment of an appropriate set of final standards and design criteria of high quality, and their approval by all tiers of regulatory authorities at an early stage of the engineering design, is of great importance. It helps produce structures of good functional quality, a track and train system with the desired performance and function, and the standardization of components (which greatly facilitates component maintenance or replacement, and substantially reduces component cost).

Standards and design criteria should include the following subjects:

- Vehicle-related data — standard vehicles, design velocity and characteristics, and clearances
- Track geometrics — horizontal and vertical geometrics, superelevations and transitions, turnouts and switches, and crossovers
- Trackwork — all trackwork components and related hardware
- Civil — drainage, utilities, soils, and stabilization
- Fare collection

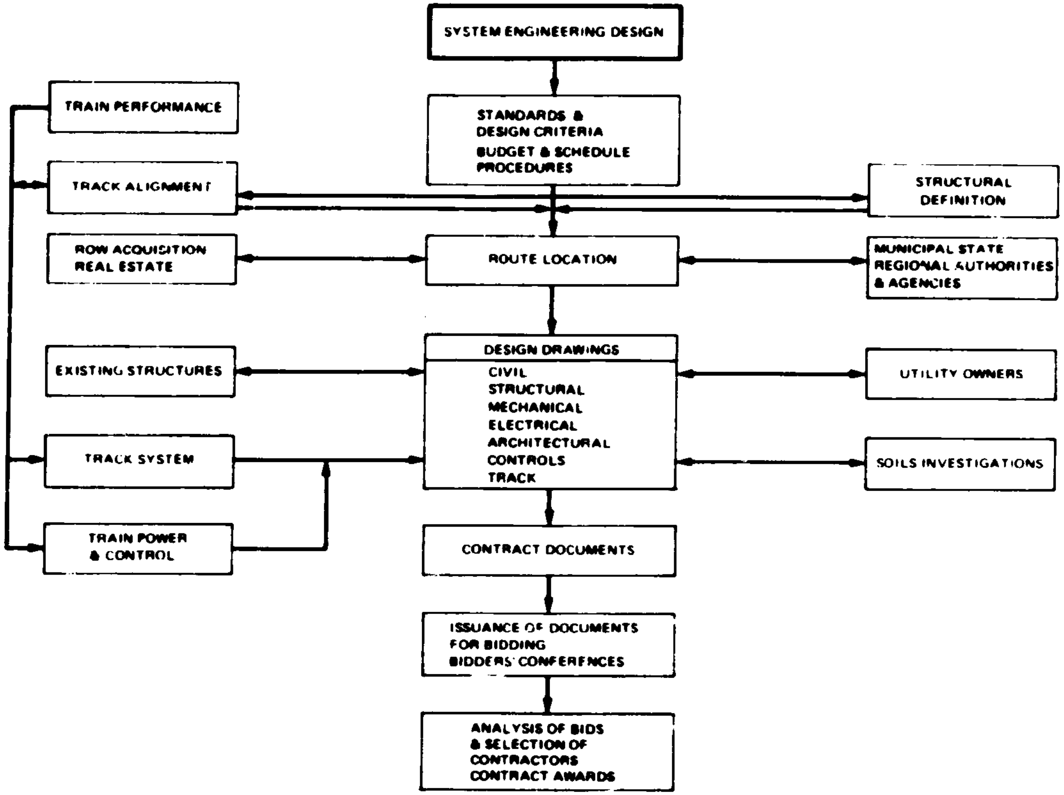


Figure 2-2. Rapid Transit System Implementation Flow Diagram,
Stage 2 – Engineering Design Through Appointment of Contractors

- Structural — trains and other loadings, and design criteria for concrete and steel cut-and-cover and tunnel structures
- Stations and underground facilities — space requirements, entrances and exits, and safety provisions
- Yards and shops — layout criteria, building requirements, and equipment
- Electrical — power electrification, auxiliary systems, and lighting
- Mechanical — ventilation, air conditioning, and fire protection
- Train control and communications — operations description, equipment functions, and design requirements
- Architectural standards — finishes, acoustics, concessions, signing, and graphics

Policy Design Decisions

In an organization where the engineering design is undertaken by an engineering consultant, decisions must be made concerning the degree of owner-engineer responsibility for the temporary works normally designed by the contractor. It is incumbent upon the owner-engineer to assume some responsibility for the safety of third-party persons and property during the construction and/or early stages of operation, and criteria and design policies must be established for the construction items listed below.

- Support of excavation — This is essential not only for safety, but for avoiding settlements outside the construction area which might result in damage to utilities, other street facilities, and existing structures.

  Criteria in this regard may require the contractor to design the excavation supports for specified loading and installation techniques. Monitoring of the system during and after installation for stress and deflection may be specified. Requirements for monitoring ground settlements and movements of buildings adjacent to the excavations may be included.

- Groundwater control — The avoidance of ground settlements and the safety of the excavation, or tunnel, often depend on the control of groundwater. With respect to dewatering, the owner-engineer may specify the acceptable methods, the required results, and the monitoring of the dewatering system. In addition, where grounds sensitive to dewatering settlements are encountered, specifications may require dewatering to be performed inside the excavation, with the groundwater being maintained outside, if necessary, by recharging to an established elevation.
- Support of existing structures — The owner-engineer may design and specify the requirements for the support of a structure, or (where the contractor is responsible for the design) he may specify the design criteria to be used, together with typical acceptable support systems.
- Tunnel construction — In addition to the dewatering requirements discussed above, groundwater control by compressed air may be specified as mandatory in certain lengths of a tunnel. Acceptable methods of supporting the ground during excavation by use of shields, breast boards, grouting, etc., are also usually specified, as are monitoring of the movements of the ground and buildings over and alongside the tunnel construction.
- Value engineering — Normally a "value engineering" clause is inserted in the specifications, which permits the contractor to submit alternative methods of work for acceptance by the engineers.

Route Location

As can be seen from Figure 2-1, finalizing of the route and station location depends on the parallel supplementary operations of finalizing track alignment and refining the route structural definition. Coordination with and inputs from the various municipal, state, and regional authorities, agencies, and citizen groups are also required.

Velocity data from the train performance profile are required for the final determination of the track alignment. The structure definitions are refined further as detailed engineering and architectural design develops.

As the route location design progresses, the necessary agreements with the various authorities and agencies can be concluded, and those with the utility owners can proceed.

Other final route-location-dependent tasks that can proceed concurrently are right-of-way and real estate agreements and acquisitions, supplementary soil investigations, and utilities modification and coordination.

Civil, Structural, Architectural, and Supplementary Engineering

The final output from this group is the contract documents for the general construction contracts of the system. The various required efforts are described below.

Existing Utilities. Along most of the transit route, the construction is likely to be in conflict with the underground and surface utilities, and in the downtown sections where utilities are the most dense, the conflict will be the greatest. As the engineering of the transit structures proceeds, the detailed conflicts are revealed, and studies and solutions for relocation, support in place, and restoration are worked out with the various owners concerned. Close cooperative effort is required from individual owners so that time and sequence schedules and agreements can be established and the work properly coordinated with construction schedules.

The transit engineering group may lead in directing this effort and promoting final agreements between the utilities owners and the Transit Authority.

Traffic and Street Modifications. The engineering group works with the municipal or other authorities responsible for traffic control and streets to determine the ways in which transit structure installation will conflict with vehicular and pedestrian traffic. Proposed structure design and installation are examined with the authorities during the design stages; specifications and agreements for maintaining (by decking excavations), directing, and rerouting traffic during construction operations are formulated; and the final determination is made of station entrance locations, street and sidewalk modifications, and street and sidewalk restorations.

Geological and Soils Investigation. At an early stage in the structure design, a detailed soils investigation must be undertaken. The scope of this investigation depends upon the amount of information available from the preliminary design effort, the sensitivity of the transit structures to ground characteristics, and the apparent type and variability of the ground to be encountered. A scope of requirements is established for the contractor or engineer specialists who will perform the work.

Existing Structures. The information gathered during the planning stage may have to be supplemented, and field investigations may be needed. Concurrent with the structure design, decisions are made on the type of existing structure support system required during construction.

Subsidiary Items. Included in this category are track system and hardware, train power and control, right-of-way and real estate acquisition, and the establishing of primary survey controls. All these items are dependent on the structural and civil design.

Schedules, Specifications, and Cost Estimates

As the various civil, structural, and architectural tasks discussed above proceed, the determination of construction contract packages and schedules is undertaken, technical specifications for the construction contract packages are written, and cost estimates are made.

Contracts and Bids

Contract documents comprise the construction design drawings; the technical specifications, including the bid quantities; specific legal and standard documents; and other material, all of which are used to assist the contractor in making his bid.

The charter of the Rapid Transit Authority usually requires public bidding for the implementation of rapid transit procurement and construction. Accordingly, the bid documents are advertised in national (and sometimes foreign) construction publications and other publications. Prequalification requirements, which include a statement of financial ability and experience from the potential bidders, are furnished in the documents and are indicated in advertising.

An important part of the bidding process is the bid conference, which is held 3 or 4 weeks before the due bid date. At this conference, the bidders get together with engineers for a question-and-answer session. Questions from bidders may relate to the scope of the work, the schedule, and the technical performance requirements. The answers to these questions may point to the need for design changes or other changes that would permit more economical construction procedures. In such cases, addenda specifying the desired changes to be made in the bid documents are issued to all the bidders.

The bids are normally opened in the order received, in public, by the Transit Authority. They are then analyzed by the engineers for compliance with the technical and legal specification requirements, and a bid comparison document is prepared. The sheet indicates the comparative cost, bid item by bid item, of the bids received and also includes the engineer's estimate.

Where applicable, the comparative differences and any deviations from the specifications are commented on and summarized. A recommendation of the acceptance or rejection of a bid is made to the Transit Authority. Normally, the bid accepted is the lowest price, conforming bid.

Before the acceptance is formalized, a preaward conference is customary, wherein the selected bidder, the engineers, and perhaps a representative of the Transit Authority meet to verify that there is mutual understanding on all points of the contract. Following the preaward conference, the bid documents of the selected bidder are made to conform to all addenda and agreed-upon modifications. The contract is then formalized on these documents by affixing signatures for the Transit Authority and the contractor.

STAGE 3 OF IMPLEMENTATION – CONSTRUCTION (See Figure 2-3.)

Construction Management and Supervision

Figure 2-3 indicates the two main organizations required in the construction process – management and construction. In the diagram, a third organization – start of operations – is shown. Although this is the corresponding end product of the operations engineering, and is not strictly part of the construction process, it has been included to give some idea of the procedures required to start system operations. Construction management may be involved if system testing reveals the need for modification or corrective work.

Construction supervision is concerned with the implementation of construction specifications and ensures compliance, quality of the workmanship, appropriateness of construction methods, and quality of construction materials incorporated in the permanent work.

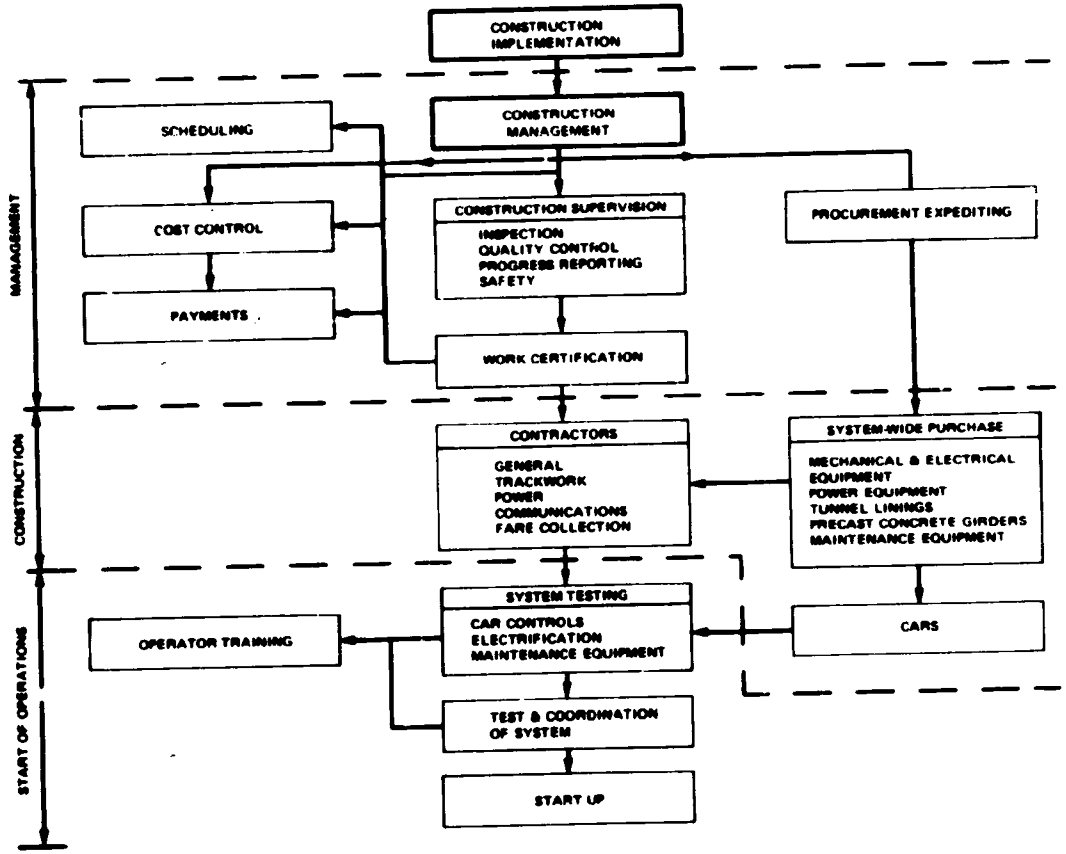


Figure 2-3. Rapid Transit System Implementation Flow Diagram
Stage 3 – Management-Construction-Start of Operations

Construction management, whether it be an arm of the owner-engineer or of a separate contractor, performs the general functions of administration; supervision; cost and schedule control; contractor payments; and procuring, inspecting during manufacturing, and expediting permanent materials and equipment.

Surveying. Surveying includes the following: establishing primary survey controls; checking the contractor-established line and level of the structure, both at the end of the job and at intervals during the construction; checking finished structure tolerances; and monitoring shoring deflection and stresses, ground settlements, water table elevations during construction, and other items to ensure compliance with the specifications and to guard against any activity of the contractor that might generate third-party liability.

Routine Checking of Construction Items. The following items require routine checking:

- Grades and embankments — fill conformance with specifications for material and compaction
- Reinforced concrete work — form work for accuracy, rigidity, bracing, and cleanliness
- Subgrade preparation — compaction, level, and moisture content
- Reinforcement — clearances, bar sizes, and numbers and laps; fixing and support
- Concrete during placing — slump, compaction, curing, and concrete strength test cylinders
- Tunnel construction — support of face, air pressures, segment placing and bolting, concrete forms, reinforcement and placing, grouting, and caulking

Progress Reporting. There are two types of progress reports: inspectors' daily reports covering work accomplished, problems encountered, and problems anticipated; and monthly reports, which are based on the daily site reports, and on other site reports. The monthly reports usually consist of charts that show the scheduled versus the actual progress and cost of the construction. The charts are supported by narrative identifying actual or potential trouble areas and forecasting activities expected to start or be completed during the subsequent reporting period.

Quality Control. This activity includes the sampling and testing of concrete, soils, sewers, water pipes, and other utilities for conformance to pressure and other specified requirements.

Safety. The construction specifications and other documents, such as the federal OSHA standards and various state and municipal safety directives, require the contractor to adopt safe work procedures and methods. Construction management is responsible for ensuring that such requirements are met. This responsibility is often discharged by a safety engineer assigned to the project (assisted by the construction inspectors) who establishes with the construction superintendent and/or his safety engineer delegate at the outset of the work the program for implementing the contract safety requirements. Such programs should include a review of the proposed construction methods and techniques, the procedure for inspection and reporting, and the procedure for changing undesirable or unsafe practices or situations. Periodic meetings should be arranged with everyone concerned with the safety aspects of the project to review the results of the various established procedures and to modify and improve them as necessary.

Work Certification

To obtain progress payments, the contractor submits documentation describing the work completed during the reporting period. This is done at periodic intervals (usually every month). Construction supervision verifies and certifies the accuracy of the documentation by on-the-site measurements and inspection.

Cost Control

At the outset of the project, cost control is instituted for each contract package. In the case of an owner-engineer-contractor organization, the cost control system is established by the budgets & estimates engineer during the engineering design stage. This engineer proportions the contract estimated cost into anticipated monthly progress payments, based on the projected schedule of work. In like manner, monthly payments for items related to the contract, such as construction supervision, system-wide purchases, and right-of-way acquisition are forecast, though the latter item will be excluded from the construction cost control.

The anticipated monthly cost payments are displayed on a schedule, and cumulative curves are drawn. During construction, the actual monthly progress payments and the actual cumulative-cost curves are compared with the anticipated costs.

Payments to the various contractors, suppliers, and other parties are made on the basis of certified work invoices. The certification is made by contract supervision, procurement, or other sections responsible for purchases.

Change Orders

During the course of the construction, the owner-engineer may occasionally require changes to the work that modify the contract drawings and specifications. If the changes affect the cost and time aspects of the contract, the following procedure is needed:

- A change notice indicating the nature of the intended work changes is issued to the contractor for his signature of acceptance .
- The contractor then sends the engineer an itemized breakdown of costs for the changed work, including labor, materials, equipment, overhead, etc. The contractor also indicates any adjustments needed in contract time for completing the work .
- The engineer analyzes the information from the contractor and then issues a change order that describes the changed work and defines the cost and time aspects. This change order becomes the contractor's authority to proceed with the work. If the changes are major, the engineer probably must obtain prior approval from the owner before issuing the change order.

Note that three parties are involved in the above procedure, and appreciable time may elapse from the initiating of the change notice to the issuing of the final change order. During this period, completion of work in the area contiguous to the changed work may be affected, thus tending to escalate the cost-time effect of the changed work item.

It is generally more expensive to change contract drawings and specifications during the course of the construction than before the signing of the contract. Therefore, an attempt should be made to keep changes during construction to a minimum whenever possible. Adequate precontract planning and monitoring of owner-controllable items will sharply reduce the number of (and can even eliminate) change orders arising from items such as interfaces with other contracts, possession of work areas and rights-of-way, agreements and contracts with utility owners and local agencies, adequate subsurface investigations, etc. Other causes for change orders are somewhat more difficult to avoid. They include traffic conditions, existing utilities, existing structures, and ground conditions, any of which may prove during construction to be physically different from what was anticipated by the contract documents.

The impact of change orders on the time and cost aspects of the contract will be reduced by adequate planning by the owner-engineer. This planning includes:

- Spelling out in the contract documents procedures for the processing and costing of change orders
- A contract manager's organization that can efficiently analyze the contractor's input to change orders
- An owner organization that is responsible for and experienced in all matters related to the approval of the proposed change orders. The processing of change orders involving the interests of both public agencies or authorities and private building owners requires considerable effort from the owner if expensive delays to the construction are to be avoided. As time is one of the most important aspects, the change order process should be streamlined as far as possible, and within each organization of the three parties involved, there should be one individual responsible for all matters pertaining to change orders

Scheduling

The specifications normally require the contractor to produce a critical path method (C. P. M.) progress schedule. This type of schedule is a graphic network diagram indicating the sequence of performance work activities planned by the contractor as well as activities by others connected with the contract. The network indicates the interdependence of the activities, their planned start and finish dates, as well as other information related to the construction schedule. The critical path(s) connect those work items whose start and finish dates must be maintained in order to complete the work on the scheduled date.

A computer printout provides similar information in numerical form, which permits a ready update when events such as change orders or delays in delivery of materials occur to affect the scheduled performance of an activity.

The C. P. M. schedule and printout is updated at regular intervals by the contractor and allows management to identify potential trouble spots in the scheduled performance of both the contractor and others (indicating owner-responsible deliverables) related to the contract.

In order that the contract progress be monitored effectively, "countdown" information on all items that are, or likely to become, critical is usually issued regularly to all concerned. For example, activities whose delivery dates by others are critical to the contractor's schedule are highlighted as the delivery dates approach.

Additional scheduling efforts are required of construction management (1) where construction work interfaces with other contracts and with agencies, municipalities, utility owners, and others, and (2) where system-wide procurement items are involved.

Liquidated Damages

When all or any part of the construction work is not completed on the dates stipulated in the contract documents, the contractor may become liable for the cost incurred by the owner on account of the delays. The liability for these costs, or liquidated damages, is usually dependent upon two things:

- It must be established that the owner incurs actual financial loss through late delivery of the work.
- The late delivery must be due to circumstances under the control of the contractor. Examples of such contractor's responsibility might include a labor and supervisory force inadequate in experience and numbers, poor job planning, insufficient lead time for supply of materials, etc.

The contract documents for both the BART and WMATA study projects contained provisions for liquidated damages. As noted in Section 6, although the BART projects (which were the only ones completed at the time of the study) were finished after the contract scheduled date, the causes for the delays were judged to be outside the contractor's control, and liquidated damages were therefore not solicited.

Procurement

The purchasing group is responsible for purchasing, expediting, and ensuring the quality control of items that are to be furnished to the contractor by the owner. Such items are likely to include mechanical and electrical equipment, power and train control equipment, tunnel lining, precast concrete, girders, maintenance equipment, and the train cars. The solicitation of quotations is made with technical specifications and drawings produced by the engineering design section.

IMPLEMENTING ORGANIZATIONS

Introduction

The efforts of three entities are required to implement a rapid transit structures system: the owner (i. e., the Transit Authority), the engineer, and the contractor. Each has a distinct objective and a well-defined set of responsibilities. In addition, each shares in the common goal of implementing the transit system structures. The process of achieving this goal requires close cooperation, understanding, and communication among the three parties.

In the discussion that follows, the objectives and principal functions of each party will be defined, the organizations that are normally formed to achieve the objectives will be examined, the inefficient areas will be described, and suggestions will be made for organizational or procedural changes to optimize the implementation process.

Objectives and Responsibilities of the Owner. The owner's objective is to have the transit system structures completed (with the necessary trackwork, electrical power, train control, and auxiliary equipment installed) within schedule and budget and ready for the start-up of system operations.

The owner is responsible for defining the system requirements with respect to the concept and extent of the proposed operation, including the quality of service and structure to be provided and the schedule for implementation. He is also responsible for the financing of the system and the payment of all services, materials, and equipment necessary to complete the system.

Objectives and Responsibilites of the Engineer. The engineer's chief objective is to translate the owner-defined system requirements into drawings, specifications, and contract documents in order to permit construction and procurement contracts to be awarded. He may have a further objective of ensuring compliance with the requirements of contract documents, including those of quality and schedule. This objective is achieved by supervising the performance of the contracts.

The engineer has the responsibility of exercising the full extent of his professional expertise and judgment, supplemented if necessary by that of specialized consultants, to translate the owner's requirements into economic and efficient engineering solutions.

Objectives and Responsibilities of the Contractor. The contractor's objective is to implement the construction, as defined by the engineering contract documents, drawings, and specifications, in the form of finished system structures, with all the appurtenant equipment installed.

The contractor is responsible for performing all his work within the true meaning of the contract documents and schedule, and within the contracted price, adjusted as appropriate for required changes in the work during the course of the contract.

Owner-Engineer-Contractor (O-E-C) Organization

In the overall organization established to implement a rapid transit system, the activities and responsibilities of the organizations of the three principal parties involved are closely interrelated. As a rule, the internal organization of each of the parties is traditional (and in relation to the functions they have to perform, they do not change), but the lines of responsibility assigned to each party vary markedly according to the objectives of the overall organization.

There are basically two possible organizations for implementing a rapid transit system. Each has the same end product objective, and each has advantages and disadvantages according to the requirements for the transit system. The two organizations may be defined as:

- Owner-Engineer-Contractor (O-E-C)
- Owner-Turn-Key-Contractor (O-T-K-C)

It should be noted that while the O-T-K-C is not presently an accepted organization for public works projects in the United States, it is worthy of discussion.

In an O-E-C organization, each of the three parties tends to act as a separate entity. In performing within such an organization, the engineer interfaces closely with the owner during the definitive design and final engineering design. During the construction, the engineer interfaces with both the contractor and owner. As an agent of the owner, the engineer supervises and coordinates the work of the various contractors and reports to the owner on the progress of the work.

The interfacing relationships are shown diagrammatically in Figure 2-4 and are typical of these established for BART.

A typical organization for an owner (Transit Authority) during the implementation of the system is indicated in Figure 2-5 and comprises two principal sections: the administrative and the technical.

The elements of the administrative section are the directive, managerial, legal, secretarial, financial, etc., and their functions are self-evident. Policy-making is of course an important function of the administrative group.

The technical section, steered by the director of development and operations, undertakes to define the system with respect to the concept and extent of the proposed operation, including the quality of service and structure to be provided and a schedule for implementation. In this work, the director of development is assisted by the various engineering groups reporting to him and by the board of consultants.

The engineer's organization during the planning-through-financial-approval and the systems-engineering-design stages (see Figure 2-1 and 2-2) usually consists of the groups indicated in Figure 2-2, without the labor relations and procurement groups, which relate to the construction-phase contractor. The construction manager is not organized as a function, but construction expertise is available to ensure that all definitive planning takes ease and economy of construction into account.

The functions of most of the groups indicated are obvious, but the following activities are worthy of note:

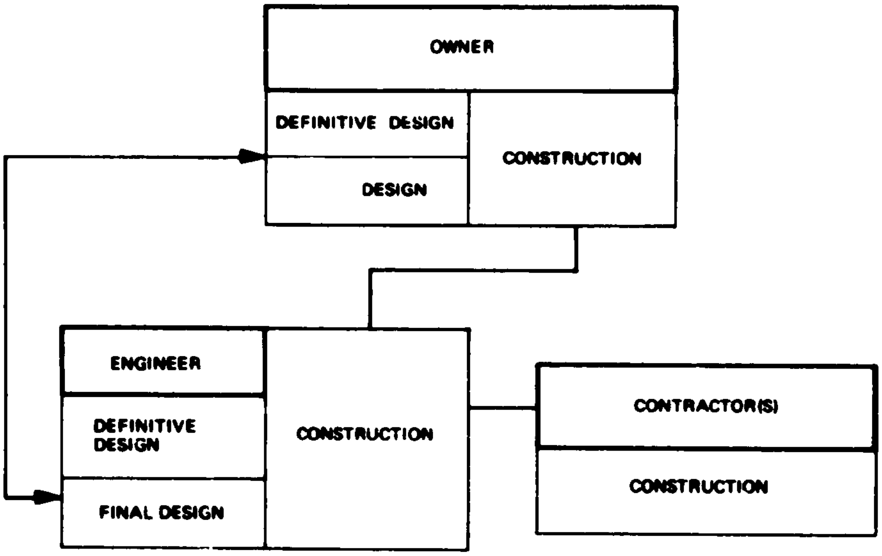


Figure 2-4. Owner-Engineer-Contractor Interface Flow Chart

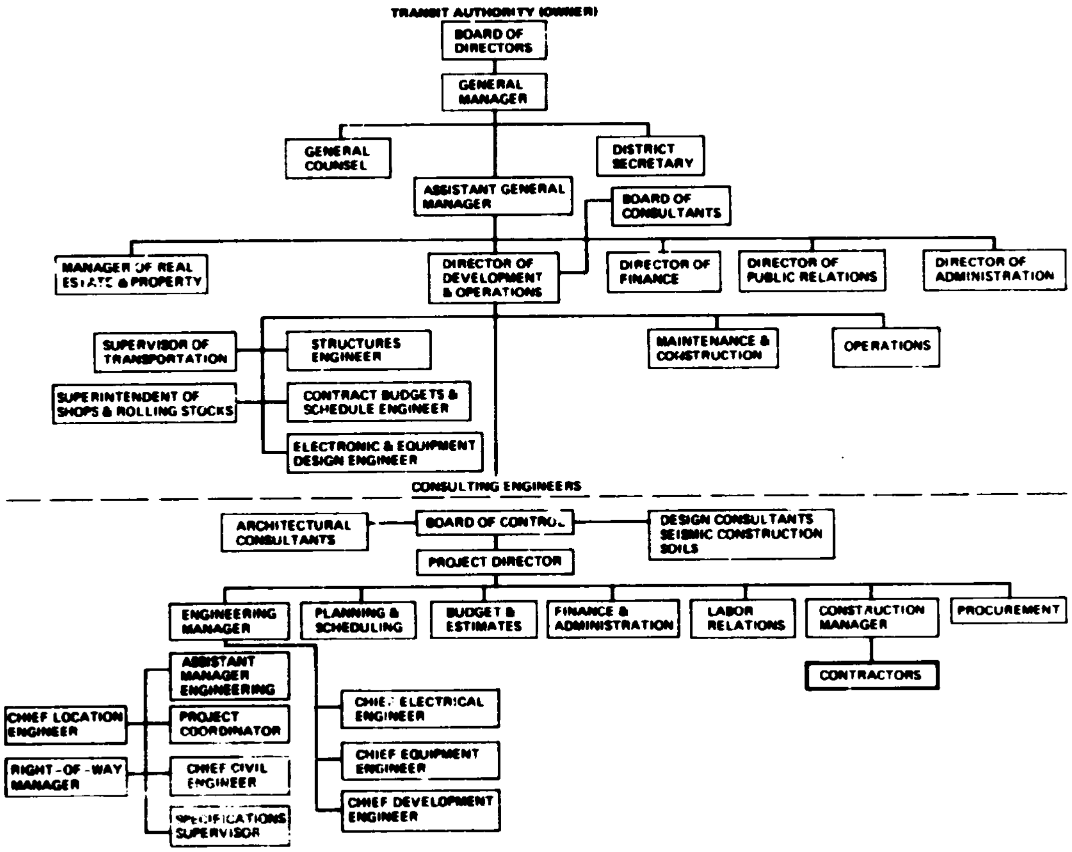


Figure 2-5. Owner-Engineer-Contractor Lines of Responsibility

- The architectural consultants and the design consultants both perform similar functions to help set up system-wide standards. The former are concerned with stations and station entrances, spatial layout, station and exposed structure finishes, landscaping, and traffic flow patterns for access to the stations within stations. The latter are concerned with design criteria, construction systems, and contract packaging.
- The chief location engineer and right-of-way manager work closely with the owner's manager of real estate and property, who is responsible for the actual purchase and leases of property.
- The other groups interface, as needed, with the corresponding related groups in the owner's organization.

For the construction management, the engineer's organization comprises the main elements indicated in Figure 2-6. These elements are responsible for the performance of all the construction-related functions indicated in Figure 2-3.

The construction manager has responsibility for the individual construction projects and for system-wide functions. Such system-wide functions involve the manager of labor relations, whose concern is the working of the system-wide labor agreement, and the safety engineer, whose responsibility is the implementation of the safety program.

For the administration of the numerous construction projects involved, the construction management organization is arranged to cover geographical areas. Each area is the responsibility of an area manager and consists of a number of projects contiguous to each other. The individual construction projects are supervised by resident engineers. Both the construction manager and the area manager have an administrative staff (not indicated in the diagram).

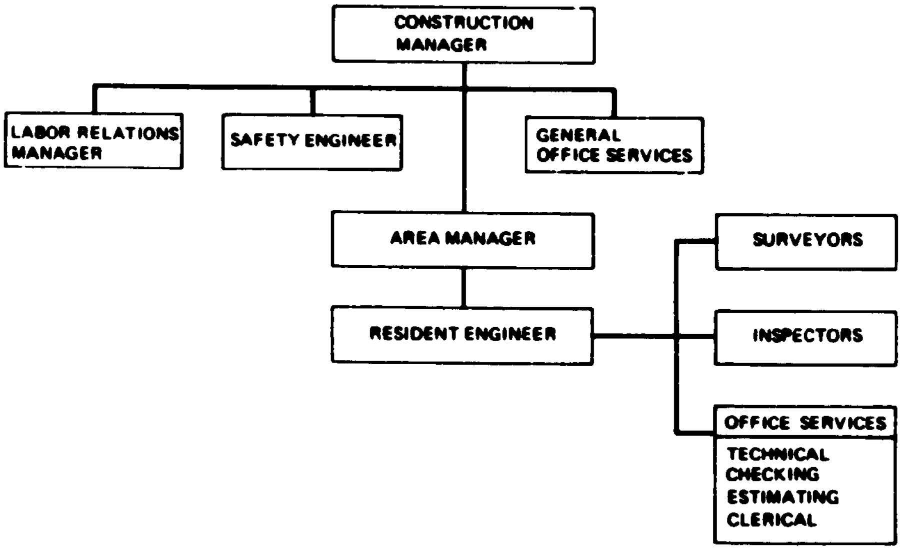


Figure 2-6. Engineer's Construction Management Organization

The resident engineer's organization, indicated in Figure 2-6, includes construction inspectors, who monitor the conformance of the construction to the specification, and surveyors, who check the conformance of the work to the geometry. The offices services group performs clerical and technical checking services, while the resident engineer is responsible for coordinating the various individual contracts with the general construction contract.

Figure 2-7 shows the individual contractors involved and the organization of the general construction contractor. The functions of the individual elements of the general contractor are fairly evident, and for the purpose of this study, a detailed discussion of the organization is not warranted.

Alternative O-E-C Organizations

An alternative owner-engineer arrangement, typical for WMATA, is illustrated in Figure 2-8. In this organization, the engineer's responsibilities as described above are divided among three entities — the general engineering consultant, the design consulting engineers, and the consulting engineer construction manager.

The general engineering consultant is responsible for the engineering functions during the planning-through-financial-approval stage (see Figure 2-1). In the system engineering design, he is responsible for all the system-wide engineering functions, as depicted in Figure 2-8.

Section design engineers are retained for each design project, i.e., for an individual station and/or line project. They produce the construction design drawings and specifications in accordance with the system standards and criteria established by the general engineering consultant and under his overall direction.

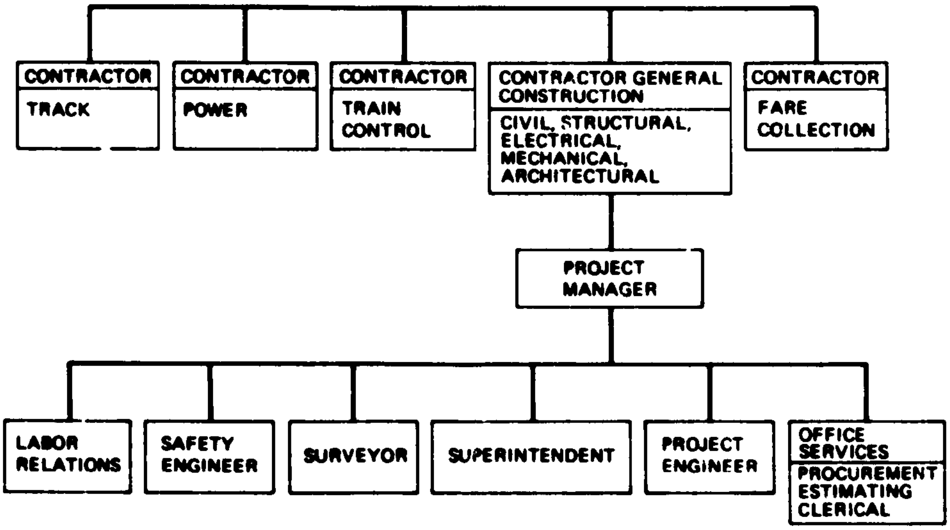


Figure 2-7. Principal Contractors' and General Construction Contractors' Basic Organization

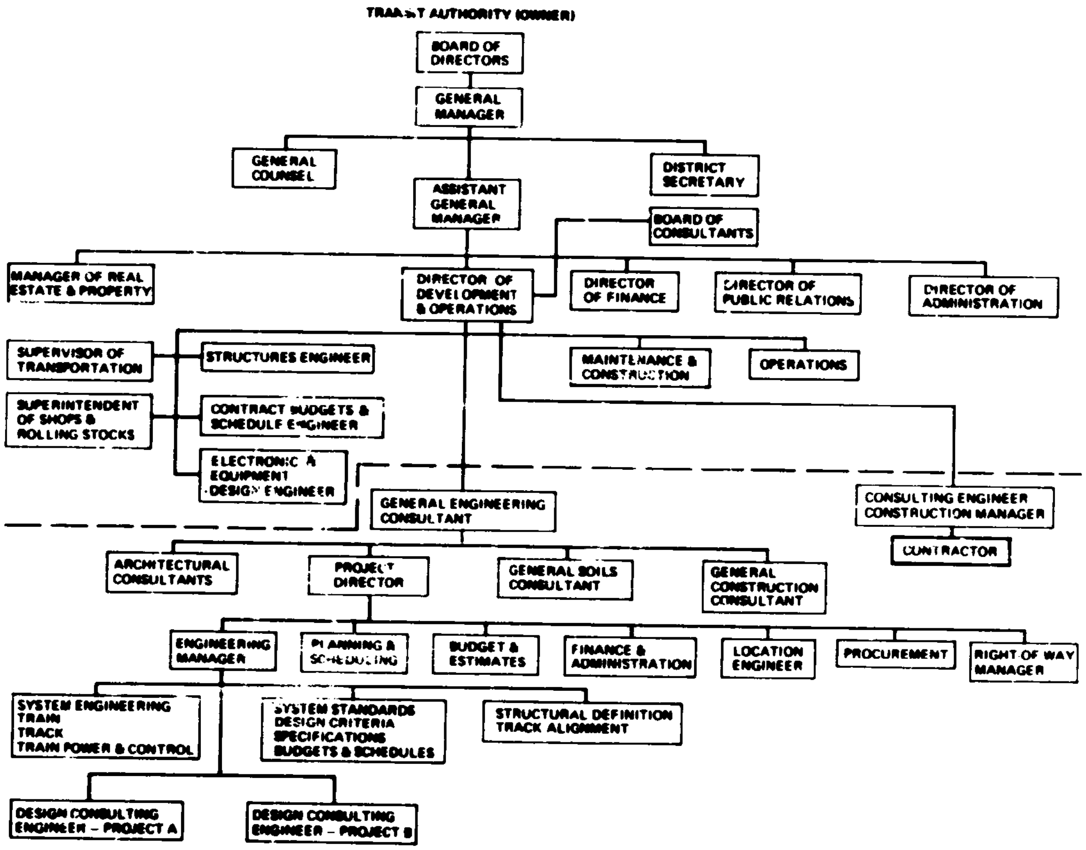


Figure 2-8. Alternative Owner-Engineer-Contractor Lines of Responsibility

The general construction consultant is responsible for the control and supervision of construction and may report directly to the owner or to the general engineering consultant.

The owner-engineer organization indicated in Figure 2-8 is basically the same as that adopted by WMATA and performs the same functions as the one used by BART. Coordination of the work of the many section designers involves considerable effort on the part of the general engineering consultant, but with a competent and experienced staff, the end product should be satisfactory.

Owner-Turn-Key-Contractor (O-T-K-C) Organization

This type of organization has two principal parties: the owner and the contractor. In this arrangement, the owner undertakes the front-end work of preliminary planning through definitive drawings as the basis on which to appoint a turn-key contractor. The contractor performs all the detailed design functions and implements the construction of the system with his own forces and with subcontractor forces, either on a lump-sum basis or with some form of cost-reimbursable and fee contract.

The interface relationships of the two parties are illustrated in Figure 2-9. A typical organization for an owner is indicated in Figure 2-10. Note that it is administratively about the same as the organization shown in Figure 2-5 except that in the latter, the technical staff answering to the director of development and operations (which is necessary during the implementation of the system structure in the O-E-C organization) is replaced by planning and engineering consultants.

In the planning-through-financial approval stage (Figure 2-1), the owner performs the necessary resolution of policies with the various public authorities and agencies, and relies upon the planning and engineering consultants for assistance in the preliminary planning and definitive plan

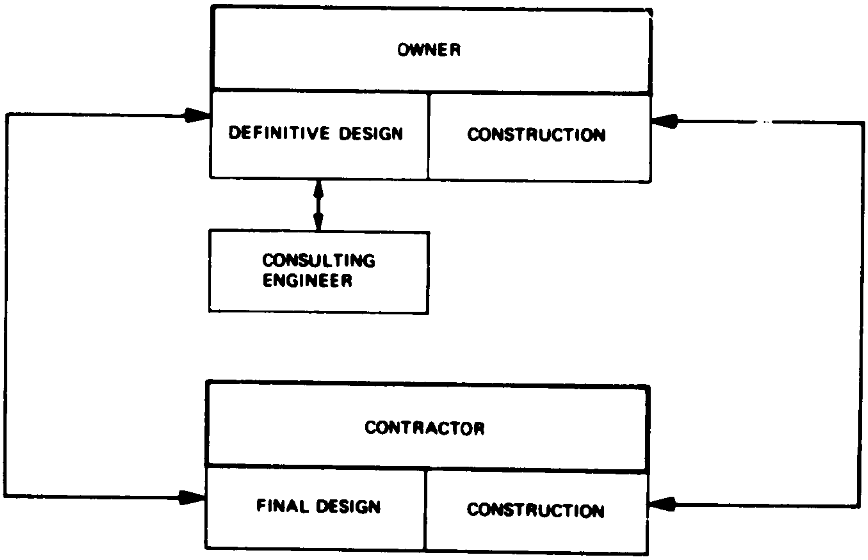


Figure 2-9. Turn-Key-Contractor Responsibility Flow Chart

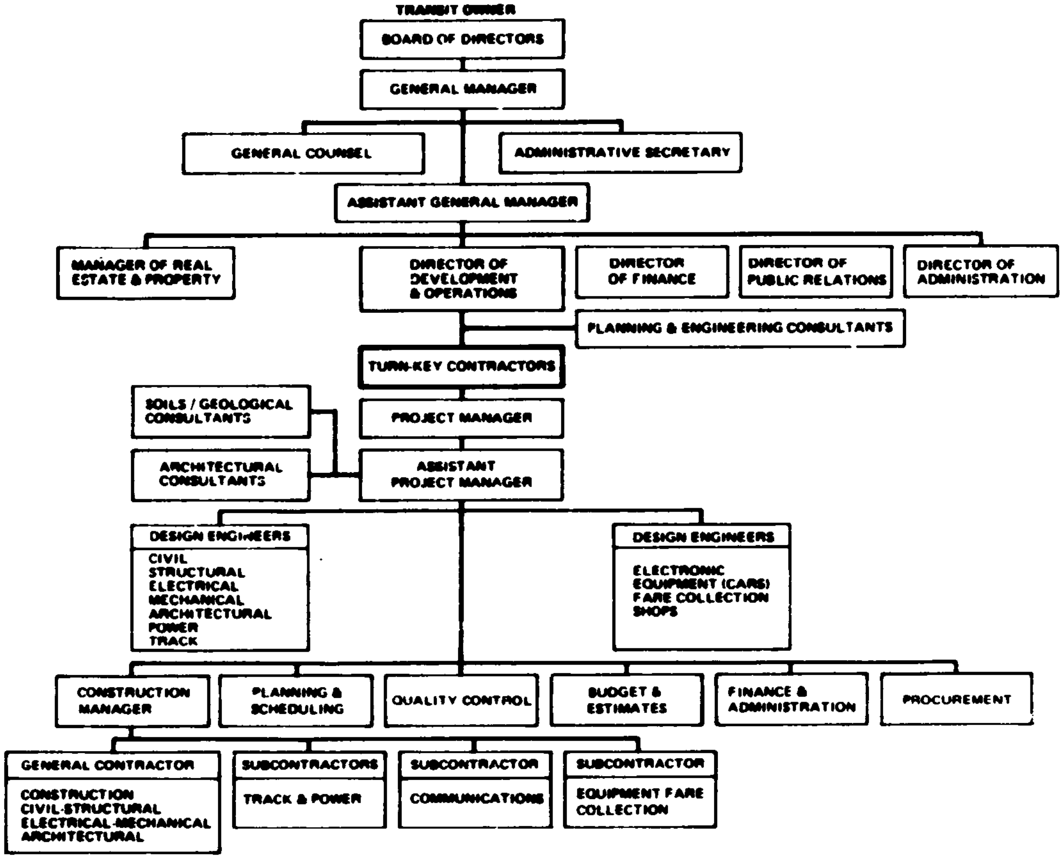


Figure 2-10. Owner-Turn-Key-Contractor Lines of Responsibility

requirements. Since the turn-key contractor will want to use his own preferred engineering systems, the definitive plan contains a good deal less engineering detail than found in the O-E-C organization.

The contractor's organization is expanded to include the design and administrative forces required to perform the duties of the engineer in the owner-engineer-contractor, as is indicated in Figure 2-10.

In addition to the detailed design, the contractor is responsible for appointing and supervising the specialist subcontractor.

Comparison Between O-E-C and O-T-K-C Organizations

The principal advantages and disadvantages of the two organizations are summarized in Table 2-1 and Table 2-2.

The owner-turn-key contractor organization seems unsuitable for major rapid transit systems. It is expected that in the next decade or so, each newly designed and implemented system will produce innovations that stimulate major technical and economic advances on which succeeding systems may be based and that the philosophy of rapid transit function and equipment is likely to be subjected to critical reevaluation. A situation such as this is not compatible with the turn-key contract approach, which is required to produce a guaranteed performance of the end product. Moreover, the O-T-K-C organization gives rise to interfacing problems with various authorities and agencies.

On the other hand, in the owner-engineer-contractor organization, the engineer is closely integrated with the owner's policy arrangements with agencies and authorities and has the flexibility of being able to evaluate the technical and economic benefits of most up-to-date developments. For these reasons, the owner-engineer-contractor organization should be the owner's first choice.

Table 2-1

ADVANTAGES AND DISADVANTAGES OF O-E-C
WITH RESPECT TO O-T-K-C

Advantages of O-E-C	Disadvantages of O-E-C
1. It maximizes the flexibility in planning and coordinating with interface authorities and agencies.	1. The inherent adversary relationship between engineer and contractor increases costs.
2. It provides the greatest possibility for incorporating latest advances in equipment development and exploiting the results of current research.	2. Three major organizations are involved, each having a tendency to separate, rather than integrate, some of the common objectives.
3. It provides the greatest opportunity for optimizing equipment systems and structure systems for the use desired.	3. The design and contract requirements may not be oriented towards a particular contractor's most efficient methods.
4. The owner has complete information on all details of the system before a financial commitment is made.	4. The project schedule may be longer, and the cost may be greater.
5. The coordination of final design and construction work with interfacing authorities is an undivided responsibility.	
6. The quality of material and work can be controlled by an entity not performing the work.	

Table 2-2

ADVANTAGES AND DISADVANTAGES OF O-T-K-C WITH RESPECT TO O-E-C

Advantages of O-T-K-C	Disadvantages of O-T-K-C
1. Two major organizations simplify the administrative procedures for the owner. 2. The components of the transit system have usually been used in other projects and are of proven worth. 3. Because the contractor has control of design engineering, he can optimize design engineering with respect to his construction methods. 4. Within the overall schedule of the project, the contractor can establish individual schedules to his best advantage. 5. The contractor has more opportunities to evaluate the risks of undertaking the work. 6. The above advantages offer the contractor the opportunity to greatly reduce the time and cost of implementing the system. 7. Because the contractor has overall responsibility for design and construction, he can reduce procedural delays and possible litigation.	1. In a large metropolitan area, the planning of a rapid transit system is fraught with complexities arising from interfacing agencies and authorities. Such interfacing involves decisions that require continuous monitoring through the construction stage. This can be difficult without the continuity that the engineer in the O-E-C organization provides. 2. For a large transit system, there may be few consortium contractor organizations with the capability of engineering and planning a completely equipped system, and the chances of obtaining the most desirable system for a particular situation may be limited. 3. The opportunity for an owner to control the quality of workmanship and materials is minimal. 4. Since the turn-key contractor exercises quality control of construction, as well as performance, he has a built-in incentive to cut corners to reduce cost. The result is often an inferior end product. 5. The owner, along with the financial donors, cannot exercise close control of either engineering or construction.

As seen in Tables 2-1 and 2-2, the present O-E-C arrangement has some definite shortcomings. These will be analyzed in the remainder of this section, and suggestions to remedy or at least minimize them will be made.

Legal Requirements

The design and construction of underground rapid transit structures are governed by numerous federal, state, and local regulatory documents and ordinances. Normally, the most severe requirements of these codes govern any particular aspect of the design and construction.

Some of the major controlling codes relating to this work are:

OSHA – Occupational Safety & Health Administration

Tunnel Safety Orders (state-issued) – e.g., State of California, State of Maryland

UBC – Uniform Building Code

AISC – American Institute of Steel Construction

ACI – American Institute of Concrete

AASHTO – The American Association of State Highway and Transportation Officials

NEC – National Electrical Code

BOAC – Building Officials and Code Administrators International, Inc.

AREA – American Railroad Engineering Association

NFPA – National Fire Protection Association

City & Municipal Building Codes – Every city or municipality

The above codes generally define the criteria for engineering design and safety procedures in construction.

Responsibility for Design Safety

The principal work events – support of excavation, groundwater control, support of existing structures, and tunnel construction procedures – were discussed under "Policy Design Decisions" on pages 2-13 and 2-14. All these events concern the safety of the public and the protection of public property, as well as the safety of the workmen and others involved directly in the construction work.

The installation of underground structures involving excavation shoring and tunnel support operations is hazardous, particularly if prudent rules of design and installation procedures are not observed. The laws covering the extent of owner and engineer responsibility for ensuring safe installation methods of underground structures, particularly in relation to the public, are subject to various interpretations. However, if the engineer assumes a supervisory role of the quality of the construction product, he cannot avoid being involved in the method of its implementation. Moreover, he cannot condone questionable construction procedures, especially where the work is undertaken within the public domain (as in the case of rapid transit construction) and the safety of the public is involved.

It seems inescapable, therefore, that if the engineer is going to enforce work safety (particularly in the design and installation of temporary works, but also in tunneling procedures), he must define minimum acceptable safety requirements for his supervisory force. In this respect, it appears to be current practice for rapid transit construction contract documents to define criteria for design and installation of these work items along the lines outlined in this section under "Policy Design Decisions."

The items discussed are not direct pay items, but are included for payments within that work to which each relates. The fact that the engineer defines minimum acceptable criteria in the contractor's design and/or construction procedures need not necessarily increase the cost of the work. Indeed, additional costs and delays in the construction schedule, which would be likely if such precautions were neglected, are avoided.

The Present Approach to Cut-and-Cover and Tunnel Construction Contracts and Specifications

Contract Documents. The objective of the contract documents is to provide a clear definition of the work to be undertaken in order to make possible a lump-sum bid price. These documents include the drawings, the technical specifications, and the general provisions.

- The drawings define the extent and details of the permanent work to be accomplished and also indicate criteria and acceptable criteria for contractor-designed temporary works.
- The technical specifications describe the quality of the materials to be used, the end product (or the completed work), the acceptable methods and procedures in performing the work, the way the work will be measured and paid for, and the way in which the bidding will be performed.
- The general provisions define nontechnical matters relating to the contract. These include: bid proposal requirements and conditions, scope and control of the work, legal responsibilities, progress and prosecution, procedures for measurement, measurement and payment, changes in the work, and changed conditions.

Construction of the Transit Structure and Performance of Peripheral Work. Two areas of work are involved in the construction of underground rapid transit structures:

- The construction of the actual transit structures
- The peripheral work generated by the excavation and subsequent backfilling operations

The transit structure type, i.e., cut-and-cover or tunnel, is selected largely on the basis of construction economics or on environmental considerations. As discussed in Section 3, present-day planning concepts generally result in a station configuration that makes tunneling uneconomical. As far as the line structures between stations is concerned, tunneled or cut-and-cover structures are equally acceptable as trainways, and the economics for selection are governed by estimated costs of dealing with ground conditions, utilities, street traffic, and existing structures. In some cases, where construction strongly affects traffic and business operations, environmental considerations often tip the scales in favor of tunnels.

When undertaking the design of either a cut-and-cover or tunnel structure, an engineer must be familiar with both the systems and details of normal economic construction practices. For cut-and-cover design, this familiarity will enable him to establish economic proportions of concrete and reinforcement details, fabricate and place reinforcements readily, incorporate so-called temporary construction elements (e.g., excavation support, walls, and struts) as part of the permanent structure, and perform other interrelated design/construction tasks.

In tunnel construction where the erection of the tunnel lining is an integral part of the construction process, a full understanding of the tunnel construction details and methods by the designing engineer is essential. For soft-ground tunnel construction, one lining system may serve both as final lining and as support for the loads from the tunneling machine (and/or shield) and the ground during construction. The lining segments must also be designed for economic erection and transport.

In cut-and-cover construction, the cost of the peripheral work, including the cost of the resulting constraints upon the excavation process, may approach 50 percent of the total cost of the work. The work events include utility relocation, support, or restoration; excavation support; groundwater control; traffic maintenance; and support of existing structures that are sensitive to ground movements and that may require underpinning.

The presence of the above work events in tunnel construction requires that ground settlements be minimized during the tunneling operations; and this requirement can increase the cost considerably.

Problems in Defining the Peripheral Events. Although current contract documents and specification can precisely describe and define the work to be undertaken on the actual transit structures, they are not nearly so satisfactory in describing the peripheral work items. The normal procedure for incorporating the peripheral work items into the construction contracts is described below.

- Utilities — The engineering drawings attempt to define all utilities that may conflict with the construction. Experience indicates that in most cities, the location of many of the utilities is not precisely known, and that the actual position may vary considerably, both horizontally and vertically, from that indicated in the utility owner's records. In addition, some utilities may be unrecorded.

  The bid documents require prices for relocating, supporting in place, or restoring the utilities indicated on the drawings. They also cover payment procedures for dealing with those utilities that are not indicated, but which are found during construction.

  In pricing the utility work, the contractor has to guess not only about the condition in which he will find the utilities he has to relocate or support, but also about the problems of locating these utilities and the effect that locating them will have upon the scheduling and installation of the other items of the work. As the density of the utilities increases, the complexities of estimating the costs will also increase, resulting in a sizable contingency spread over the utility bid price.

- Excavation and Excavation Support – The contract documents make available for inspection the soils and geological investigation reports and reproduce the soils and geological boring information in the drawings. They also normally provide disclaimers of any responsibility by the owner-engineer for the accuracy or interpretation of the information.

  For the cut-and-cover excavation, the specifications define minimum loading and other design criteria for the contractor-designed support, as well as the requirements and limitations for the ground dewatering. The contractor nevertheless must assume the full responsibility for the adequacy of the design and the dewatering system.

  In preparing his bid, the contractor must evaluate the soils information provided, estimate the shoring and dewatering requirements, assess the behavior of the ground (as represented by the information provided) during excavation, and estimate the problems and costs of disposing of the excavated material.

  In tunnel construction, the drawings may define the permanent linings to be used, and the specifications may establish criteria for minimum excavation support (e.g., shield with breast boards) and procedures (e.g., sequence of erecting lining, grouting, etc.) and groundwater control, such as dewatering, compressed air, grouting, etc.

  Notwithstanding the specific requirements given in the contract documents, the contractor must assume full responsibility for the safety of the work. The most important unknown factor to be assessed in determining the bid price is the rate of tunnneling progress, which depends for the most part on the behavior of the ground under construction conditions. (Soils information from bore holes often provides only a general indication of the way the soils may behave during actual construction.)

  The problem of handling and disposing of the material after excavation are similar to those for cut-and-cover construction. The costs of disposal (which is a contractor's responsibility) depend upon the suitability of the material for use as fill, the demand for such fill, the distance of haulage to the disposal point, and the cost of wasting if there is no demand for the fill. To resolve the economics of these matters and arrive at factual costs at the time of bidding is quite difficult.

- Support of Existing Structures – The contract documents furnish any information available at the time of bidding on the existing structures contiguous to the proposed transit structures. This information may or may not provide satisfactory details of the foundation design.

  The drawings give the engineer's estimated loads of the columns and walls, and any other structural components requiring underpinning or support during the construction; they also indicate acceptable details for the contractor-designed underpinning and support.

  Most work of this type is "labor-rich" and time-consuming. This fact, added to the uncertainty of the actual conditions of the existing foundations and any unexpected physical obstruction that may be encountered during the excavation, makes an accurate cost estimate extremely difficult. As a result, the contractor's bid under conditions of such uncertainty must contain adequate provisions for contingencies.

- Traffic Support and Control – For this event, the contract documents (established from the engineer's discussion with the City Street & Traffic Departments) define the areas of excavations to be decked, the sequence in which the decking may be placed and removed, the extent of the decking, the requirements for traffic control and rerouting, and the restrictive hours of working in the day and (for certain construction operations) during the season. The specifications provide criteria for the design of the decking by the contractor.

  It is difficult during bidding to assess the effect of street traffic on the various construction operations, such as the ingress and egress of materials.

SUMMARY

Rapid transit system implementation is accomplished over a number of years in three major phases that can be broadly identified as planning, design, and construction.

Planning

The planning phase involves establishing a transit authority to develop conceptual plans for the proposed transit system. At this juncture, numerous governmental agencies/authorities, utility owners, transportation owners/authorities, and citizen groups become involved in an intricate decision-making process of detail planning and implementation. A feasibility report is then completed delineating approximate route locations, estimated patronage, and order-of-magnitude cost; also, an environmental impact analysis is prepared. Preliminary engineering plans are then developed to further define routes to estimate the cost of the system, and to provide details for integration with other existing transportation systems. Next, a financial feasibility report is compiled. Finally, the total system plan and financing proposal are submitted to the area voters for approval, which involves many prior public hearings and intensive publicity. Once the project is approved by the voters and financing agencies, it can proceed to the final engineering design.

Design

The system engineering design phase is complex since it includes not only the system structures, stations, and the design of the vehicles, but also track geometrics and trackwork, electrification, mechanical details of ventilation, train control and communications, architectural design, and yards and shops. During the final design, decisions are made regarding type of construction (tunnel or cut-and-cover), station design, and precise route location. The final plans, specifications, and schedules are developed into contracts for bids, and engineer's cost estimates are prepared.

Once the contract bids are let, actual construction is monitored by construction supervisors, who are the owner's representative at the site.

The supervisors are responsible for compliance with plans and specifications, quality of workmanship and materials, appropriateness of construction methods, and certification of completed work.

Construction

Three parties are involved in the construction phase: the owner, the engineer, and the contractor. The owner is concerned with the overall completion and eventual operation of the transit system; the engineer is principally responsible for translation of the owner's requirements into the most economic and efficient solutions; the contractor is charged with implementing the facility in accordance with the plans and specifications. There are two possible organizations for implementing a rapid transit system: owner-engineer-contractor (O-E-C), and owner-turn-key-contractor (O-T-K-C). In the O-E-C organization, the engineer develops the plans and supervises construction as the owner's agent. In the O-T-K-C organization, the engineer is a consultant to the owner, who in turn deals directly with the contractor; the contractor develops design detail drawings and implements the construction.

Section 3

CUT-AND-COVER AND TUNNELING TECHNOLOGY

INTRODUCTION

Cut-and-cover and tunneling technology may be defined as all the actions and tasks that result in a completed cut-and-cover or tunnel structure. Many of the contractual aspects of such actions and tasks, as well as the associated organizational processes, have been discussed in Section 2. The subject of this section is the specific interactions between engineering design, the structures, and the resultant construction process.

Present-day technology for the installation of underground rapid transit systems has developed around the existing planning concepts (e.g., system layout and station layout) of the system's functions. From a review of the BART and WMATA study projects (discussed in Section 6) and other related material, it is apparent that these concepts, as presently implemented, impose certain constraints on potential major improvements in cut-and-cover and tunneling technology, and consequently lessen the likelihood of reductions in the time/cost factors of the construction.

For instance, the system layout often is the major factor influencing the selection of the structural system and the time/cost aspect of its implementation. (System layout is a geographic definition of the system, including stations, lines, and components that are related to the areas that the system will serve.) In the usual procedure, a planning engineer establishes a system layout to determine the location of stations on the basis of passenger patronage, transfer points to supplementary transportation modes, and consequent revenue production, and then optimizes the horizontal and vertical track alignment. This forms the basis of the definitive engineering design upon which the system is funded and approved. In general, however, the planning engineer does not get involved in detailed design and construction economics, and frequently he is not construction-oriented. Thus, at the final design stage, when the layout is given to the design engineer, the latter is virtually locked into a plan that is far from optimum from a construction viewpoint. This difficulty can be avoided if detailed design and construction investigations are made in the preliminary planning stage.

The second major existing planning concept is the station layout. As a rule, space planning of the station results in a mezzanine (or upper level booking hall) which extends over the full width of the underlying trainway and in length is at least equal to that of the station platform. In some cases, architectural dictates have caused ceiling heights to be raised beyond those required for strictly functional requirements. The resulting large area and volume requirements have led to the adoption, in cut-and-cover construction, of station design that gives rise to all the problems and costs associated with utilities, road and pedestrian traffic, and existing buildings in the vicinity of the construction.

Cut-and-cover station construction also produces lengths of line tunnel construction (which connect the stations) that are too short to be economical.

However, even with the existing planning concepts, improved design and construction techniques can reduce current costs and lessen adverse environmental effects. In this section of the study, these techniques will be examined, possible changes of planning and design concepts will be described, and the impacts upon future construction technology will be reviewed.

BASIC MANAGEMENT DECISIONS

The technological decisions made by management for the design and construction of rapid transit structures determine the time/cost efficiency of the implementation of the construction contracts. Such management decisions, their impact upon the design contract documents, and the resulting effects on some of the principal construction events of the BART study contracts are described below.

Preconstruction Contract Preparation

Soils Survey. Two types of contracts were let to soils engineering firms to obtain soils and geological information along and adjacent to the transit route.

The purpose of the first project was to gather and define all information available from previous soil investigations. The purpose of the second project was to supplement the information gathered in the first project by making supplementary borings and tests.

The result of these two contracts provided a fairly comprehensive soils profile, including soils classifications, characteristics, and groundwater elevations along the transit route. In some cases where ground conditions were particularly difficult, the designers of individual section projects called for additional soil borings and/or test pits. In Contract K0016, two test pits were excavated to determine the probable techniques required in supporting the ground during tunneling operations.

Utilities and Other Street Facilities. At an early stage in the design of the system, utility owners were informed of the proposed transit construction plans and schedules. This was done in order to decide, in principle, (1) which utilities should be rerouted ahead of construction,

(2) which could be abandoned, (3) which would be supported in place during construction, and (4) which should be restored when construction was completed.

As structure plans and schedules became firm, preconstruction utility relocation contracts were undertaken, usually by the utility owner but occasionally by the BART contractor.

City Traffic Control Departments. Meetings were convened with the Traffic Control Departments to establish the methods and sequence of installing the underground cut-and-cover and tunnel construction. Such decisions included:

- Traffic rerouting and control
- The extent of the decking for the excavation
- The sequence of decking installation
- The sequence of street restoration

City Street Departments. Planning of rapid transit facilities, particularly stations, involved the modification of sidewalks at station entrances, the modification of bus stop facilities, and the provision for ventilation shafts. At the same time, the Streets Departments planned the upgrading of the street and sidewalk. This added complexities to the total planning.

Discussions during the preconstruction planning and design peri [illegible] with the Streets Departments were held at regular intervals to resolve these matters.

Existing Structures. A comprehensive survey was undertaken of all buildings and other structures along, or in the vicinity of, the planned underground structures of the transit system. Information gathered included design drawings, where available, and/or a field survey of the structure to obtain structural details and other data. Prior to construction, all buildings that had to be underpinned or supported, or that could be disturbed by underground construction, were surveyed by photograph and sketch by the system-wide insurance company. Access permits for the contractor to enter and perform work in the structures were obtained for the contractor.

Contractor's Work Areas. Arrangements were made to lease or purchase work and parking areas for the contractors during the construction period.

Policy Design Decisions

For protection of third-party life and property during the contractor's construction operations, management adopted the following policies:

Support of Excavation. Minimum loading and installation criteria were established with which the contractor had to comply for the design of his excavation support. Such criteria included soil, traffic, and other superimposed loadings; preloading of horizontal bracing members; maximum spacing of structural members; and instrumentation to check bracing stresses and, in some cases, deflections.

Support of Existing Structures. Support for an existing structure was based on the structure's importance and its sensitivity to underground construction. There were three categories of support. These are listed below in decreasing amount of required support.

- Mandatory underpinning of multifloor buildings and other important or vulnerable structures
- Mandatory maintenance of level by jacking and wedging columns, walls, minor structures, and low-rise buildings, all of which may be sensitive to underground construction

- Protection and repair of all other structures within a possible area of disturbance

An alternative method of protecting structures without the need to underpin was to require rigid ground support by specifying slurry wall construction for the temporary support system. (This was used in the WMATA C0041 Contract to protect a hotel against the effect of possible ground settlement during the construction of the adjacent underground tunnel.)

Groundwater Control

Owing to the importance of groundwater to construction operations and schedule, existing structures, and public safety, the degree to which groundwater was to be controlled was specified.

Tunnel Construction. The specifications called for the use of certain types of equipment and construction procedures in order to maintain a minimum standard for safe working. These included:

- Protective shields
- Compressed air for groundwater control
- Methods of supporting the face of the excavation
- Grouting of voids between lining and ground

Value Engineering. Although the contractor had to bid on the contract documents as specified after the award was made, he was permitted to propose alternate designs or construction methods which would result in an equivalent or better structure at a reduced cost. For example, in K0016, where ground conditions proved more favorable than expected, the contractor's proposal to tunnel in free air (instead of in compressed air, as required by the bid) was accepted, and a construction cost saving was effected.

Alternate Designs. Where there was more than one way of achieving the same result, alternate designs were included in the bid documents. This permitted a contractor to select the most economic method of working for his particular proposal.

PROCESSES IN CUT-AND-COVER TECHNOLOGY

Introduction

As the name implies, the cut-and-cover construction process involves the main work events of excavation to the plan and depth of the structure, the building of the structure, the backfilling over the structure, and the restoration of the surface. Peripheral work events relate to existing utilities and structures that conflict with or may be disturbed by the excavation process and to street and pedestrian traffic. Figure 3-1 shows a typical twin-cell cut-and-cover box structure installation. Figure 3-2 illustrates the typical interaction of the construction events for a combined cut-and-cover and tunnel project.

A description of the work events for a cut-and-cover installation is given below.

Relocation and Support of Utilities

Relocation. Most of this work is performed by the utility owners before the award of the general construction contract. The work consists of rerouting the affected utilities outside the construction area. In some cases, the rerouting is permanent; in other cases, when the utility is restored after or during the backfilling operation, the rerouting is temporary.

In cases where the construction contractor is responsible for the relocation of utilities, he will perform the work in the same sequence and use the same method as the utility company.

From a technological standpoint, most utility relocation work consists of straightforward trenching, shoring (if required), utility installing, testing, backfilling, and surface restoring.

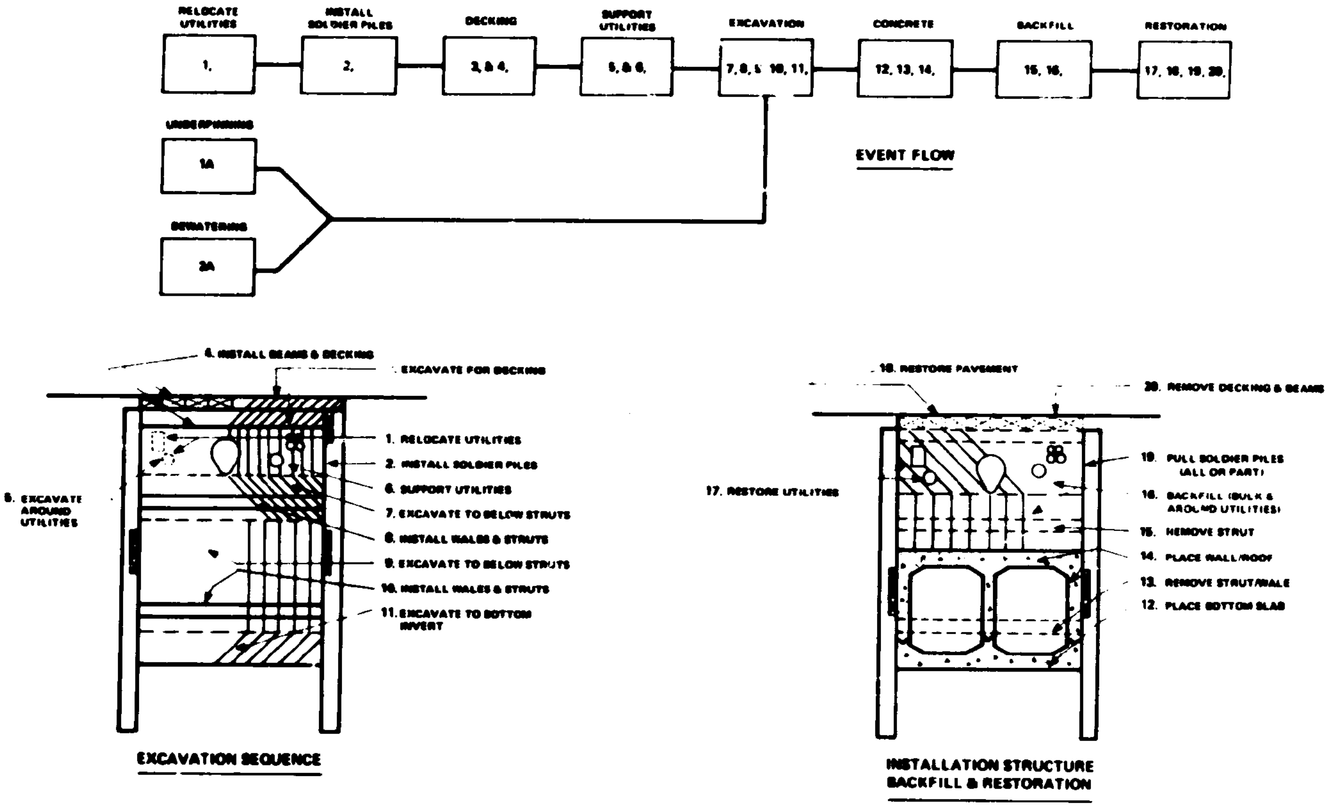


Figure 3-1. Cut-and-Cover Construction Sequence

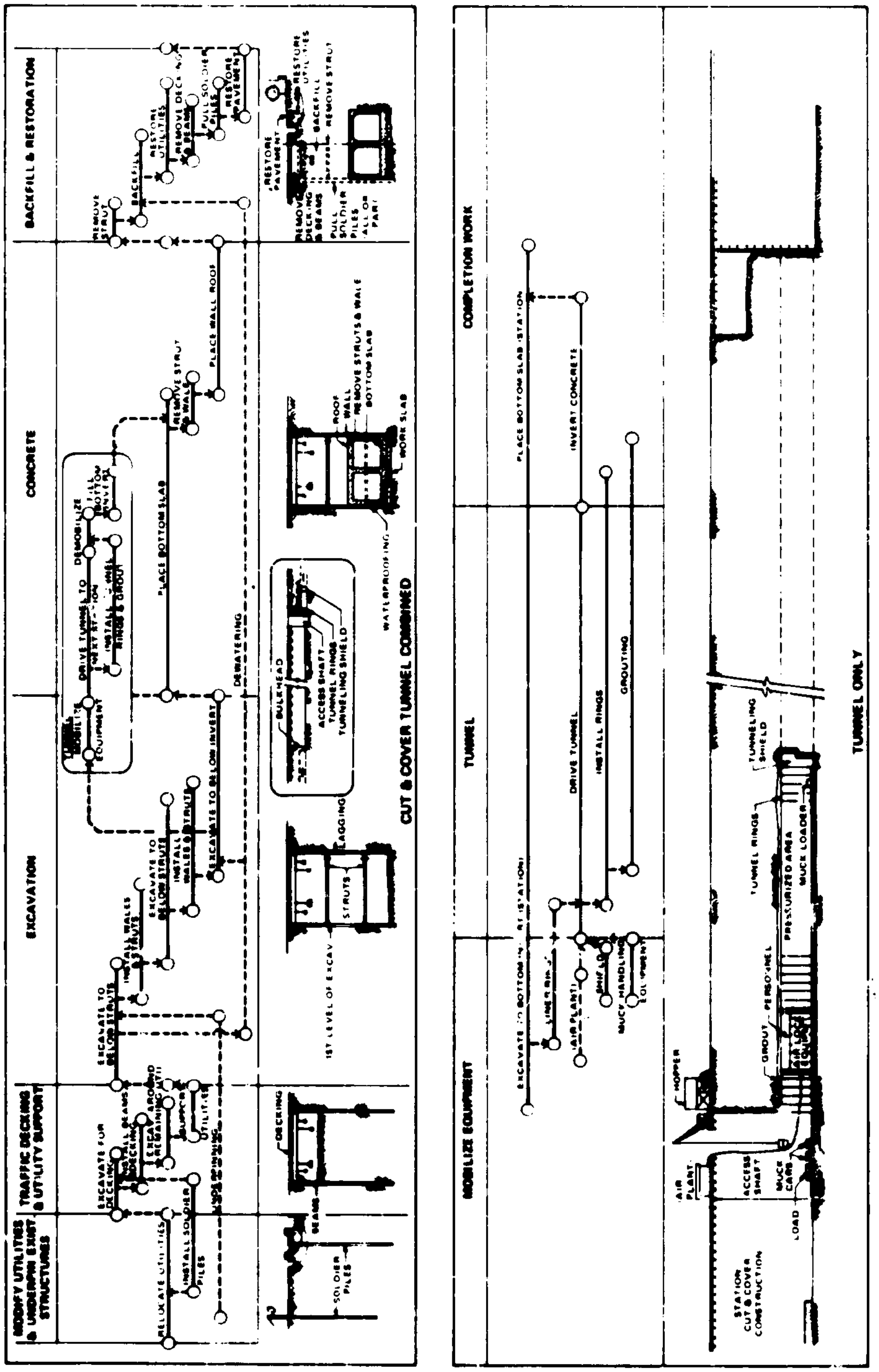


Figure 3-2. Cut-and-Cover and Tunnel Construction Flow Diagram

Items that materially affect the cost include congested working areas, the presence of multiple utilities in close proximity, and traffic conditions. The problems and costs multiply at cross streets where utilities interleave, particularly when utilities are being restored during completion of the construction.

Support. Such utility support work is normally the responsibility of the construction contractor. Occasionally, however, the actual operation of protecting and supporting (as opposed to providing the main structural supports) is undertaken by the utility company.

The support of utilities within the excavation areas is preceded by the installation of soldier piles, the placing of the deck support steelwork, and normally the placing of the decking. Owing to the imprecise data generally available on the in-place position of existing utilities, their exact location must be established before pile installation by probing or excavation by hand. Excavation to the underside of utilities is performed slowly and carefully under the decking, often manually, or with light mechanical equipment.

Steel pipes or monolithic reinforced concrete sewers may be supported directly by hangers from the deck steel work. Other utilities, such as electrical utilities in tile ducts and vitrolite sewers, require protection. This is done by encasing them in reinforced concrete or in timber and/or steel beams. The timber and/or steel beams also provide longitudinal support for the utilities when the latter are suspended from the deck beams.

Gas lines present a particular hazard to underground construction. Generally, prior to excavation, all gas lines will be relocated either temporarily or permanently outside the area of excavation or area of expected ground disturbance.

Decking and Traffic Control

Specifications require all or part of the area of the excavation to be decked in order to maintain the street traffic. Decking is accomplished structurally in the following way:

- Bearing piles are installed along both sides of the excavation area. Supplementary intermediate piles are also installed where the excavation width requires it.
- Deck-supporting girders are placed on the piles, generally across the excavation, with longitudinal stringers and bracing, as required. As the elevation of the deck surface must either be the same as that of the replaced street surface or not appreciably above it, excavation to the underside of the deck girders must precede the placing of the girders.
- The deck units are placed on and secured to the supporting structural members. These units normally consist of pallets made up of several 12" x 12" timbers bolted together. Traffic curbs and handrails are provided as required.

Traffic control involves most or all of the following tasks:

- Rerouting some of the traffic in the construction street into the adjacent street system
- Changing directional traffic flows and lanes both in the streets where there is construction and in adjacent streets
- Erection of temporary curbs, barriers, and handrails
- Relocating traffic lights, changing and producing new traffic signs, and road striping
- Provision of flagmen

The specifications attempt to define and detail the traffic control procedures and guide the sequencing of the various operations, both for installation and removal. Normally, the contractor must maintain frequent contact with the City Streets and Traffic Departments as the traffic control operations proceed.

Underpinning of Existing Structures

Structures, adjacent to the construction area, whose foundations are likely to be disturbed by the excavation operation require protective action. Where structures are founded on compressible material, the groundwater table outside the excavation is maintained by the combination of a relatively impermeable shoring wall, dewatering within the excavation, and (if necessary) a recharging of the groundwater table outside the excavation. The shoring wall may be of slurry-tremie concrete or steel sheet piling.

Structures of importance, with foundations at elevations that are within the excavation zone of disturbance, require foundation underpinning. There are two principal methods of underpinning: (1) installing drilled piles, to an elevation below the disturbed zone, under or alongside the foundations, and effecting the structure load transfer to the piles; (2) performing the same operation by installing piers in pits excavated under the foundations.

Light structures that are not particularly sensitive to small ground settlements can be maintained at satisfactory elevation by inserting jacks between the columns or walls and foundations. If settlement of the structures exceeds a predetermined amount during the construction excavation, the structures are jacked back to level. When the construction is completed, the space between the columns and walls is wedged and packed, and the jacks are removed.

In many cases, the operations described for important structures and for light structures can be avoided by using slurry-tremie concrete shoring walls with preloaded struts. Not all grounds, however, will give satisfactory results for this method; and the principal factor in selection is economics.

Excavation Procedure and Support

Specifications define the minimum soils loading to be used in the contractor-designed excavation support and the installation procedures for soldier piles and bracing. Lagging between soldier piles is normally employed in good ground conditions. Sheet piling or slurry-tremie concrete walls are specified when the ground is bad, or when the maintenance of the water table outside the excavation or the presence of existing structures adjacent to the excavation makes them a requirement.

Soldier Piles. Soldier piles serve double duty as traffic decking structure support and excavation support. Environmental control requirements of noise and vibration dictate predrilling for the installation of soldier piles. This predrilling normally goes to the bottom of the excavation, with the embedment length of the pile driven, or the whole length of the pile drilled and the embedded length concreted below the bottom of the excavation. A bentonite slurry is generally used to prevent caving of the hole during drilling, and after installation of the pile, this slurry is displaced with a weak sand and cement concrete.

Dewatering of the Ground. This is accomplished by (1) the installation of deep wells and submersible pumps, (2) the installation of well points with suction headers, or (3) the pumping from sumps placed in the excavation itself, the water being removed by sump pumps. In the first two methods, the wells may extend some 15 ft below the excavation. As a rule, the installation is made and the pumping operations started some months prior to the completion of the excavation. In order to avoid possible flotation of a structure, dewatering often has to continue until part of the backfilling operations is completed.

Groundwater control is effected by well pointing or with deep wells, the effectiveness of which is established by periodic reading of observation wells. Specifications require that the groundwater table be maintained at certain elevations below the excavated levels and that standby pumps with alternative power sources for cases of emergency be available.

Where compressible ground exists and existing structures and facilities are susceptible to settlement, limitations are imposed on the levels to which the water can be lowered. In cases of cut-and-cover construction, if the allowable lowered groundwater level is above that of the construction excavation, the contractor is required to excavate within steel sheet piling or within slurry wall construction. In addition, in some cases recharging of the groundwater table outside the excavation is necessary to maintain the required level.

For tunnel construction, where maintenance of groundwater levels is required above the bottom of the tunnel, compressed air tunnel working is specified to balance the residual water pressure.

In order to verify compliance with the specifications, the contractor is required to install, maintain, and read observation wells which are placed to indicate the elevations of the lowered groundwater along the route.

Excavation. Where utilities remain in place during the construction, the excavation around them must be undertaken with care (often by hand) until they can be supported. Excavation with sizable earth-moving equipment can proceed below the supported utilities to the successive levels of bracing. When lagging is used, it is placed between the soldier piles as the excavation proceeds. Muck is brough to the surface either in trucks up ramps or by clamshell working through the decking. In either case, the muck is transported from the construction site to the soil disposal area in trucks.

Bracing. In deep excavations, the bracing of the soldier piles to prevent lateral earth movements (and consequent vertical movements) is of prime importance. The bracing consists of horizontal walings which are positioned in direct contact with the soldier piles and struts (which, in turn, are in contact with the walings) and span the excavation transversely. In order to minimize movements of the soldier piles, specifications require the struts to be preloaded, by means of jacking, to about one-half of the design load.

The bracing levels are usually placed a few feet above the levels of the horizontal slabs of the permanent structure. When the concrete slabs are in position and have attained sufficient strength to support the lateral earth pressure, backfilling and removal of struts are carried out in sequential operations.

Ground Settlements. To maintain a control on ground movements and on the movements of existing structures and facilities, periodic measurements by the contractor are required at the following places:

- Over the centerlines and at either side of the tunnels
- At specified positions within structures that are likely to be disturbed by cut-and-cover or tunnel construction
- At elevation datum points on the street and sidewalks at various distances from the excavation
- At reference points on buildings fronting the excavation

At periodic intervals, the elevation datum points and reference points are checked for settlement against base datum points placed outside the zone of influence of the excavation.

Concrete

Reinforced concrete is the predominant construction material for cut-and-cover structures. In some instances in the study projects, horizontal steel bracing was incorporated in the station structure as a main beam element.

The construction techniques for forming and placing the concrete in the structural elements are orthodox. Whenever possible, the designer attempts to use standard details, both in concrete outline and reinforcement, to permit the contractor to take advantage of repetitive operations.

The major elements of an underground station are ground slabs, walls and columns, and suspended floor or roof slabs.

Installation of Ground Slabs. The installation of ground slabs is done as follows:

- Subgrade is prepared, e.g., made into hard, level surface to the correct grades and levels.
- Electrical conduits, drainage pipes, and other miscellaneous items to be imbedded are positioned.
- Forms and screeds are set.
- Reinforcement is placed.
- Ground slab is concreted.
- Forms are stripped and the concrete cured.

Walls and Columns. The installation of walls and columns is performed as follows:

- Bottom construction joints are prepared.
- In wall construction, the outside form is erected, the rebars are placed, inner forms are erected, and concrete is placed. In column installation, the reinforcement cage is placed and the form fabricated around it,

or the prefabricated forms are placed over the reinforcement. The concrete pour is usually made in accordance with the specified limits of height and horizontal travel.

- The forms are stripped and the concrete cured.

Suspended Slabs. Suspended slabs are installed as follows:

- Formwork is erected.
- Reinforcement is placed
- Screeds are set.
- Concrete is placed and finished.
- Concrete is cured and formwork is stripped — typically, slabs after 5 days, secondary beams after 12 days, and main girder (props) after 28 days.

Items of work that also fall under the heading of "concrete" include sumps, electrical and mechanical rooms, fan room ventilation shafts, stairs, and provisions for escalators. These items generate a number of subitems such as pipes, conduits, louver frames, hatchway frames, ladders, and other miscellaneous iron and steel work which must be placed prior to the concreting.

Backfilling

Although usually not a high-cost event, backfilling is important to the time schedule. It cannot begin until the various elements of the structure have attained sufficient strength, and it cannot be completed until some of the utilities have been relocated or released from their supports and the decking has been removed.

Specifications define the height of each layer of fill placed, and the density to which it must be compacted.

The placing of backfill is often performed in confined spaces: between walls and shoring, between the decking and the top of the structure, and under and around supported utilities. Because of these restrictions, the compaction of backfill normally involves a considerable amount of manual labor.

Restoration. Restoration, including that of utilities, is the last major event in the construction process. It involves relaying streets, sidewalks, curbs, gutters, and related drainage systems.

PROCESSES IN TUNNEL TECHNOLOGY

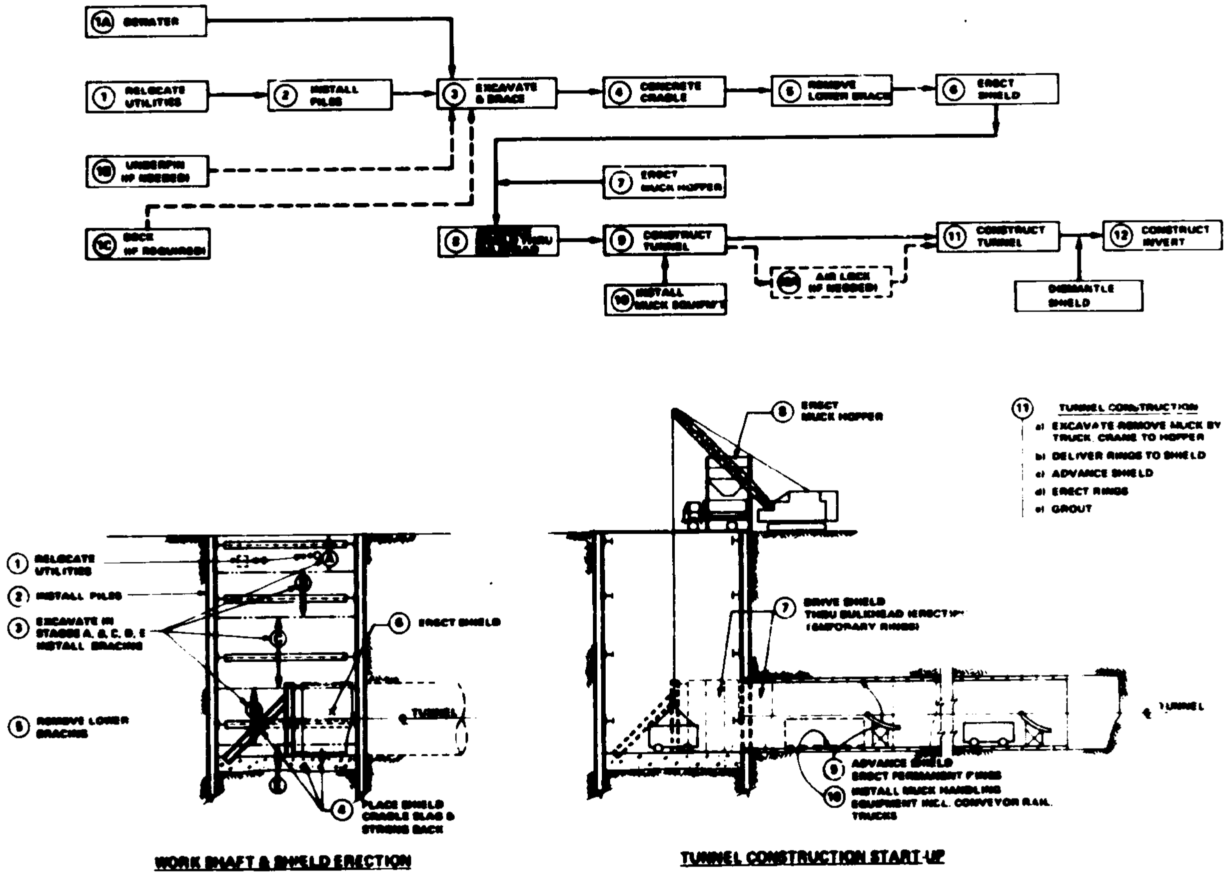
Introduction

In the context of this study, a tunneled structure may be defined as one that is constructed below the ground surface, as distinct from a cut-and-cover structure, which is constructed by excavating from the ground surface.

A typical rapid transit tunnel construction process is illustrated in Figure 3-3 As can be seen in this figure, the peripheral work events required are similar to, but may vary in degree, from those in the cut-and-cover process discussed earlier. A description of the work events in a tunnel project is given below.

Utilities

The degree of relocation is determined by the area of the workshaft and ventshafts, and by the sensitivity of both the ground and the utilities over the tunnels to probable settlements from the proposed tunneling operations. Given reasonable ground conditions and good tunnel construction practices, it is customary to leave all utilities along the tunnel routes in place. An exception to this may be cast iron gas pipes or gas-filled electric mains,



WORK SHAFT & SHIELD ERECTION

TUNNEL CONSTRUCTION START-UP

Figure 3-3. Tunnel Construction Event Sequence both of which are particularly sensitive to damage from even small ground movements. Some utilities may have to be supported over the workshaft, but since there are so few of these, the cost factor involved is relatively small.

Decking and Traffic Control

The decking is limited to the workshaft and vent shafts, and traffic control is needed only around the surrounding work area. In general, decking and traffic control are not high-cost items for tunnel work.

Underpinning

As is the case with the utility event, the degree of underpinning is determined by the likelihood of ground movement arising from the proposed tunneling operations, and the sensitivity of the existing structures to this ground movement. Given reasonably stable ground and well-controlled tunneling techniques, ground movements in the area of the foundations of the adjacent existing structures are normally small, and underpinning or other support of the structures is not necessary. However, underpinning will be required where the tunnels are close to the foundations of existing structures and the ground is sensitive to the tunneling process.

Tunnel Construction

The tunneling methods described below are for soft-ground construction: i.e., a shield is required to provide substantial support to the ground as it is excavated.

Tunnel construction is illustrated in Figure 3-3. When any work on utilities, traffic control, and underpinning is sufficiently advanced, the construction of the workshaft may proceed. Workshaft construction, and any ground dewatering that may be required, uses a sequence that is identical to that used in cut-and-cover construction. When the excavation for the workshaft is complete, a concrete shield cradle is installed at the bottom of the invert, with a shield reaction framework at the end of the cradle remote from the tunnel portal. The shield is lowered, assembled in position on the cradle, and jacked through the portal bulkhead into the ground. As this is done, temporary rings are erected behind the shield to transfer the jacking forces to the reaction framework. When the tunneling is sufficiently advanced, airlocks, if required, are installed together with muck-handling equipment.

Tunnel driving is performed as follows:

- The excavation is removed one ring width, and the shield is jacked forward.
- The lining is erected and bolted together.
- The lining is grouted, and caulking is installed to provide watertightness.
- The process is repeated for the full length of the tunnel.
- At the end of the drive, the shield is either dismantled or removed intact.
- When differential movements between the structures are anticipated, the tunnel lining is sealed to the portal structure with a flexible joint.
- The trackway invert and walkway are concreted.
- The construction is completed, either by placing tunnel linings through the workshaft, backfilling, and restoring the street; or by constructing a ventilation shaft in the workshaft, backfilling, and restoring the street.

Tunneling Shields. To protect life and property, tunneling in downtown city areas is normally performed under the protection of a tunnel shield. A typical shield with mechanized excavation equipment, illustrated in Figure 3-4, is a braced steel cylinder whose diameter is slightly greater than that of the outside of the lining to permit the erection of the lining

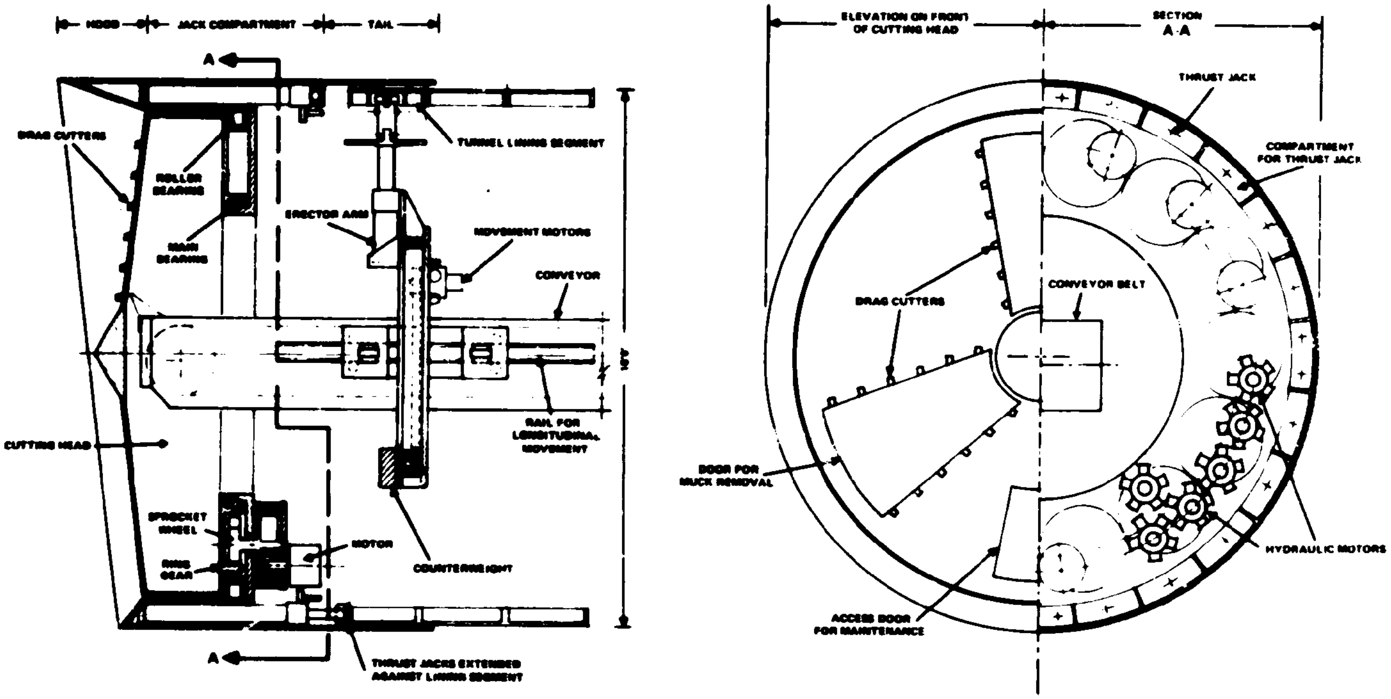


Figure 3-4. Soft-Ground Tunneling Machine

within the shield tail. In a typical setup for a shield with an 18-ft o.d., twenty-two 125-ton hydraulic jacks are arranged around the shield tail perimeter and advance the shield during or after the excavation cycle has been completed by reacting on the tunnel lining, which is already in place. An erector arm is usually provided with the shield to lift the segments and place them in position in the ring. If the shield is not fully mechanized for excavation, breasting jacks are provided near the face of the shield to permit the excavation face to be supported by breast boards.

Excavation Methods. These methods can be either manual or machine-assisted.

In the manual excavation, workmen working on platforms extending from the shield use air spades to remove the ground from the crown of the tunnel downwards.

In machine-assisted excavation, the following machines are used: small face shovels, such as the Eimco, which throws the spoil into rail trucks behind; the Gradall, which has a universally articulated excavating bucket head; backhoes; and front-end loaders, which in short tunnels can both excavate and transport the muck to the bottom of the workshaft for hoisting to the surface.

The excavation equipment may be fixed to the shield; it may be on rails within the shield; or, as in the case of the face shovel, it may be independent of the shield. With all these methods, support of the excavated face is provided to the degree needed by the breast boards and jacks.

The tunneling machine is a shield that is mechanized to provide push-button excavation of the full tunnel face as the shield advances. The excavation is achieved by rotating or oscillating arms or plates upon which cutting or scraping teeth are fixed. Both kinds of machines (rotating and oscillating) were employed in BART tunnel projects. The two machines were the MEMCO tunneling machine, which uses rotary cutting plates, and the Calweld tunneling machine, which uses oscillating cutters.

Figure 3-4 also shows the main components of the MEMCO tunneling machine, which was employed on several BART projects, including the S0022 Project. A photograph of the MEMCO machine is shown in Figure 3-5. The chief features of this machine are as follows:

- The cutting head can be fully rotated in either direction. This feature prevents the whole machine from rotating to the off-plumb position and permits the machine to be plumbed, if required.
- The three hinged doors through which the muck is removed, and upon which the cutters are mounted, can be opened in either direction and to the extent best suited to the ground encountered.
- The muck that enters the rotating plates through the doors is deflected onto the conveyor, located near the center of the machine, and then discharged by the conveyor onto the removal equipment.

A photograph of the Calweld tunneling machine is shown in Figure 3-6. In this machine, the cutters are mounted on arms, three to a quadrant, each of which oscillates independently through a 30° arc. Behind the cutting arms is a bulkhead to support the face in bad ground. As the machines advances, the muck is channeled through the bottom of the shield and the bulkhead, drops onto a drag chain conveyor, and is then discharged onto the conveyor removal system.

Both machines appeared to be potentially capable of advancing 70 ft per day (three shifts per day), but a more realistic average is 45 ft per day. This compares with an average of 25 ft per day for manual excavation on comparable lengths.

Figure 3-5. Photograph of the MEMCO Tunneling Machine

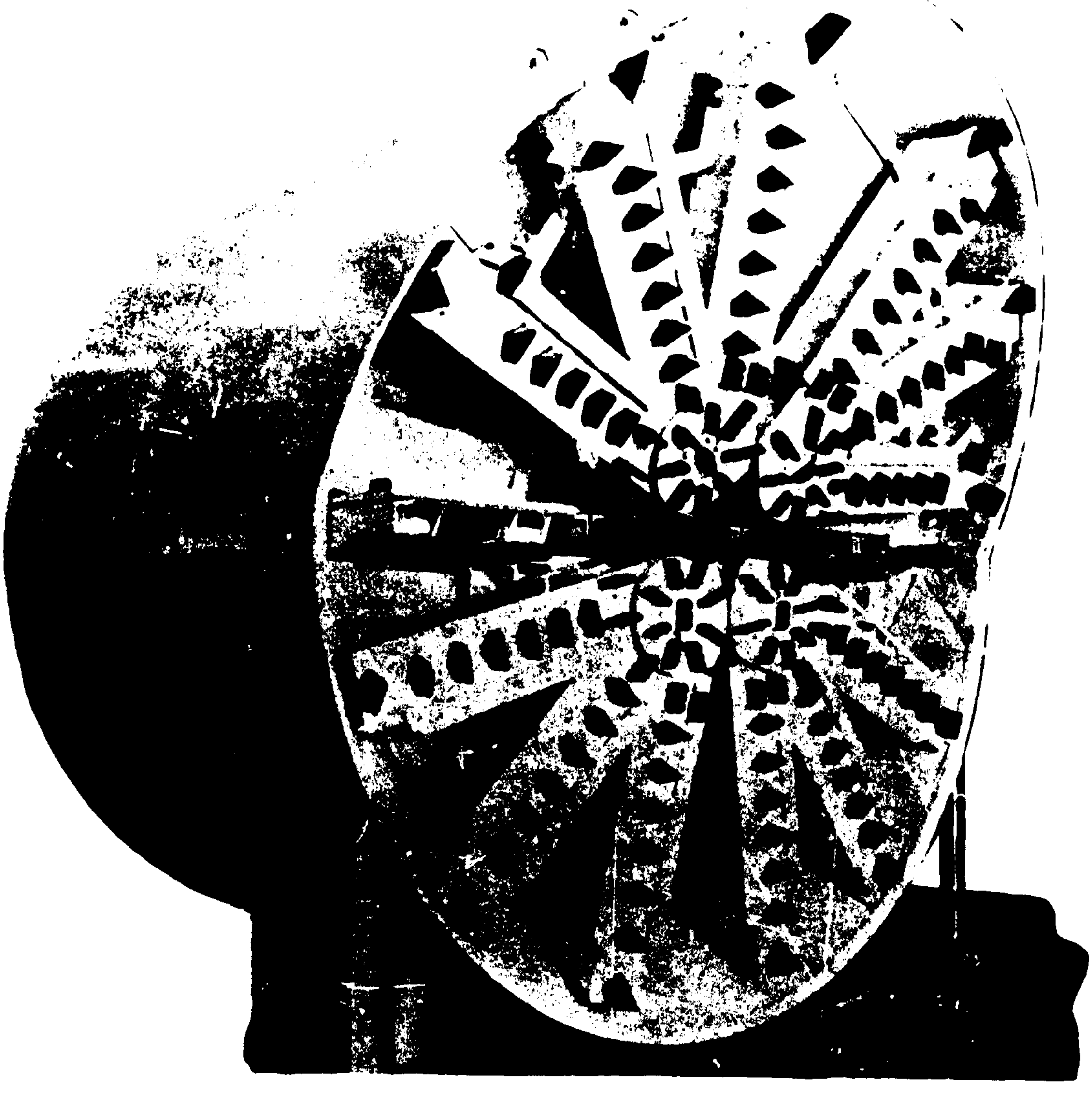


Figure 3-6. Photograph of the Calweld Tunneling Machine

Mixed ground consisting of rocks or boulders in various proportions with clays, sands, and silts presents a challenge to tunneling machines. One machine that appears to have been successful under such conditions is the modified Robbins rock tunneling machine, which is shown in Figure 3-7. From this figure, it can be seen that the cutting arms are fitted with roller-type rock cutters as well as soft-ground drag cutters.

Muck-Handling Equipment. This equipment transports the muck, removed by the shield, through the tunnel and to the ground surface. Equipment in common usage today includes:

- A narrow-gauge rail system with the trucks loaded at the tunnel heading by conveyors or mechanical loaders
- Rubber-tired front-end loaders, which self-load and transport

A typical rail system and vertical hoisting system used by the contractor of the BART S0022 Project is illustrated in Figure 3-8. The main elements are:

- A conveyor from the tunneling shield to the truck loading station. The conveyor was connected to the shield and moved with the shield as the latter advanced.
- The truck and track equipment. The track work had to be extended from time to time as the construction proceeded.
- The skip pit and hoist. The trucks side-tipped into the skip, which was hoisted vertically.
- The overhead conveyor and truck hopper. The skip discharged onto the conveyor, which transported the muck to the truck hopper, and the truck hopper loaded the road disposal trucks.

The hoist system served both tunnels, with the rail trucks discharging on opposite sides of the skip. As the tunneling was performed under

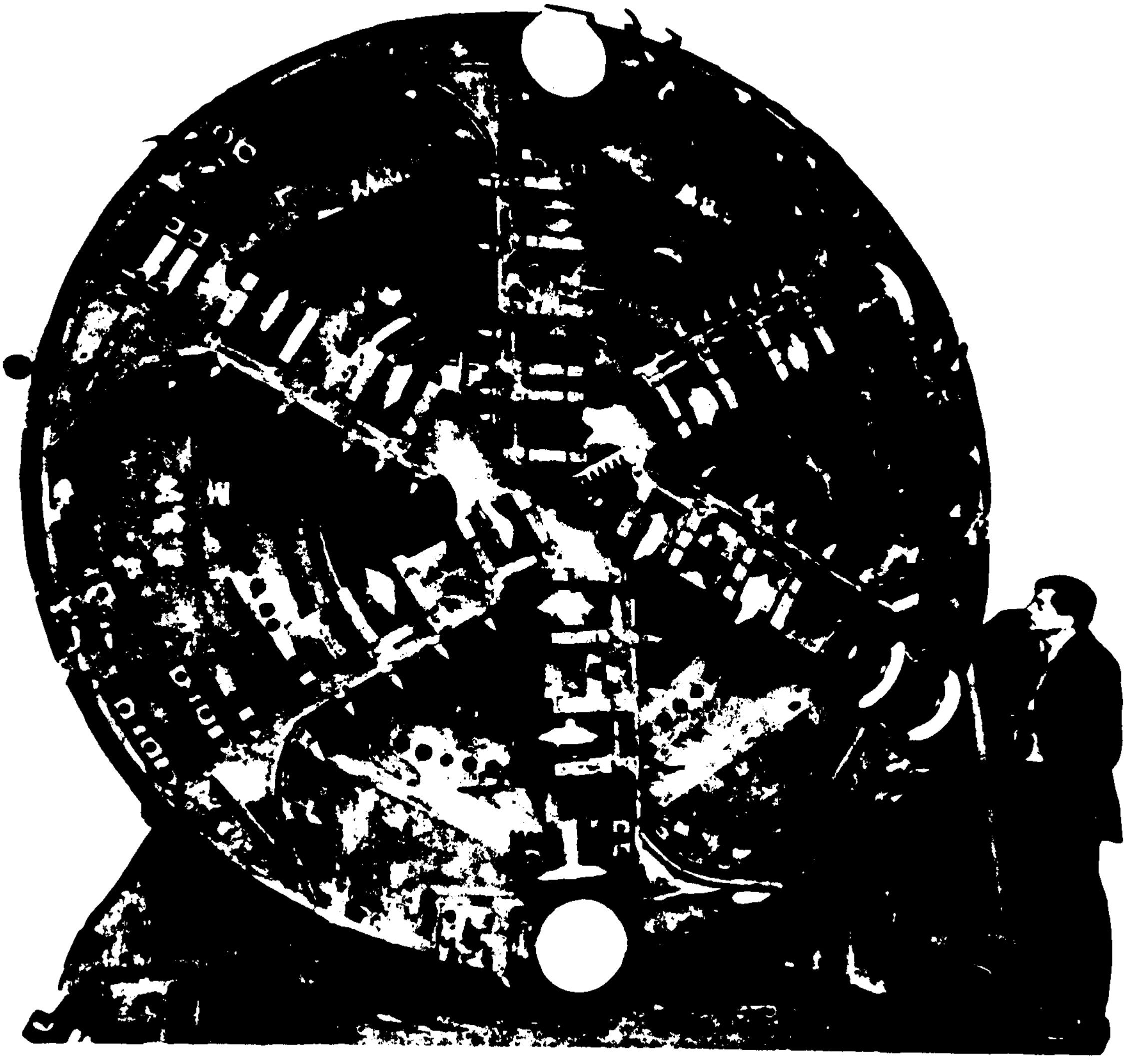


Figure 3-7. Photograph of the Robbins Rock Tunneling Machine

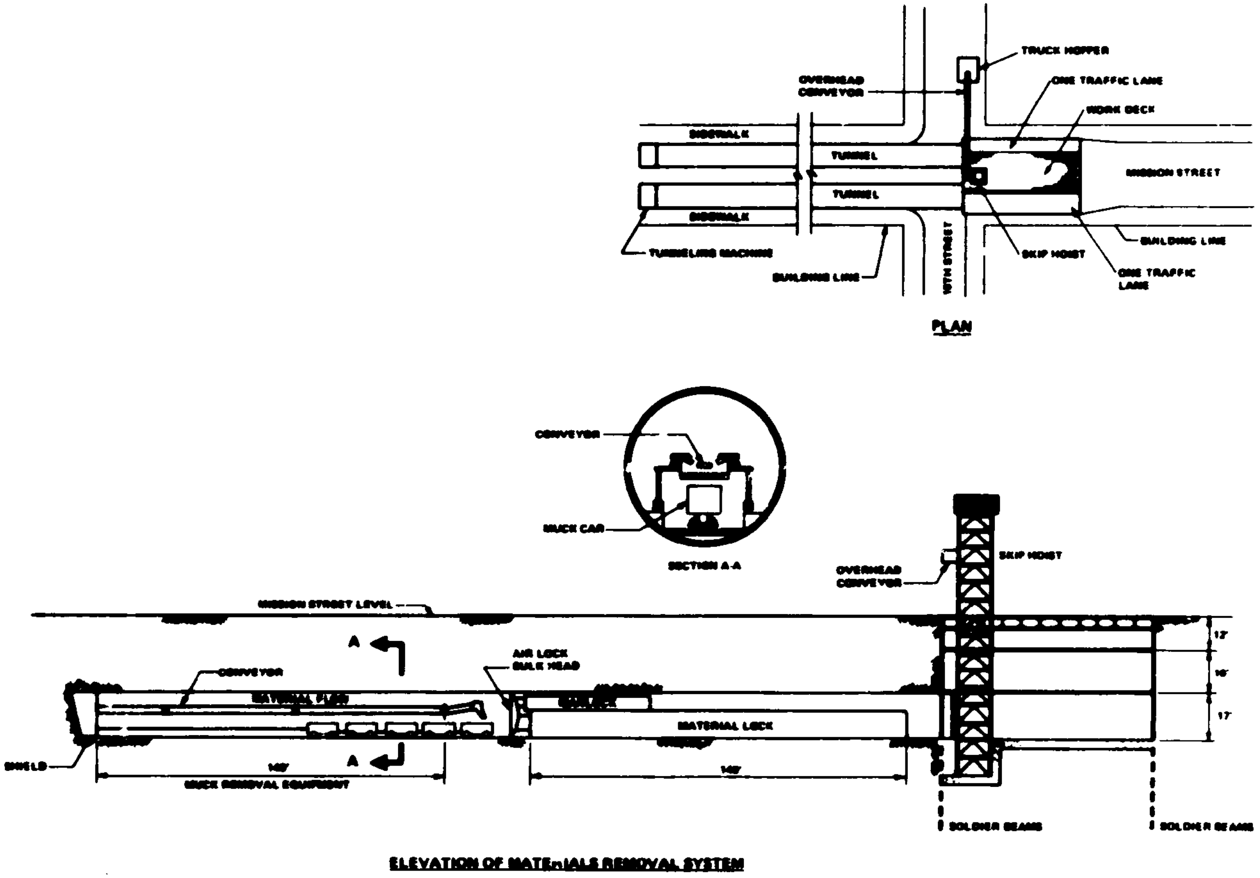


Figure 3-8. BART Project S0022, Sixteenth Street Station to Civic Center, San Francisco – Tunnel Workshaft

compressed air, the rail system had to pass through the material compressed air lock, shown in Figure 3-8.

Front-end loaders of about 5 yd^3 capacity were used successfully in a BART Tunnel Project and also for the WMATA C0041 Potomac River Tunnel Project (soft-ground). In both projects, the front-end loader proved attractive for the following reasons:

- The tunnels were short — 1600 to 1800 ft in length.
- The ground was firm, had little groundwater, and required minimum support at the heading.
- Open-face shields could be used to permit the front-end loader access to the face and to perform some of the excavation directly. This minimized excavation.

On a few occasions, muck has been transported from the face by hydraulic pumping, a method with some attractive features, including greatly reduced tunnel space requirements and horizontal and vertical conveying of material within one system.

A typical hydraulic system consists of:

- A screened sump, and perhaps a crusher, at the tunnel heading
- A pumping station, also at the tunnel heading
- A delivery pipe to the surface and a recycle water pipe back to the heading
- Settling facilities with muck-handling equipment at the surface.

Figure 3-9 diagramatically illustrates such a system. This system has several drawbacks: many grounds, particularly clays or clay mixtures, are difficult to pump; disposal of excess dirty water is often a problem; and the surface facilities occupy considerable space.

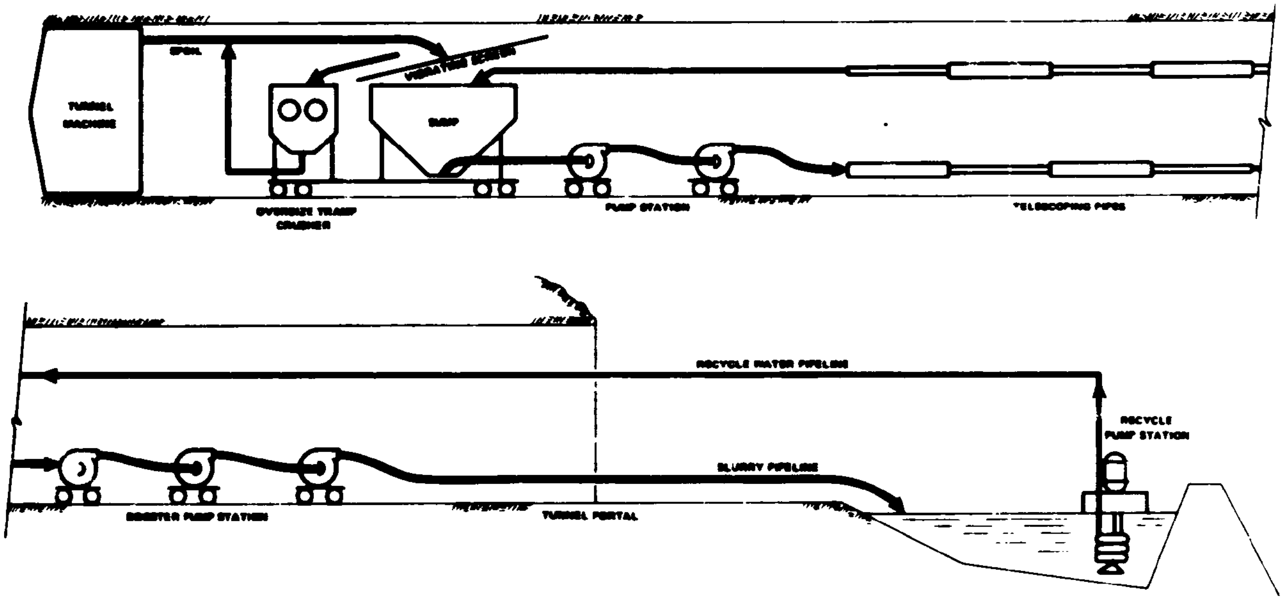


Figure 3-9. Hydraulic Muck-Removal System

The selection and sizing of muck-handling equipment is largely dependent upon the method of excavation used.

For the BART tunnels, a tunneling machine that can excavate a ring width representing about 25 yd^3 of muck, in 10 minutes or less, accelerates the rate of overall progress of the tunnel construction. Obviously, this accelerated process requires more surge and transporting capacity from the muck-handling equipment than does a manual excavation or machine-assisted system.

Segmented Lining Erection. The most common type of lining, the segmented lining, consists of a series of segments bolted together to form rings which are bolted one to another to provide structural continuity. Ring erection proceeds within the shield tail when the excavation and shield advance cycle has been completed. Segments are placed by the erector arm, starting at the invert, and alternating from side to side. The placing of the key segment near the crown completes the ring construction.

When the shield advances, the last erected ring leaves the tail space, and an annular void of 3" - 4" remains between the outside of the ring and the ground. Specifications require that this space be filled to provide uniform transference of ground loading to the tunnel lining and to minimize ground movements. The filling may be accomplished in two ways:

- By injecting a cement grout into the space through grouting holes provided in the segment for this purpose, starting at the invert and finishing at the crown
- By using a pea gravel as an initial filler, followed later by cement grouting

The first system has two major advantages: it minimizes ground movements; and it encapsulates the tunnel lining in a more or less uniform ring of cement-sand concrete, which increases both watertightness and (in the case of metal rings) corrosion protection. It has the disadvantage of requiring somewhat difficult sealing details between the inside of the tail skin of the shield and the outside of the tunnel lining.

The second (two-part) system of initial pea gravel injection has much less of a shield-to-lining sealing problem and is simpler to use in the congested area at the work face. However, because of the difficulties of completely filling the tail space and because of the migration of the fines in the ground into the gravel, unacceptably large ground movements may develop. In addition, uniform penetration of the voids of the pea gravel (particularly when it becomes mixed with the ground) by the secondary grouting is difficult to achieve, and this results in reduced watertightness and corrosion protection.

Final watertightness of segmented lining is obtained by caulking the grooves in the segments. The caulking material is usually lead. In this operation, the grooves must be cleaned and lead wool or lead strip must be caulked or peened into place with pneumatic caulking irons. For the caulking to be sufficiently watertight, good workmanship and proper equipment are essential. If ground movements are likely to occur after the tunnel construction, it is particularly important that the segment bolts be properly tightened.

Concrete Invert and Walkway. The concrete invert and walkway, with attendent drainage and electrical conduits, are usually contructed using traveling forms, with the concrete being deposited by pump.

Nonsegmented Lining Erection. Rib and lagging with cast-in-place final lining is a nonsegmented system lining that is often used as an alternative to the segmented lining system. It was employed to some extent in the WMATA project where 5" steel ribs spaced at 4-ft center• supported wood lagging in between. In this type of lining, the ribs are erected in the tail of the shield, the lagging placed, and as the shield jacks advance the shield, the tail moves away from ribs. The next-to-last rib from the tail is expanded by jacking in two places at the spring line to take up the space between the ground and the lagging (i.e., the tail space). Steel packing is subsequently inserted in the resulting rib space.

After the tunnel drive is completed, a permanent reinforced concrete lining is placed in a separate operation. The invert and the walkway are placed as an integral part of the lining. Traveling forms and pumped concrete placing techniques are employed in the operation.

The principal disadvantage of this lining system is the potentially large ground surface settlements that occur during tunneling. These appear to arise from the lack of ground support that exists when the unexpanded temporary lining emerges from the tail of the shield.

Control of Tunnel Geometry. The centerline of the tunnel, as indicated on the engineer's drawings, is calculated from the rail track alignment and is adjusted horizontally and vertically for the superelevation of the rail track. This centerline is normally displaced from that of the track by the requirements for a walkway.

For the control of line and level of the tunnel structure, a workline is established within the tunnel, and this workline is used to control the alignment of the shield. The workline becomes a number of chords around alignment changes.

The centerline of the tunnel is mathematized horizontally and vertically at every segment interval off the workline in order to facilitate the control of the shield. The worklines are established by transit, originating from points that are carried down the tunnel workshaft from the surface primary survey control line.

Modern techniques for shield drive control employ a laser beam which is set up and moved along the worklines at intervals as the tunnel construction progresses. It is normally convenient to mount the laser on top of a transit-head so that the laser can be related to the workline. From the predetermined locations of the laser, the centerline of each tunnel ring is related by angle and, in turn, the beam is related by the vertical and horizontal distance to targets (or bull's-eyes) that are mounted on the vertical centerline of the shield.

This method allows the position of the shield to be checked after every shove and the necessary steering correction to the shield to be established prior to the next shove so that design alignment changes can be made and errors can be corrected.

Changes of alignment for a segmented liner tunnel are made using tapered rings. A tapered ring is obtained by inclining one circle face to the other by reducing the width of the ring on one side. For the BART tunnels, rings with three degrees of taper were used and were obtained by reducing the normal ring width of 30" on one side by 3/4", 1-1/4", and 2". The rings with the greatest taper were used for small-radius curves. (The minimum radius was 500 ft.)

Tunneling in Compressed Air. Such tunnel construction is required when the ground and groundwater conditions are such that the water cannot be sufficiently controlled by pumping, grouting, or chemical stabilization to stabilize the working face during excavation. Compressed air is commonly required in variable water-logged ground having pockets or lenses of silt or other unstable material, such as running sands, which cannot be effectively dewatered or grouted. Very soft clays and muds underlying water also fall into this category. In other situations, dewatering may be limited because it affects compressible ground in such a way as to cause undesirable settlements of adjacent property.

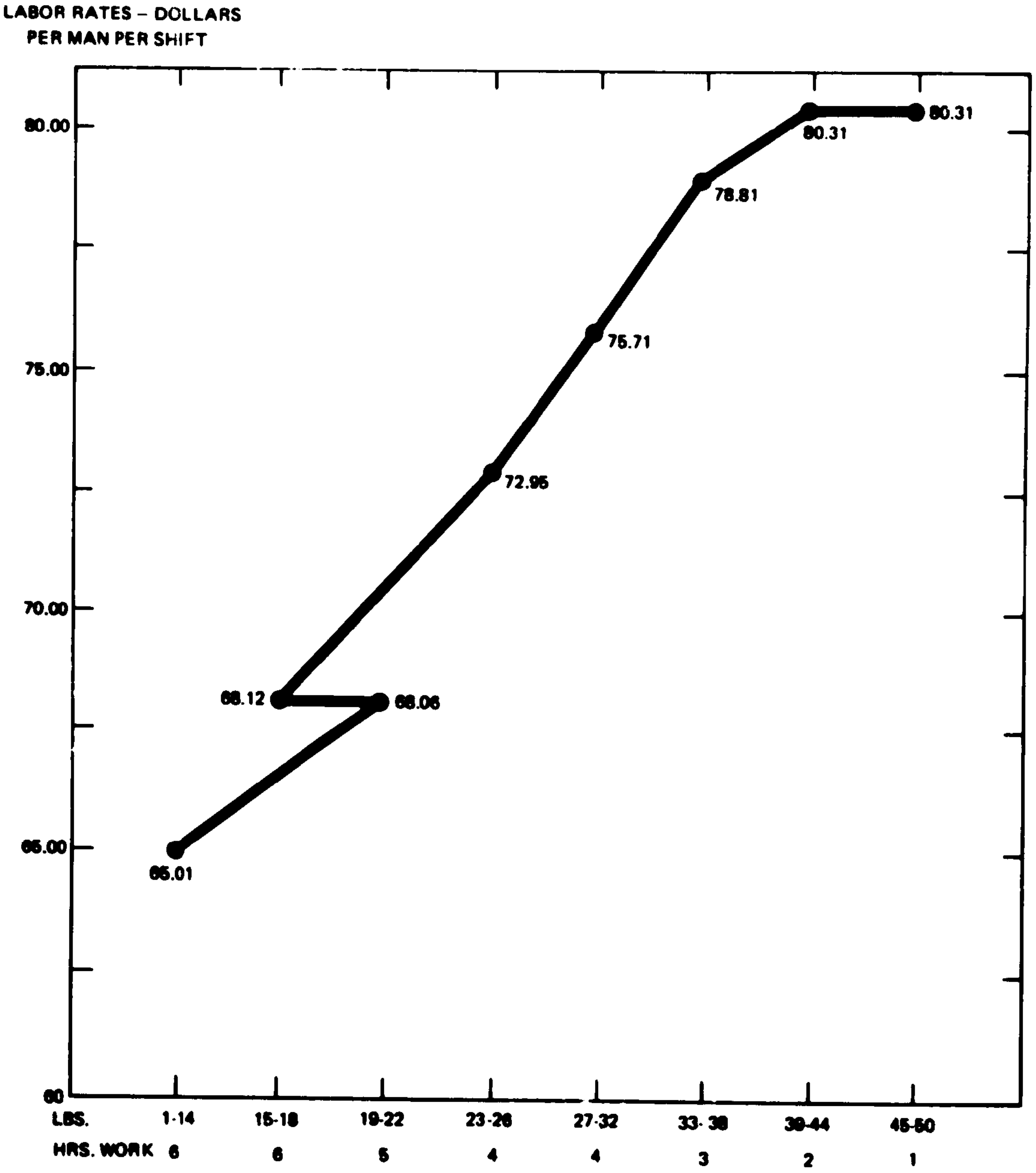
A compressed air plant is expensive and typically may require several compressor units, each capable of delivering 4000 ft^3 per minute at 30 to 50 psi. Standby generator units or other alternative power sources are needed in case of power failure, and air locks for men and materials, with attendants to operate them, must be provided. Such an installation may cost upwards of $1,000,000 (1974 prices). Labor for compressed air working is also expensive, with labor costs escalating rapidly with increase of pressure.

In Figure 3-10, labor costs are plotted against working pressure. In Figure 3-11, total tunnel cost is plotted against working pressure.

The above costs were estimated from data derived and extrapolated from representative BART tunnels.

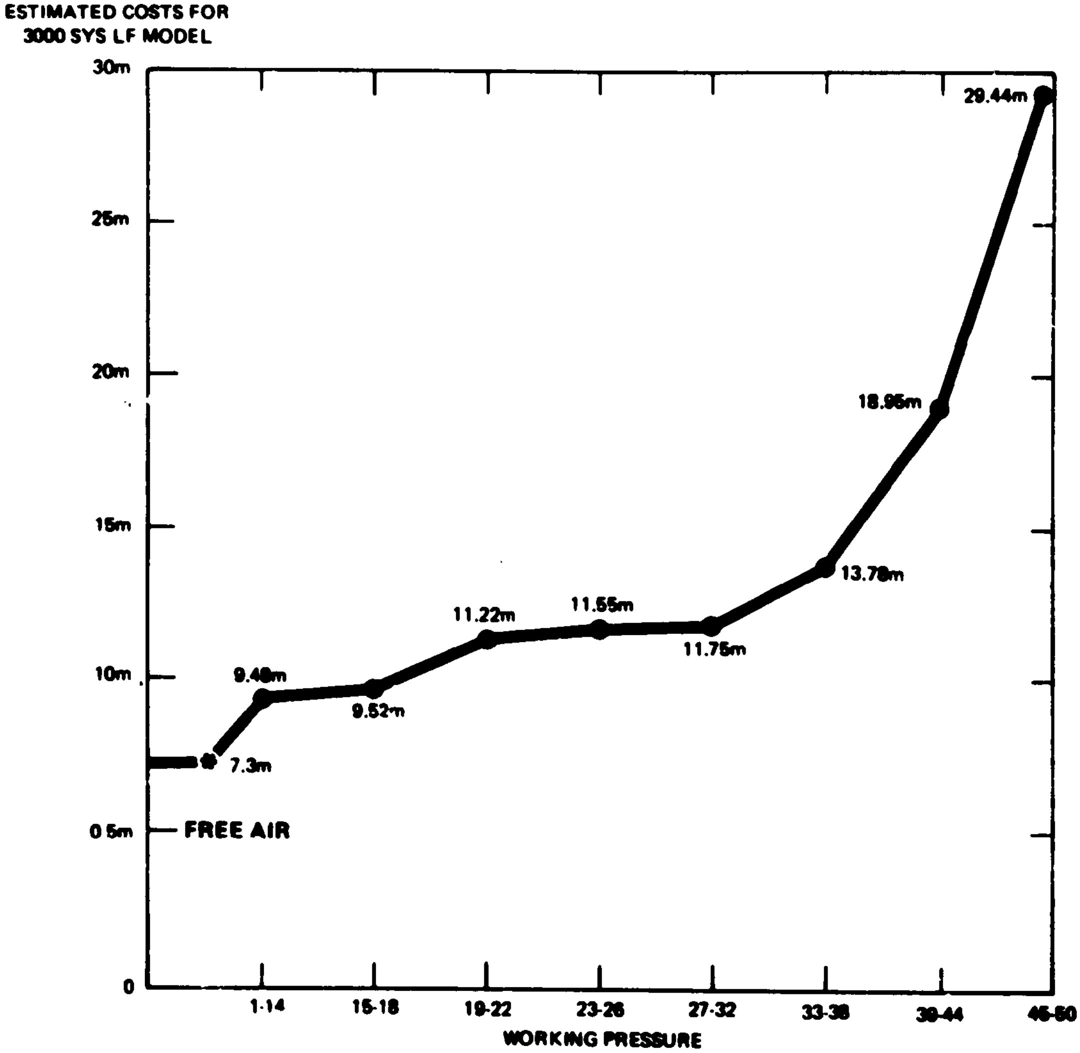
Normally, as in the case of the BART S0022 Project, dewatering is undertaken from the surface, as far as possible or permissible, to minimize the air pressure.

Several states, California among them, have compressed air safety regulations, similar to the OSHA regulations. Briefly, these regulations govern the safety aspects of equipment and define the requirements for personnel working in compressed air. Such requirements include the duration of compression and decompression and the duration of work shift for various levels of air pressure. The regulations also specify medical procedures to qualify personnel entering or working in compressed air, and the medical facilities to be provided for compressed air operation.



SHIFT RATES FOR COMPRESSED AIR LABORERS UNDER INCREASING PRESSURES
WAGE RATES ARE FROM SAN FRANCISCO AREA, JAN. 1974 BASE PAY

Figure 3-10. Relation of Shift Labor Rates to Working Pressure



m = MILLIONS OF DOLLARS

LABOR RATES UNDER PRESSURE TAKEN FROM JAN., 1974 SAN FRANCISCO AREA

Figure 3-11. Relation of Tunnel Working Pressure to 3000 System Ft Contract Costs, Estimated Under Different Pressures

Tunnel Technology Parameters

From the foregoing descriptions of tunneling, it will be noted that the geological conditions encountered, the tunnel lining, and the tunnel construction technique are all closely interrelated.

Geology. The geological formation in which the tunnel is to be constructed will determine the tunneling system and lining. There are, broadly speaking, two principal geological divisions:

- Rock that requires little or no temporary support during the excavation. Tunnels constructed in such rock usually have a final concrete lining installed when the excavation has been completed, but if the rock is sufficiently competent, the lining may be omitted altogether.
- Ground that requires immediate support during all phases of the excavation. Such support may consist of a temporary lining comprising steel sets, supporting wood or metal lagging, or steel or concrete segments, all followed at a later date by a permanent concrete lining. Alternatively, the lining may be made up of metallic or precast concrete segmented rings designed for both the temporary construction loads and the final tunnel structure.

With respect to lining design, ground may be grouped as granular or firm (with or without water), or plastic. It can be further subdivided into its excavation characteristics, such as removal and handling properties, standup time, and groundwater control. These characteristics determine the selection of the excavation equipment and procedures.

In general, the final segmented lining system is the most satisfactory for rapid transit construction, in ground, in downtown areas where control of the ground movements and surface settlements are usually of importance.

Design of Tunnel Liners. Rock and ground differ in their effects upon tunnel construction and the related lining design. These differences are summarized below.

	Rock	Ground
Effect on shield or tunneling machine	Machine obtains forward thrust reaction from rock.	Machine reacts off lining.
Effect on lining design	Rock movements and pressures are generally less than in ground. The design of rigid lining is required.	Ground movements and pressures are relatively large. The design of flexible lining is permitted, (provided that the ground is not plastic).
Support of excavation	Rock may be self-supporting during excavation to permit (1) dispensing with the shield, and (2) an initial temporary lining, followed by a permanent lining at a later date.	The following is required: (1) a shield and (2) a lining erected in the shield to provide immediate ground support

In keeping with the scope of this document, the discussion of design will be limited to tunneling in ground.

The lining is required to support both the total weight of the overburden (or some proportion of it) and to resist the bending moments that arise from the ground movements. That is, the lining is designed for both compression and bending moments in the circumferential direction.

For the construction loads, the lining is designed, not only for direct thrust of the shield jacking forces (which are on the order of 50 tons per circumference foot), but also for the bending moments that arise from the forces being applied eccentrically to the transverse center of gravity of the segments.

The standard BART lining designed for these conditions was a segmented ring system comprising six segments and a key bolted together to form a ring. The rings are bolted together to form a continuous lining. To achieve watertightness in the segment matching faces, the grooves formed for this purpose in the toes of the segments are caulked with lead.

Figure 3-12 illustrates a typical welded steel segment, cast iron segment, precast concrete segment, standard precast concrete segmented ring with key, and bolt assembly and caulking for steel segments.

In the construction of segmented linings, welded fabricated steel and ductile iron have three major advantages: their ductility and high ultimate strength permit the rings to undergo considerable distortion from both excessive ground movements or shield-jacking forces without losing integrity; the segments are lighter than those of other materials; and they suffer rough handling better during installation.

Cast iron segmented rings are heavier than fabricated steel and are relatively brittle. As a consequence, rings of this material are prone to damage if overstrained or roughly handled. The production of cast iron segments requires a sizable investment in foundry plant and equipment.

The cost of manufacture of the precast concrete segments is less than the cost of fabricated steel, cast iron, and ductile iron. In good firm ground with moderate groundwater pressures, they perform satisfactorily. However, in very adverse ground conditions, their structural performance and watertightness are sometimes considered inferior. Precast concrete is also relatively brittle and requires care in handling and erection if spalling and cracking of the concrete are to be avoided.

The design philosophy discussed for the flexible segmented lining in granular, firm ground is also appropriate for the temporary lining composed of sets and lagging, or steel segments, followed with a permanent concrete lining. The final concrete lining is normally 10" to 12" in thickness and is comparatively stiff. However, by the time the concrete is

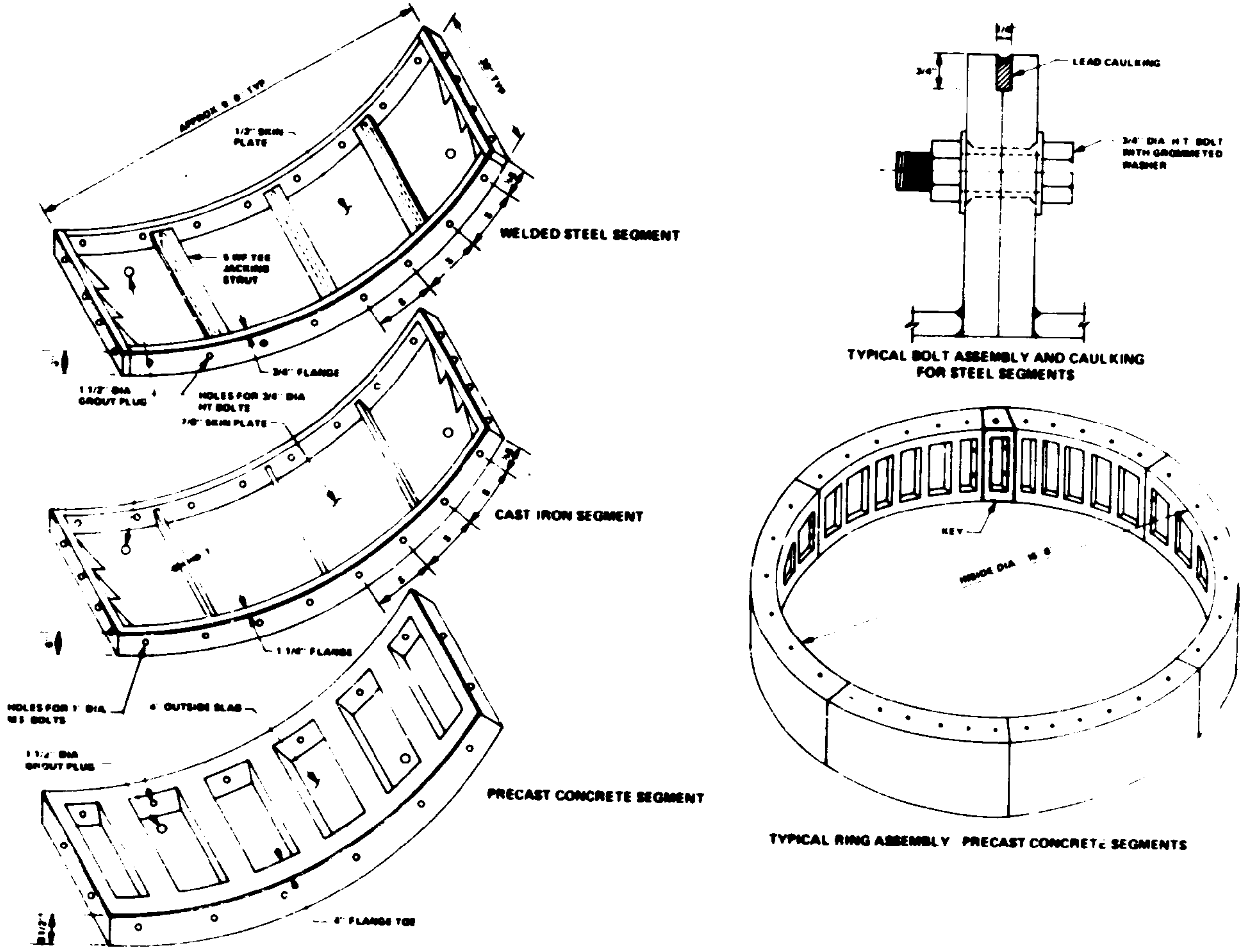


Figure 3-12. Tunnel Segments in Typical Materials

placed, most of the ground movements required for uniform radial loading will have occurred, and temporary lining will have been correspondingly distorted. Thus, for granular, firm ground, the final lining will be required to support mainly the long-term radial loading. For very plastic ground, the temporary liners should be steel segments, and the final lining designed for the radial and differential ground pressures.

The principal parameters governing the design of tunnel liners in ground (and as adopted by BART) are described below.

For the granular, firm ground, the segmented linings of the dimensions indicated in Figure 3-12 will be flexible with respect to the ground. Consequently, such a lining is designed for a uniform radial ground pressure to the height, or a proportion of the height, of the overburden. In addition, account is taken of bending moments and shearing forces, arising from the distortion of the tunnel, that are required to produce the uniform ground pressure.

The design parameters for BART were:

- Full radial pressure to the height of two tunnel diameters plus half the remaining distance to the ground surface
- A distortion of ± 1/2" on the diameter for overburden heights up to two diameters, and 5/8" for heights above

For plastic ground, the lining will be stiff with respect to the ground and therefore is designed to support the differential vertical and horizontal pressures. In the case of the BART designs, the horizontal pressures were assumed to be 85 percent of the vertical pressures.

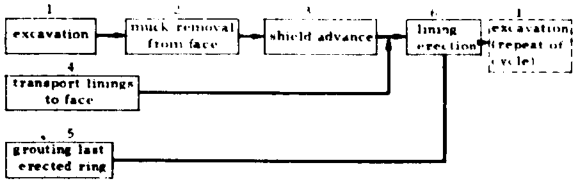
Both linings were designed to support the loads of the tunnel shields or tunneling machines, which applied a total jack thrust of up to 2700 tons transversely to the lining segments. To achieve watertightness, high-tensile bolts were used to provide continuity across the segment joints, and lead was used in the segment caulking grooves.

Comparison of Tunneling Construction Techniques

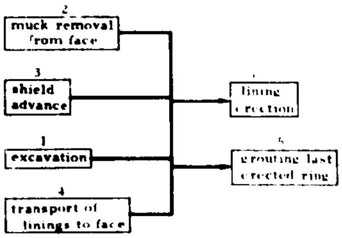
Tunnel construction may be undertaken using various installation procedures; the basic work events, however, are always the same. These events, which were discussed in detail previously, may be summarized as:

- Excavation of the tunnel face under the protection of a shield
- Removal of the muck from the tunnel face and from the tunnel
- Advancing the shield
- Transportation of the linings to the tunnel face
- Grouting the shield tail space
- Erection of the lining (caulking where appropriate)

Present-day techniques permit the above tasks to be accomplished in either of the two System-Work Flows, indicated below.



WORK FLOW 1 – MANUAL EXCAVATION

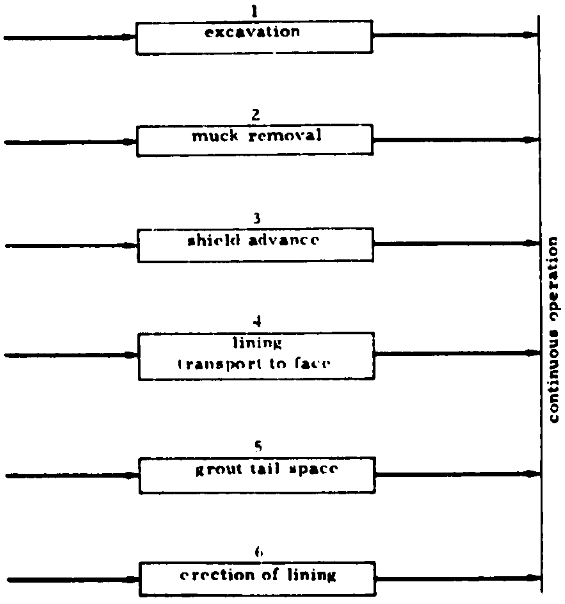


WORK FLOW 2 – MACHINE EXCAVATION

Work Flow 1 is typical for manual or equipment-assisted excavation with a shield. Work Flow 2 shows the sequence for a tunneling machine that excavates as it advances.

If the two work flows are compared, it can be seen that the essential differences are that in Work Flow I the major tasks – excavation, muck removal from face, and advance of shield – are three distinct operations, whereas in Work Flow 2 these three tasks are performed simultaneously by the tunneling machine operation. The latter process, therefore, eliminates some of the inefficiencies arising from the intermittent operations in Work Flow 1.

To achieve the ideal of continuous operation, the lining erection in Work Flow 2 should be undertaken at the same time as the excavation. The tail space grouting should also be a continuous (or semicontinuous) operation. This concept is indicated in Work Flow 3.



WORK FLOW 3 – CONTINUOUS OPERATION

As far as is known, the system whereby the lining is erected continuously during the excavation cycle has not been developed at the present time. The key for the system lies in the lining type, and at the present time two promising possibilities for linings exist. These are:

- Segments deployed in a helical ring, which would permit the segments to be placed continuously while the tunnel machine was advancing. This system might be improved further with the introduction of a rotating shield tail, which would permit the segments to be placed one at a time against the ground. This would eliminate the tail space grouting. (In some situations, though, contact grouting might be required.)
- Cast-in-place concrete using slip-forms. This appears to require some type of reaction jacking ring which would react off that portion of the concrete that has sufficiently hardened.

Both these possibilities will be discussed in greater detail later in Section 8 under the heading of "NEW TECHNOLOGY."

SUMMARY

Prior to actual construction, many meetings and decisions are necessary with city officials, utility companies, and owners of buildings affected by the proposed construction. In addition, as much geology/soils information as possible must be assembled and acquired. Rights-of-way and contractor work areas must also be purchased or leased.

A cut-and-cover project begins with the relocation and support of existing utilities. Ideally, major relocation work should be done by the utility companies prior to the award of the construction contracts. Support of utilities remaining in the work areas is the contractor's responsibility. Traffic control and decking of the street over the underground construction are important elements, particularly in downtown areas. Before excavation proceeds for either a station or line structure, existing building foundations susceptible to damage must be supported against movement. Installation of the excavation support system and street decking will follow. Dewatering of the excavation is a major phase of the construction process and must be carefully done so that soil conditions beyond the construction area are not adversely affected. Once the permanent walls, columns, and floor slabs are installed, backfill is placed and the street restored.

In the tunneling process, the principal disruption at the surface is the workshaft, which serves a considerable length of tunnel. Thus, traffic control, decking, and utility relocation are generally confined to the work area significantly less than is the case with cut-and-cover construction. Underpinning of adjacent structures is usually confined to the workshaft areas and to areas where the tunnels are close to foundations. Tunnel excavation can be done by either manual or machine methods, with the excavated material removed through the workshaft. As a tunnel progresses, it is immediately lined to support the excavation, the lining being grouted and caulked to provide watertightness. Where groundwater cannot be controlled by pumping or grouting at the tunnel face, compressed air must be used. Compressed air operation is very costly in terms of equipment and labor.

Section 4

ENVIRONMENT, SAFETY, AND INSURANCE

INTRODUCTION

The environmental conditions, as discussed in the context of this study, relate to those of two distinct but interconnected areas.

The first area is the one outside, but generally contiguous to the project construction and includes both the places of business and the streets used by the public. There are many impacts, both immediate and long-term, of underground construction upon this area, and because of their complexities they can be discussed in this report only in general terms.

The second area is the one within the construction zone itself and relates to both the work operations and the worker. Within this area, the environmental conditions are affected by two sources: those external to the work area, such as the traffic and buildings alongside the construction; and those generated by the actual construction operations and the related safety policies and insurance programs. The latter are interdependent and are important determinants of work efficiency and productivity.

The effectiveness of the contractor's safety program is to some degree a function of the environmental conditions in the construction site area. For example, weather, an uncontrollable factor, influences working conditions, particularly in open excavations. However, the more major influences are such things as the amount of traffic, the need for underpinning, rerouting of utility lines, etc., all of which can increase already hazardous working conditions and necessitate the inclusion of new safety procedures and a general expansion of the safety program. Although the safety supervisor's scope of concern is different for cut-and-cover than it is for tunneling, his need for a safety program that is flexible with respect to environmental factors is independent of the type of construction, and this flexibility is of the utmost importance.

After the safety procedures for the job are established, the reporting system and follow-up activities undertaken by the safety supervisor may become one of the central indices of productivity. Therefore, it is of crucial importance that the reported statistics be accurately maintained, not only for the information they supply to the contractor during the performance of the work, but also for future contract bidding and safety program analysis.

Accident data relate directly to the job's insurance policies and programs. Without good record keeping and follow-up to prevent similar occupational injuries, the value of insurance programs may be difficult to assess. Many of the occupational injuries shown in the available BART and WMATA data are minor and usually do not involve any significant lost time to the job. Yet these records, especially the ones related to the more hazardous working conditions (such as compressed air tunneling), are an indicator of overall safety program effectiveness in dealing with varying work areas and diverse (experienced vs. newly trained, skilled vs. unskilled) types of employees. In the long run, if all job-related injury and environmental data are complete and factual, the insurance program can serve as one of the indices of productivity.

Productivity as reflected by these three elements — environment, safety procedures, and the insurance program — will take on an increasingly significant role in the 1970's and may become a major factor in prequalifying contractors during the bidding process. With skyrocketing workmen's compensation and other insurance payments, not to mention total construction costs, a contractor's accident record rating will be weighed heavily by both the owner and the taxpayers, who shoulder much of the economic and noneconomic burdens of a transit project; and these elements of a tunneling or cut-and-cover excavation job can have an effect that is large enough to determine the business development future of a contractor. In a period of inflation and tight money, this point cannot be stressed too often.

ENVIRONMENTAL IMPACTS OF UNDERGROUND CONSTRUCTION IN THE PUBLIC DOMAIN

The major environmental impacts of cut-and-cover and tunnel construction are:

- Transportation and Traffic
- Physical Environment
- Visual and Urban Design
- Historical
- Economic
- Social

In urbanized areas, especially in the central business district, transit construction is the source of many adverse, but usually short-term environmental impacts (e.g., physical obstacles for pedestrian and vehicular traffic). The degree of impact is often contingent on the staging schedule of the proposed project, which in turn is dependent on the availability of funds, construction capacity, and the necessity of minimizing disruption of street traffic and access to adjacent buildings.

Traffic and Transportation

Short-Term Impacts. In cut-and-cover excavation, the following alternative ways of handling the street traffic are possible.

- The street is partially or totally closed, and no decking, or a limited amount, is provided. The traffic is rerouted to adjacent streets, which tend to become overloaded. This approach probably causes the most inconvenience to the general public, but reduces the construction time and cost.
- The street is closed block by block during the installation of the decking. This approach reduces decking installation time and cost and results in less inconvenience to the public than the method described above.
- The streets are kept open during heavy traffic periods, and the decking is installed during off-peak traffic, a lane width at a time. This approach minimizes the impact on the traffic, but maximizes decking installation time and cost.

Long-Term Impacts. The underground component of the rapid transit system reduces vehicular traffic within the central city boundaries, particularly within the CBD (central business district). A modern and attractive transit system within the CBD offers a safe and convenient alternative to the use of the automobile and eases congestion, especially at peak hours. In addition, underground construction can alleviate hazardous traffic conditions at grade and can generally provide a safer environment for pedestrian and vehicular traffic alike.

Physical Environment

Short-Term Impacts. Gas, water, sewer, and electrical lines may have to be rerouted or supported during construction and restored at completion.

Airborne dust and dirt is more prevalent, especially in a cut-and-cover excavation.

Objectionable noise is caused by the equipment and construction methods employed, particularly pile driving. This noise can be minimized by the use of the noise-suppressing devices in compliance with local noise ordinances or alternatively installing the piles in predrilled holes.

Muck and backfill materials in the streets are by-products of cut-and-cover excavation. This problem can be alleviated by continuous sweeping of the street area and washing the wheels of dump trucks.

Heavy truck traffic for delivery of materials and removal of excavation and debris cause temporary traffic and pedestrian delays and congestion near the site. This can be minimized by employing nearby 'holding" areas for trucks waiting to load or unload.

Long-Term Impacts. Most of the adverse physical impacts of tunnel construction are more than counterbalanced after the completion of the rapid rail transit system. Significant reductions in vehicular traffic, particularly in the CBD, result in a sharp decrease in vehicular pollutant emissions and noise.

Visual and Urban Design

Short-Term Impacts. The visual intrusion of construction could of course be lessened by shortening the construction schedule, but this would result in higher costs. A more practical way of dimishing the unpleasant visual impact is to pay careful attention to the details and layouts of the work areas and to provide neat and attractive fences and billboards.

Long-Term Impacts. The long-term result of underground construction is the general improvement in the appearance of streets currently crowded with traffic. In the case of BART's Embarcadero Station, electric overhead wires that are now needed to power the local streetcar service will be combined with the rapid rail system underground and will disappear.

Historical Impacts

Special care must be taken that buildings of historical and architectural significance adjacent to tunnel construction not be damaged Areas and individual structures of historical interest may cause temporary inconveniences in terms of access and physical separation of parts by the transit project, but these disruptions can be kept to a minimum, and no long-term adverse effects should be allowed to occur.

Economic Impacts

Short-Term Impacts. The construction of a proposed transit tunnel in the CBD will cause disruption and short-term slackening of business activity. Those businesses that rely on pedestrian access (e.g., retail stores and restaurants) will experience the greatest losses in revenue. Hotels and office buildings whose tenants require minimal office space may experience declines in occupancy as their clienteles seek quieter, more accessible locations. Large commercial high rises, however, will probably not undergo any substantial changes in rental patterns.

If the private sector can work out in advance a plan to accommodate vehicular and pedestrian traffic with as little inconvenience as possible, the potential economic impacts upon the businesses involved can be mitigated. Length of time of disruption is also an important factor since the public can tolerate an adverse impact, such as the closing of a business, for a limited period before its patronage is diverted. Efforts to inform the public of the duration and extent of construction and to maintain as much pedestrian access as possible can help to alleviate heavy economic losses in the CBD.

Long-Term Impacts. Transit construction should have wide-ranging economic benefits. A modern transit system is a positive factor in revitalizing urbanized commercial areas. Providing the central city with ready access to the surrounding environs — urban and suburban — ensures a continuous flow of manpower and capital into the CBD.

The flight of businesses from a rundown CBD can be stemmed by an attractive transit system linking outlying populated areas to the central city.

Social Impacts

Short-Term Impacts. The short-term social impacts of transit tunnel construction are likely to be access disruptions to commercial enterprises, offices, and human services; increased levels of noise and vibration; adjustments of transit service in the construction area; and some decline in retail sales along the affected streets. A few commercial enterprises may choose to relocate their businesses outside the immediate construction area because of the falloff in business. All these adverse impacts cannot be avoided while the tunnel construction phase is being implemented. However, with the cooperation and patience of all involved parties, the inconveniences can be minimized to avoid undue hardship to any particular group in the affected area and to the general public.

Long-Term Impacts. In the long run, the benefits of transit underground construction to the entire community will more than compensate for the disruptions of short duration in traffic patterns and in access to services in the affected area. Improved public accessibility from the entire region to the central city will enhance that district's role as the center of commercial, cultural, and social activities. This is of special significance to those transit-dependent individuals in low-income areas and to the handicapped, who will have a safer and more direct route to employment and human-service facilities within the CBD.

INSURANCE PROGRAMS

Introduction

Construction safety, workmen's compensation, and protection of third-party life and property have a direct bearing on construction economics and relate directly to the project insurance and safety programs. In recent times, the federal government has taken a strong interest in these two aspects of construction, and any insurance program or safety program established by the owner must take into account the documents issued by OSHA and HEW relating to construction site safety and workmen's compensation.

In the system-wide insurance concept, the owner provides the insurance on behalf of his contractors and normally receives any premium handback resulting from a contractor's good safety performance. The owner therefore has an additional interest in providing safe construction conditions, and, accordingly, the contract documents require the contractor to implement safety programs, which the engineering construction manager administers.

The details of these safety programs are discussed later in this section, and the benefits arising from a system-wide approach will be apparent. However, under the present requirements of public bidding required for publicly funded construction projects, there are some drawbacks. These are:

- All contractors with experience and financial capability must be allowed to bid for the work. No demonstration of good safety rating is required.
- The safety ratings of contractors selected on a low-bid basis can range from good to poor. (This is borne out by extensive experience.)
- The insurance premiums are normally based on the poorest safety rating anticipated, and the premium handbacks are also influenced by poor safety performers.

- As neither the good nor the average performers share in premium handbacks, they have less incentive for safe working than they would if they bought their own insurance. The poor performers have no incentive to improve their safety ratings since the higher premiums do not come out of their pockets.

Insurance administrators are alarmed at the fact that compensation to injured workers is likely to be subject to very sharp increases in the future. Consequently, where public bidding procedures are in force, these administrators are becoming more selective about the contractors they will insure. Since contractors who are bad insurance risks will materially increase the cost of system-wide insurance, it appears that a method of prequalifying bidders with respect to insurance rating must be considered. In addition, the possibility of sharing of the premium handbacks, which would increase the contractor's incentive to make his projects safer, should also be looked into.

BART Insurance Programs

BART provided system-wide insurance coverage on behalf of its contractors at the outset of construction. WMATA provided similar insurance at a later date in its program and after study projects C0021 and C0041 had been contracted.

The principal details of the BART programs are given below.

The insurance program underwritten by the transit insurance administrators provided a system-wide coverage. The insurance administrator and his field respresentatives evaluated and processed claims submitted by the contractor and his subcontractors.

The following insurance coverages applied to the prime contractors and to their subcontractors of $10,000 or more in value:

Workmen's Compensation and Employer's Liability. This insurance covered personal injury (workmen's compensation), bodily injury, and property damage. The premium rates per $100 payroll were:

Tunneling (free air)	$14.86
(compressed air)	$31.09
Cut-and-cover work	$ 8.86
Aerial structure work (general)	$ 8.90
Average for all classifications in the overall construction project	$ 7.82

Premium payments amounted to a total of $26,725,000, of which $10,000,000 was applicable to bodily injury liability and property damage liability, and $16,725,000 was applicable to workmen's compensation.

The premiums for these coverages were based on contracts totaling $850,000,000.

Bodily injury liability claims and property liability claims amounted to $19,030,000.

BART expects to receive $6,000,000 workmen's compensation dividends, thereby, reducing the overall project premium from $26,725,000 to $20,725,000. This would amount to 2.45 percent of the value of the contracts covered.

All-Risks Course of Construction (Builder's Risk Coverage). This was limited to $50 million, subject to deductibles for any one occurrence of:

$1,000 for fire, extended coverages, vandalism, and malicious mischief

$1,000 for damage caused by earthquake

$25,000 for damage from any other cause

BART paid the premiums for all of these coverages, but charged the contractor for the actual premiums for workmen's compensation and employer's liability insurance for the contractor and his covered subcontractors.

The program did not offer coverage for contract bonds, contractor's equipment, automobiles, automobile bodily injury, and automobile property damage liability.

All contractors and subcontractors who were covered by the program had to provide coverage at their own expense and had to supply evidence of such coverage to BART for automobile bodily injury, and property damage liability (for bodily injury limits of $500,000/$1 million and property damage limits of $250,000). In addition, they had to provide coverage to these limits for aircraft and watercraft bodily injury and property damage liability if aircraft and watercraft were used in the operation.

All contractors and subcontractors who were not covered by the insurance program had to provide coverage at their own expense, and supply evidence of such coverage, for workmen's compensation and employer's liability insurance and personal injury, bodily injury, and property damage liability insurance (including automobiles, products, and/or completed operations coverage), with limits of at least $100,000/$300,000 for bodily injuries and $100,000 for property damage.

The insurance protection afforded to the contractor under the BART's insurance program ceased upon final acceptance of the work. Consequently, if a contractor was required to perform work after final acceptance, such as might be required in connection with the guarantee, or otherwise, it was necessary for the contractor to obtain his own insurance.

Under the terms of the system-wide insurance contract, BART was the sole beneficiary of all savings and dividends from the workmen's compensation insurance. Because of a favorable overall safety record (including all BART contracts), BART received approximately 35 percent on paid premiums from the refunded workmen's compensation insurance.

WMATA Insurance Programs

The contract documents for the WMATA Projects C0021 and C0041 required the contractors to procure and maintain the following insurances:

Insurance Type	Minimum Policy Limit	
Workmen's Compensation	$ 250,000	
Contractor's Comprehensive General Liability		
• Personal Injury	$ 300,000	each person
	$ 5,000,000	each occurrence
	$ 5,000,000	annual aggregate
• Property Damage	$ 1,000,000	each occurrence
	$10,000,000	annual aggregate
Automobile Liability		
• Bodily Injury	$ 1,000,000	each person
	$ 5,000,000	each accident
• Property Damage	$ 1,000,000	each accident
Protective Liability (issued to and covering the liability of the owner, engineering consultants, inspectors, and others)		

• Personal Injury	$ 300,000	each person
	$ 5,000,000	each occurrence
• Property Damage	$ 5,000,000	each occurrence
	$10,000,000	annual aggregate

The contractors for both projects were approached to obtain information concerning the premiums paid and the claims settled with respect to the various insurances, but neither appeared willing to release the figures at the time of the requests. In addition, information concerning the claims settled or premium handbacks made was not available while work on the projects was still proceeding.

COMPRESSED AIR MEDICAL CENTER

All BART tunnels under compressed air were served from a Transit Compressed Air Medical Center operated by transit insurance administrators located in San Francisco. The medical center performed all the medical services required by the state and federal compressed air safety orders.

A schematic layout of the medical center, which was located in San Francisco, is shown in Figure 4-1.

The medical center consisted of three locks for testing workmen and treating compressed air sickness. Each of the two locks had two compartments inside its 7-ft-dia. by 18-ft-long cylinder. The inner one was for treatment and was equipped with oxygen equipment, two cots, and telephones. The small airlock permitted entrance to the inner lock in the event of emergency. Another lock, 7 ft in diameter and 24 ft long, was similarly equipped and operated.

A mobile portable lock was provided for transporting severely injured workmen directly from compressed air tunnels (thereby avoiding the requirement of a decompression cycle).

56 JULIAN AVENUE, SAN FRANCISCO, CALIFORNIA, 94103

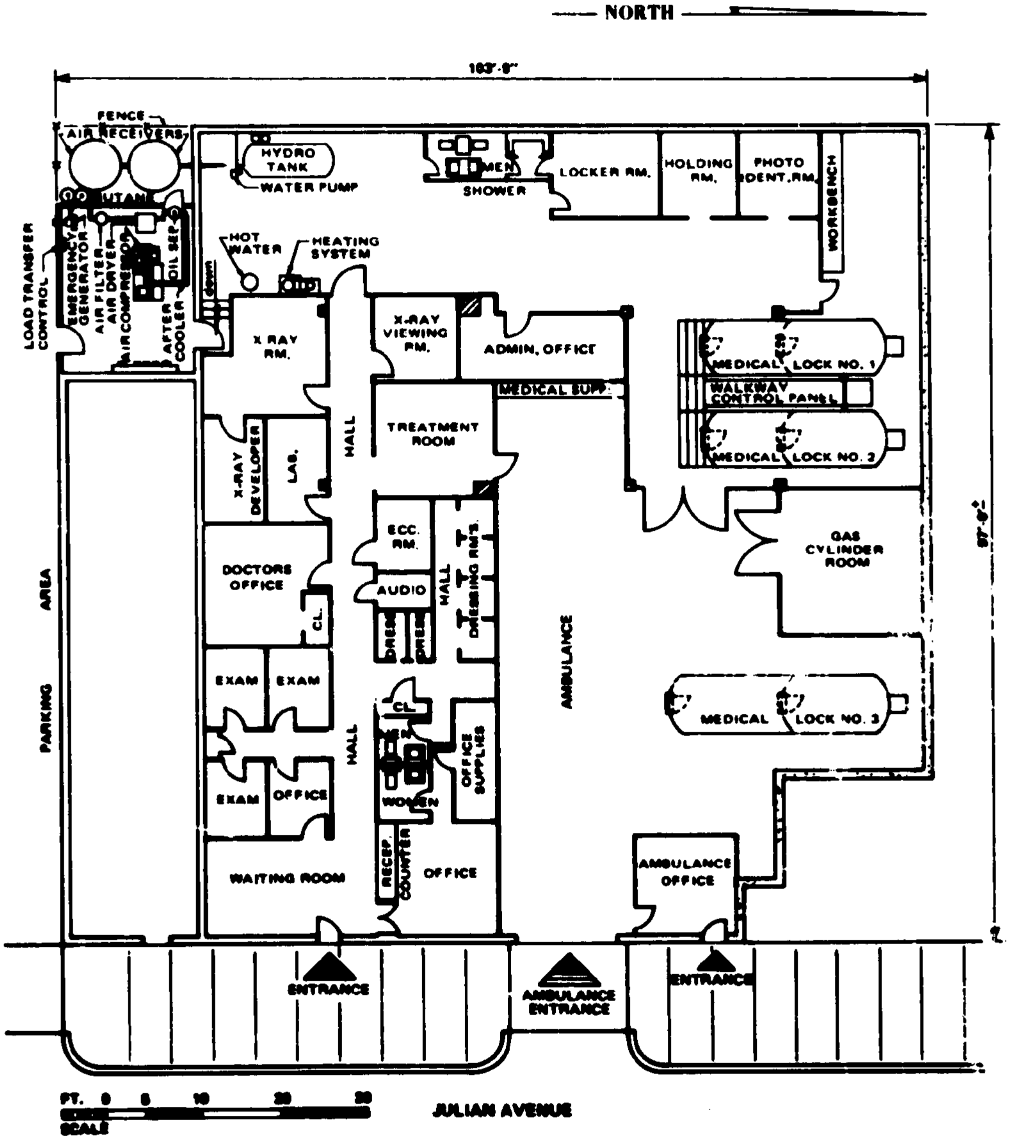


Figure 4-1. Transit Compressed Air Medical Center
San Francisco, California
Floor Plan

Capital Costs of the Medical Facility

The following capital costs were incurred:

Medical locks supporting facilities and installation	$124,178.37
Medical and laboratory equipment, medical instruments, and miscellaneous medical items.	$ 7,717.31
Office furniture and hyperbaric and radiograph equipment	$105,796.76
Medical center rental lease period 3 years:	
For 1 year (1st floor only) @ $600/month	
For 2 years (1st and 2nd floors) @ $810/month	
Rental Cost	$ 26,600.00
Total Cost	$246,196.68

Staffing of Medical Center

The Transit Compressed Air Medical Center had a staff of 14 and provided 24-hour, 6-days-a-week medical service. This was accomplished with three physicians, seven medical technicians, one medical lock supervisor, one TIA coordinator, and two office employees.

One physician and one medical technician were assigned to day shifts. Swing and graveyard shifts were covered with one physician and two medical technicians on each shift. On weekends, one medical technician was on duty and one physician was on standby status.

A minimum of two people were required for treatment: one, generally the physician, in the chamber with the patient; and the other, a technician, for operating the chamber on the outside of the lock. A third, a technician, was on standby for other emergencies.

The operating costs of the medical center were approximately $1,500,000.

Treatment Records

The following records were compiled:

Number of compressed air contracts served		6
Number of people processed		
Total physical examinations		3,344
First aid occupational cases	— 2,036	
Doctor's cases	— 2,636	
Total first aid and doctor's cases		4,672
Total number of decompression illnesses		138
Total number of decompressions		97,170

INDIVIDUAL CONTRACTOR RESPONSIBILITY

The state and federal compressed air regulations require 24-hour availability of medical facilities and personnel during compressed air tunneling. If the individual contractor is made responsible for this requirement, he must provide at least one medical lock, one portable lock, and most of the medical equipment noted above. He must also provide for the services of at least one doctor, his assistant, and lock attendants to work on a full-time daily basis and to be on call during the swing and graveyard shifts.

When multiple compressed air tunnel projects are in progress simultaneously, as in the case of the BART system construction, the savings due to owner-provided medical facilities are readily apparent.

ACCIDENT EXPERIENCE SUMMARIES

Insurance administrators develop monthly summaries to provide cumulative statistical accident data. Such data include the following for each project:

- Man-hours worked
- Time lost to injuries
- Incident rates that relate to "lost work day cases"

The incident rate for the WMATA insurance was a monthly index calculated as follows:

$$R = \frac{N \times 200,000}{MH}$$

where N = number of injuries

MH = total hours worked by all employees during the month

200,000 = base for 100 full-time equivalent workers @40 hours per week, 50 weeks per year

This index is used by insurance groups as a measure to evaluate a contractor's insurability on a national statistical basis.

The current average index for heavy civil engineering construction appears to be between 6 and 7. An examination of some of the WMATA accident experience summaries indicates that over several typical months, many of the project contractors attained an average index within or below the national index. A few contractors appear to have indexes well above this index, some dramatically so. (The implications of this are discussed at the end of this section.)

If this form of statistical reporting could be keyed to the data that should be provided in the injury reports, a useful tool for determining the cause of injuries and their effects on productivity would be obtained, and guidance for the necessary corrective actions would be provided.

Representative WMATA accident experience summaries are included in the Appendix. None was available for BART.

ACCIDENT CLAIM SETTLEMENT RECORDS

At the outset of the study, it was hoped that the BART project claim settlements, particularly with respect to workmen's compensation, could be plotted against either the task performed or the work events being undertaken at the time of the accident. This would have furnished some measure of the hazard-proneness of any particular work operation or event and would have provided a further check on similar statistics taken from the safety reports. Unfortunately, this information could not be identified from the settlement claim sheets.

In order to provide an indication of the type of work being performed at the time of the accidents, the settlement claims were aggregated monthly and plotted against the construction bar schedules. This is shown in Figures 4-2, 4-3, and 4-4.

As several work events may have been proceeding simultaneously at the time of the accident, no detailed inferences can be obtained from these displays. However, they do demonstrate

- The cumulative settlement payment claims made for each project for workmen's compensation, bodily injury, and property damage
- The cost of claim settlements in terms of the total cost of the project

The data of interest were for the threee BART projects and are displayed below.

	Project K0016		S0022		S0031	
	$ Payment	% of Total	Payment	%	Payment	%
Property Damage	290,000	46	17,000	8	150,000	35
Bodily Injury	280,000	45	5,000	2	175,000	41
Workmen's Compensation	60,000	9	200,000	90	99,000	24
	630,000		222,000		424,000	
Cost of Projects	$20,194,000		$18,371,000		$10,817,000	
$\frac{\%\text{ Total Claim Settlement}}{\text{Project Cost}}$	3.1		1.2		5.1	

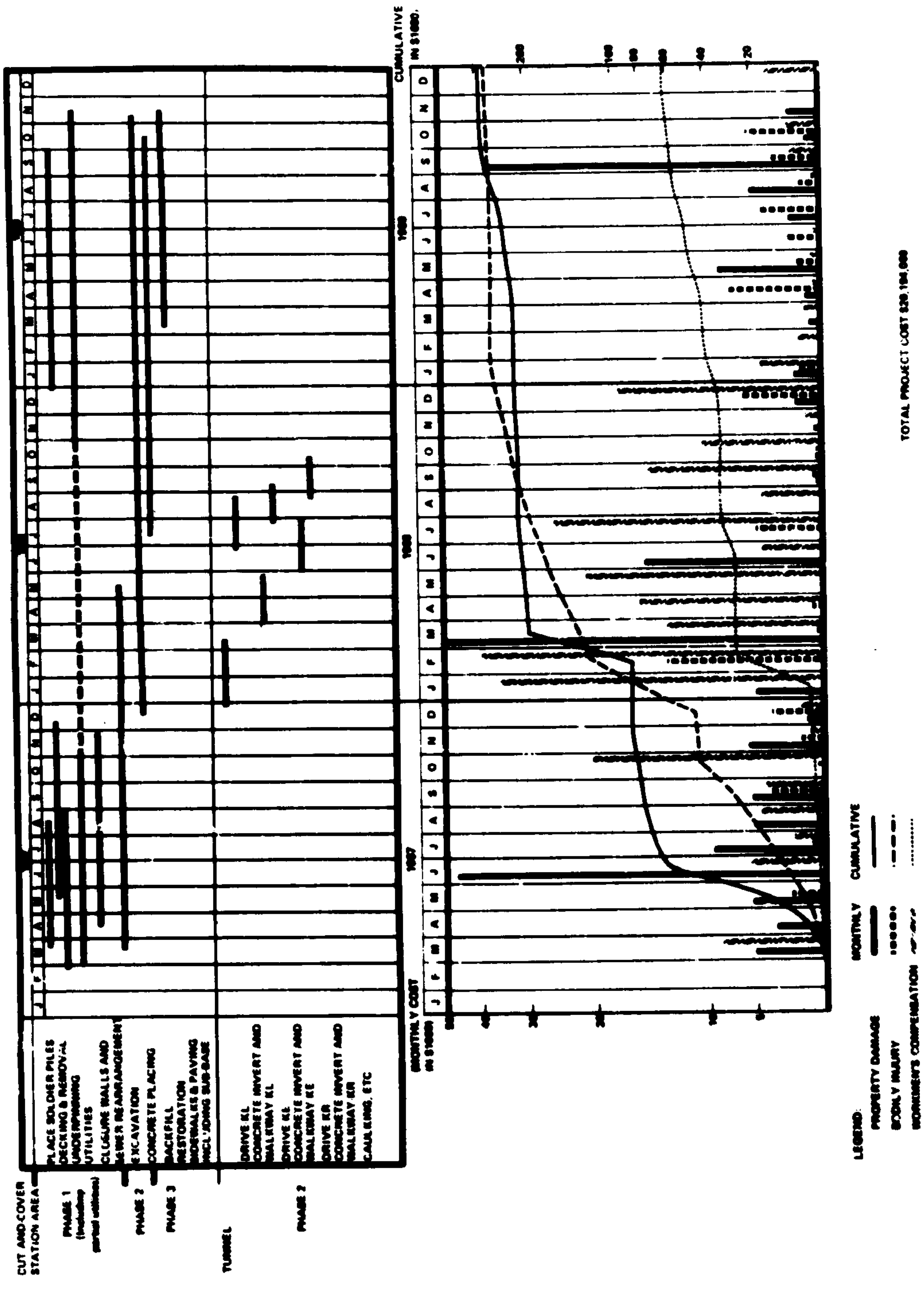


Figure 4-2. Claim Settlements vs. Construction Schedule - BART Project K0016

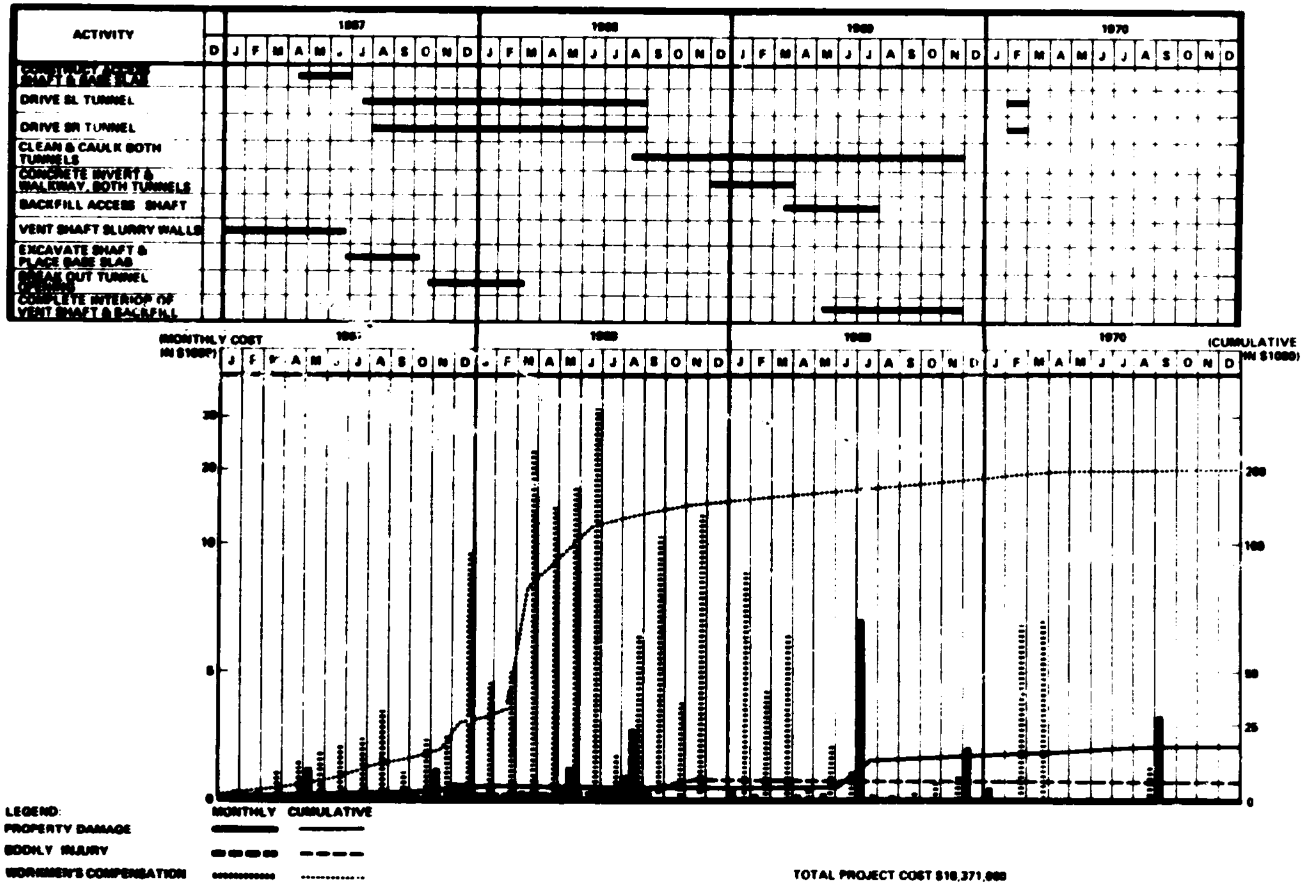


Figure 4-3. Claim Settlements vs. Construction Schedule – BART Project S0022

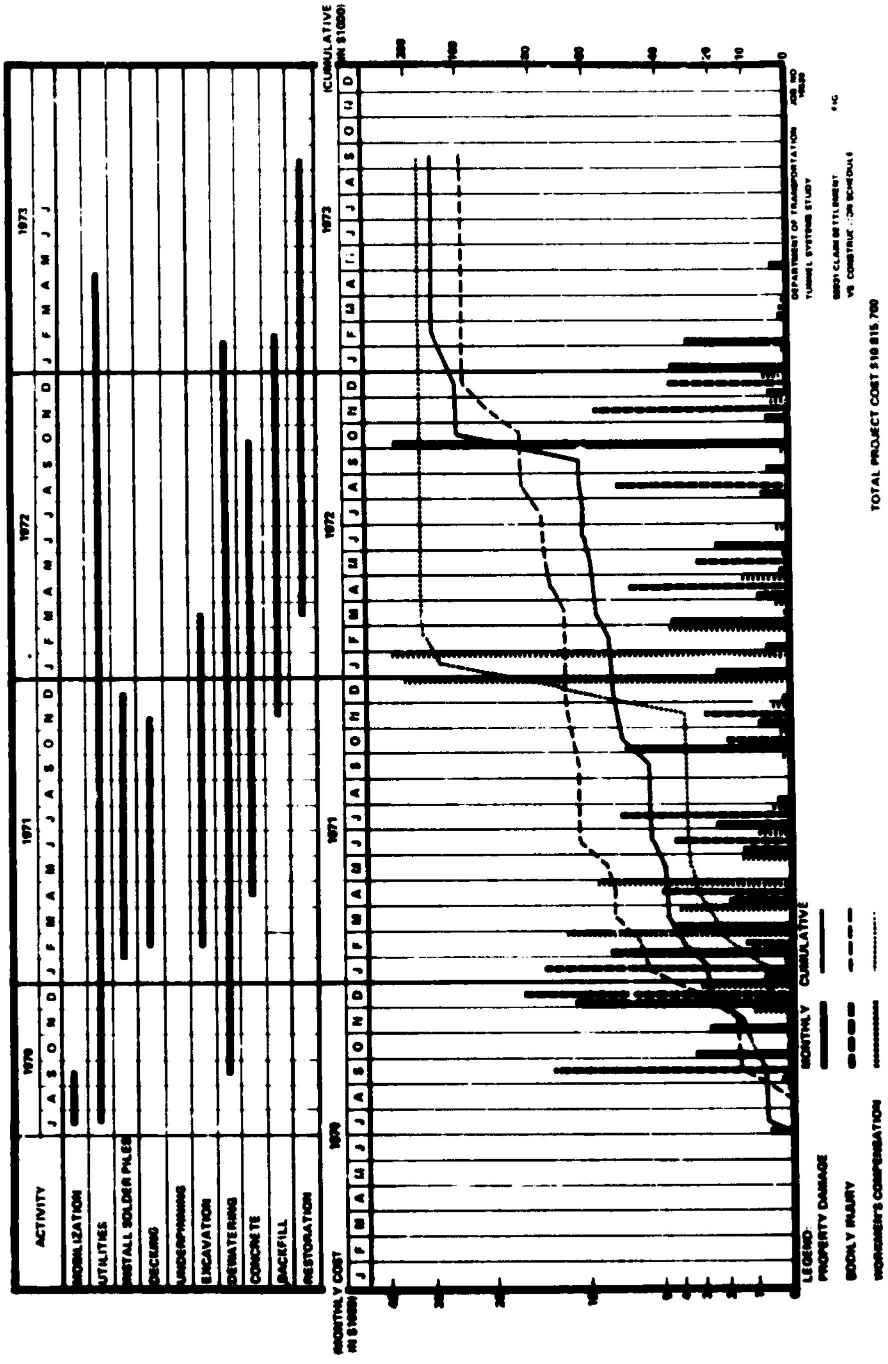


Figure 4-4. Claim Settlements vs. Construction Schedule – BART Project S0031

If the figures for these projects are compared, the following points of interest can be noted:

- In tunnel Project S0021, property damage and bodily injury claims were low, and the workmen's compensation was high compared with the compensation in cut-and-cover projects. This underscores what is common knowledge in the construction industry — namely, that tunnel construction, particularly in compressed air, is hazardous to the workmen, but if the construction is undertaken with care, property damage can be minimal.
- Cut-and-cover Projects K0016 and S0031 apparently were more dangerous to the general public than to the workmen.
- Total claim settlements for the cut-and-cover projects substantially exceeded those for the tunnel project.

It must be emphasized that the above observations apply to three projects only, and therefore the results should not be taken too literally. However, the exercise does demonstrate the type and potential value such statistical data might have in assessing both the environmental aspects of different types of construction and the impact of the related project costs.

SAFETY PROCEDURES

Introduction

The specifications on both the BART and WMATA systems required that prior to starting the work, the contractors had to submit written safety programs covering all phases of the construction. Extensive measures were to be undertaken for the safe performance of the work to avoid undue danger to the personnel employed and to public life and property. These safety programs required compliance with all provisions of local, state, and federal safety laws and regulations. The contractor was required to provide full-time safety supervisors to monitor the safety programs, to make frequent inspections of the work areas, and to provide daily accidents reports to the engineer. In addition, he had to submit to the engineer a monthly report giving statistical data on accidents, including the total number, type, and severity of injuries, and the damage to property and material.

The contractor was required to participate in monthly meetings of a safety committee composed of supervisory personnel of the engineer, the insurance company's administrator, and the contractor's representative. At these meetings, the contractor's accident record was reviewed and his compliance with the contractual safety requirements was discussed to establish the effectiveness of his safety effort. This procedure allowed improved approaches to the implemented.

Accident and Injury Reports

There were two objectives of the safety study: (1) to define the hazardous project tasks and recommend remedial measures by studying the safety reports and other available statistical material; and (2) to determine the effect of the accidents on labor productivity.

To this end, copies of the accident reports, the medical injury reports, and the monthly accident experience summaries were obtained for the study projects in both systems. Copies of the representative reports and summaries are displayed in the Appendix.

The accident and medical reports for both systems lacked in the following key information, which was needed to satisfy the objectives of the study:

- In most cases, the time lost by the employee due to injury was not given.
- The description of the task being performed and the nature of the work being undertaken at the time of the accident were seldom described.

In addition, other data required by the report forms were not furnished by supervisors, and data that would have been useful for the study objectives were not included in the forms.

The accident and medical report records for both WMATA study projects were obtained, but the records for only one BART project (S0031) was available at the time of the study.

To provide a statistical summary of the only consistent information given in the reports, the types of accidents and the resulting injuries were recorded and displayed on vertical bar graphs. See Figures 4-5, 4-6, and 4-7.

The information displayed, although quantitatively limited, indicates for illustrative purposes the frequency of types of injuries and the frequency of types of accidents for a cut-and-cover line, a cut-and-cover station and line, and a tunnel project.

SUMMARY

The installation of underground rapid transit affects the environment of the areas adjacent to the construction area and establishes the environment for the employees within the work area. Adverse environmental impacts upon the areas adjacent to the construction can be lessened by means of presently available alternative construction sequences, but these involve the expenditure of more time and money.

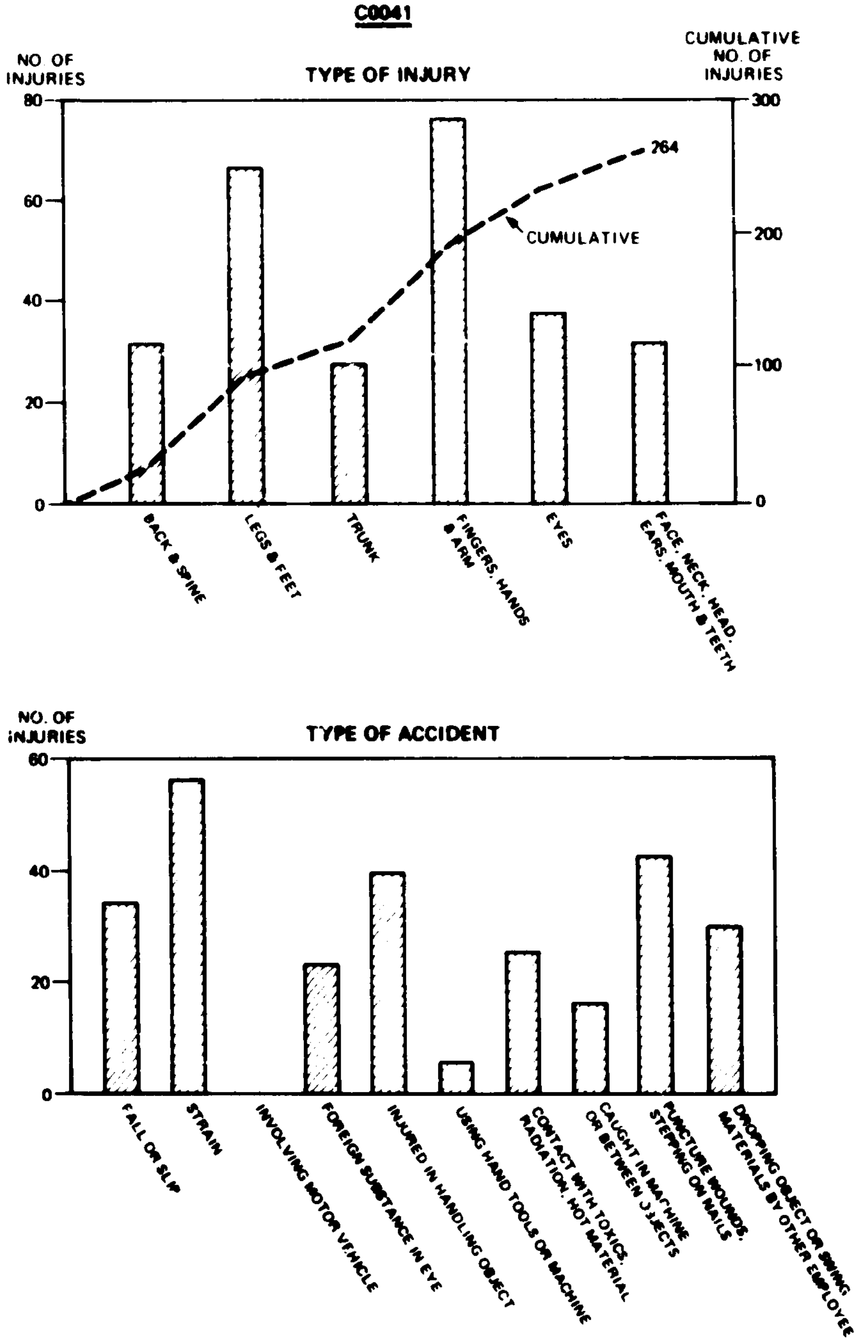


Figure 4-5. Number of Injuries vs. Type of Injury and Number of Injuries vs. Type of Accident for BART Project C0041

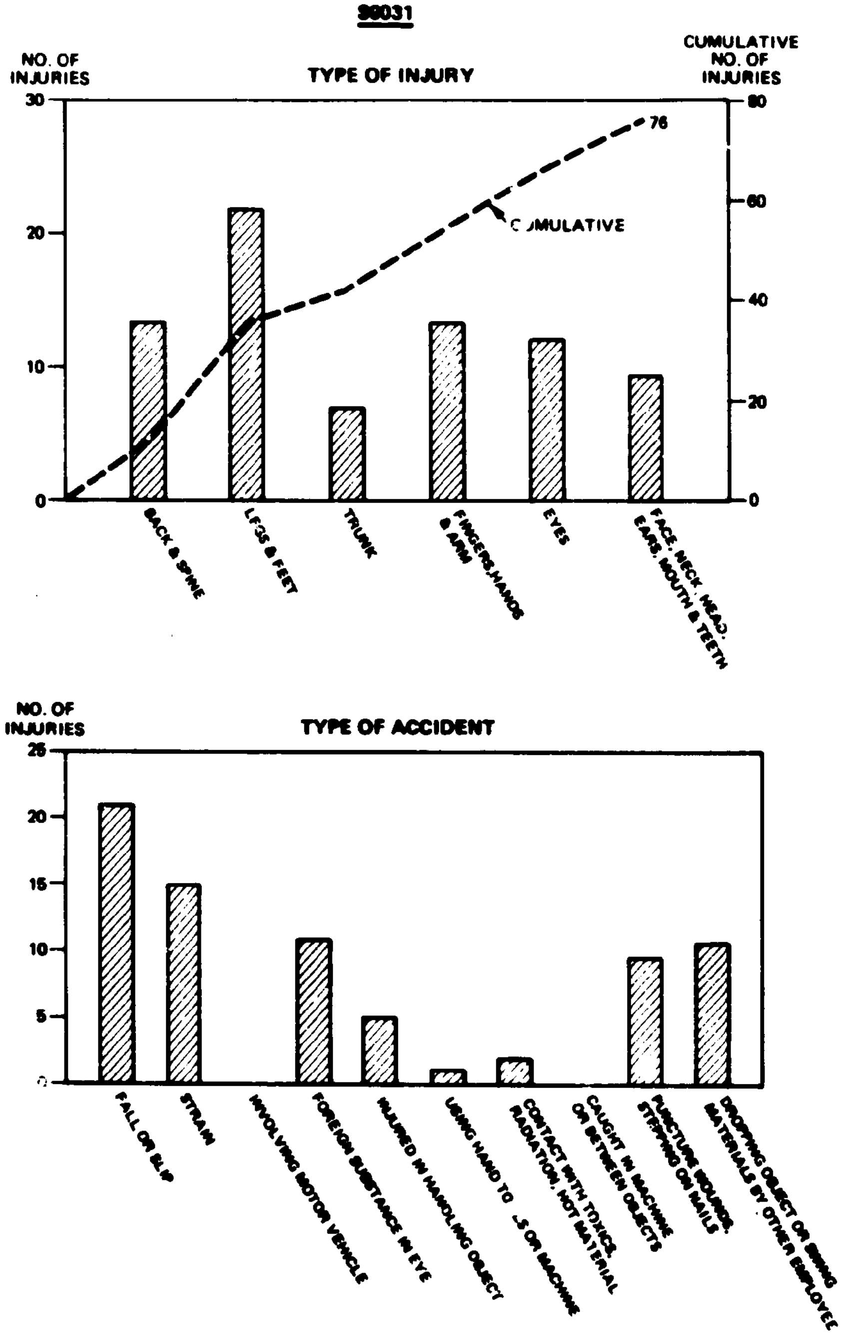


Figure 4-6. Number of Injuries vs. Type of Injury and Number of Injuries vs. Type of Accident for BART Project C0031

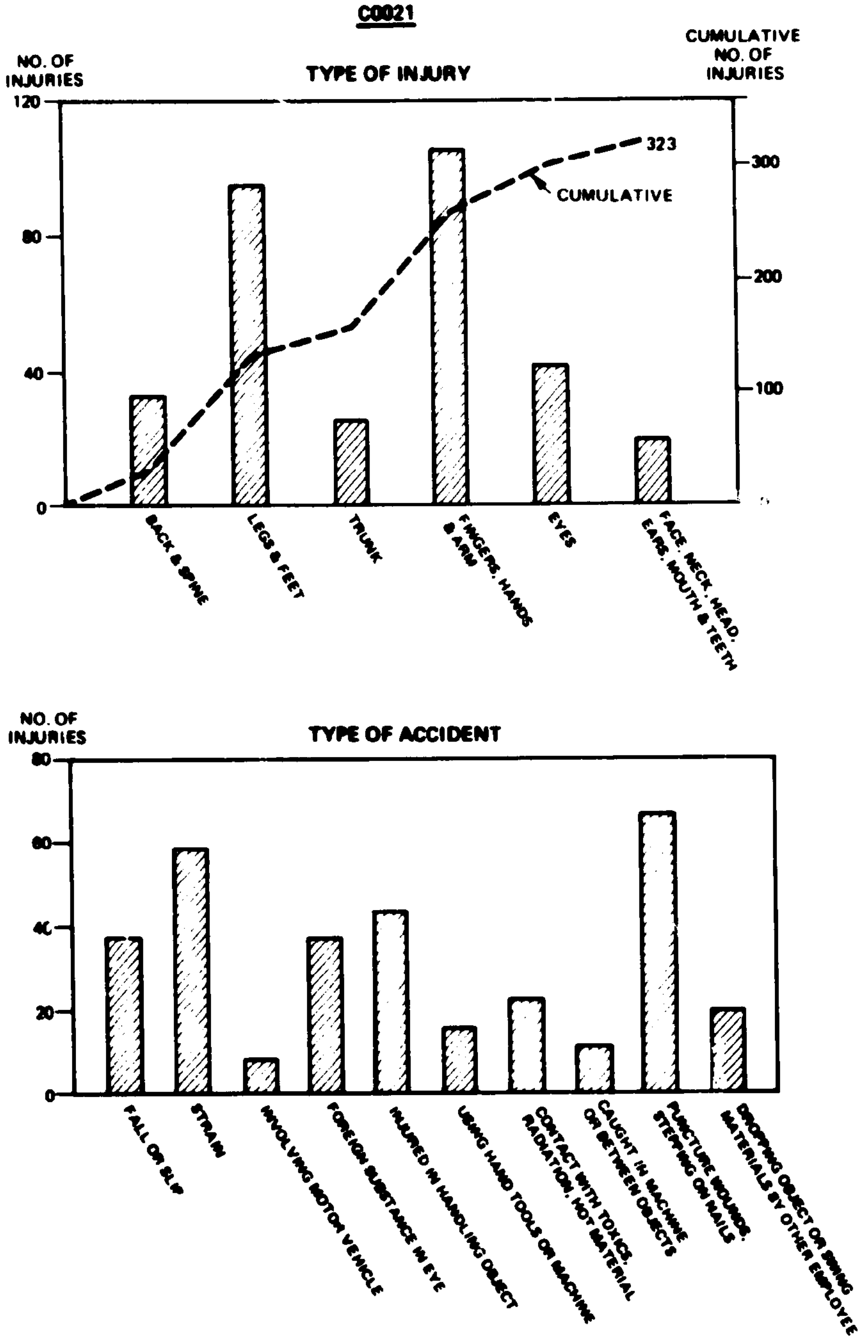


Figure 4-7. Number of Injuries vs. Type of Injury and Number of Injuries vs. Type of Accident for BART Project C0021

Short-term adverse impacts of major construction include: noise and vibration, traffic congestion, and potential loss of business. Major benefits resulting from the completed work are: reduced traffic congestion, improved access to the CBD, reduced travel time and cost, and revitalization of the CBD.

Although the accident statistical data and the insurance claim payments for the two transit systems studied were not adequate to provide satisfactory quantitive evaluation of the effectiveness of safety programs on the study projects, a clear indication of the economic impact of such programs upon the underground was obtained.

Conclusions regarding insurance and safety programs are as follows:

- **System-wide insurance has definite advantages in that it can provide a positive, unified, and routine approach to construction safety.**
- **In general, safety and productivity are axiomatic. A project with a good safety record normally is well-organized, is completed on schedule, and is profitable to the contractor.**
- **Complete statistical recording of accidents, injuries, and claim settlements (as discussed in this section) is important. This permits the identification of accident causes with subsequent corrective actions.**
- **Construction safety is having an increasing effect on construction economics.**

Section 5

SENSITIVITY PARAMETERS

INTRODUCTION

The construction of station and line structures of rapid transit systems involves three sets of costs:

- The costs that relate to the quantities of labor and material needed to install the structures desired. These costs may be regarded as independent of any particular location and specific project.
- The costs that relate to a set of influences (including additional work events) that exist with reference to a specific project. These influences have been defined as the physical controls. The major physical controls include:
  - Utility density
  - Traffic conditions
  - Existing structures
  - Ground conditions
  - Fill demand
  - Architectural requirements
  - Weather
- The costs that relate to a set of influences that are determined on a system-wide basis. These influences, as they pertain to specific projects, are called institutional controls. The major institutional controls include:
  - System-wide labor agreements
  - Owner-supplied materials
  - Owner-purchased insurance
  - Labor productivity
  - Efficient cash flow

Physical Controls

The physical controls of utility density, traffic conditions, and existing structures are occasioned by, or closely related to, the peripheral work events of utilities, decking and traffic control, and underpinning, and consequently are termed peripheral physical controls.

The costs for work events in any segment include the basic costs plus additional costs due to a series of influences on these basic costs by the physical controls. The work events that are influenced by the physical controls for cut-and cover construction are:

- Utilities
- Deck and traffic control
- Underpinning
- Excavation
- Muck disposal
- Concrete
- Backfill
- Restoration

All the work events are fully described and discussed in Section 3.

The corresponding major work events for tunnel construction are:

- Tunnel construction
- Liners
- Workshaft
- Vent shaft
- Concrete invert
- Underpinning

The work events of utilities, deck and traffic control, and underpinning are items of work that are incidental to the main construction process of installing the structure, which involves the work events of excavation, muck disposal, concrete, backfill, and restoration. In terms of sensitivities, these three work events are classed as peripheral work events.

In any project, some of the work events in either forms of construction may not apply or may be so small as to be insignificant.

Institutional Controls

The owner-engineer can, to a large extent, influence most of the institutional controls. In this study, institutional controls are discussed in terms of their major cost effects:

- Schedule/time
- Direct cost
- Productivity of labor
- Financing

The sensitivities of costs to physical and institutional controls have been studied in two ways:

(1) For the five study projects, estimates were made of the influence coefficients for physical controls on the basis of underground construction experience, and for institutional controls on the basis of contracting and management experience.

(2) The generalized model, which is based on four idealized underground construction situations, was used for a sensitivity analysis of all of the independent variables in the constructions.

In this section, both the physical controls and the institutional controls are described in terms of their influence on the underground construction process. Sensitivities to physical controls are quantified and discussed for the five study projects. Sensitivities of the four generalized models are evaluated in terms of deviation from baseline project costs. Medium controls were assumed in determining these costs.

SENSITIVITY FACTORS – PHYSICAL CONTROLS

Utility Density

General Discussion. The term "utility density" refers to the number of utilities; the relative size, condition, and sensitivity to support or movement of each utility; and the accuracy with which utility company records can be used to identify the "as-built" position of their underground utilities. Utility density is measured by the degree to which it affects the cost/time schedule of each unit event with which it interacts.

Decisions Related to Utility Density. Direct decisions involving utility density include: which utilities are to be relocated, which utilities are to be supported, how the utilities are to be supported (to satisfy the utility company owner), how much work the utility companies will perform themselves, how much in the way of materials the utility companies will supply, how financial responsibilities will be allocated, and how the work will be coordinated.

Effect on Work Events. The effect of utility density on unit work events is as follows:

Work Event	Effect
Modification of Utilities	Major effect
Dewatering	Minimal effect
Underpinning of Structures	May restrict the work space and thus may have a small effect on the cost
Traffic Deckings	Minimal effect
Utility Support	Major effect
Excavation	Major effect upon the time/cost schedule of the excavation areas involving probably the first 8 ft: little effect on excavation below this depth

Work Event	Effect
Concrete	Restriction of the working space in the upper level of construction
Backfill	Major effect
Restoration	Little effect

Traffic Conditions

General Discussion. Traffic conditions relate to the average and peak volumes of vehicular and pedestrian traffic, the widths of the streets and sidewalks, the capacities of contiguous streets, and the short- and long-term reduction of traffic flow that can be tolerated during the construction period. They determine the extent of decking required and can have considerable impact upon most of the construction operations. Traffic conditions are measured by determining the degree to which they affect the time/cost of the decking or other unit work events.

Decisions Related to Traffic Conditions. Decisions relating to traffic conditions are those that establish the extent, schedules, and sequence of decking installation, schedules for street or lane closures, and the resulting traffic control procedures.

Effect on Work Events. The interaction of traffic conditions with work events is as follows:

Work Event	Effect
Modification of Utilities	Can affect those utilities that have to be modified prior to other construction events
Dewatering	Can affect installation and demobilization of the system to some extent. However, as dewatering wells can usually be located off the streets, the influence is generally small.

Work Event	Effect
Underpinning	Because of high labor requirements and relatively small material/equipment needs in underpinning operations, the time/cost schedule can be affected only to a small degree.
Traffic Decking	Completely determined by this control item
Utility Support	Little influence
Excavation	Will be affected as follows: The most economical way of removing muck is by truck direct from the excavation up ramps to the point of disposal. If a control such as the requirement for decking prevents this, double handling increases the cost of muck removal. Cost will also be increased if traffic conditions are such that transportation is slowed or hauling is limited to certain periods of the day.
Concrete	May affect the placing techniques, particularly if surface work areas and positions of delivery through the decking are restricted
Backfill	The placement and compaction techniques, and consequently costs, can be affected considerably if delivery points and areas through the decking are restricted.

Existing Structures

General Discussion. Under this heading is a whole range of buildings, including small dwellings; apartments; commercial buildings (including offices, shops, theaters); institutional buildings (including hospitals, governmental buildings, schools, libraries, historic monuments); industrial and manufacturing buildings; and other structures, including bridges and overpasses. Preservation of important or historic trees can be of concern in underground construction, but is not discussed in this section.

Aboveground structures can be classified as heavy, medium, and light. They may be supported on spread footings near enough to the underground excavation as to be affected by it, or the foundations may be piled. In the latter case, if the bottoms of the piles are above the bottom of the underground excavation, or if the piling is sensitive to horizontal movement of the soil, these structures become a control on underground construction. In general, cut-and-cover construction passing under existing structures is subject to the restraints imposed by the requirement for underpinning of the existing structures.

Structures below ground, e.g., tunnels and sewers, require the prevention of ground movement from excavation or piling operations related to the unit events of underground construction. Such preventive measures may include rigidly braced excavations, or other more expensive installation techniques.

Decisions Related to Existing Structures. Decisions concerning existing structures may include:

- Whether support of the foundations is required. If so, whether underpinning or another method of support is more appropriate
- Installations of the underpinning entirely outside the building in order to avoid disruption of the owner's business
- Purchasing of the building and demolition
- Purchasing of the building and restoration

Effect on Work Events. The measurement of the effect of existing structures upon the work events is by cost and by effect on the construction schedule. The cost includes the total of the lease or price paid to the owner of the structure for possession of the part of his structure needed for the underpinning work; the cost of engineering design, the negotiations with the owner, the restoration of the structure, etc.; and the cost of the actual underpinning.

The effect of existing structures on the construction schedule may appear as a controlling (or critical) point on the schedule, as the work of underpinning must be completed ahead of underground excavation. The restoration of the structures may appear as one of the last events in the schedule.

The interaction of existing structures with unit events is as follows:

Work Event	Effect
Modification of Utilities	None
Dewatering	Major effect if founded on compressible ground
Underpinning of Existing Structures	Major
Traffic Decking	Usually very small
Utility Support	None
Excavation	Can have a major impact on the method of support for the excavation along the length of the structure
Concrete	Where the existing structure is outside the underground limits, there is no effect. Where transit structures underpass the existing structure, they may have to support the structure.
Backfilling	Probably small
Restoration	Can be appreciable

Ground Conditions

General Discussion. Ground conditions have a considerable influence on the construction of underground rapid transit structures. The type and condition of ground encountered in the construction, such as sand, clay, silt, rock, or mixed face, and the degree of groundwater present are all-important to the cost and the progress of the construction work.

Effect on Work Events. Ground conditions affect unit work events in the following way:

Work Event	Effect
Modification of Utilities	Major effect in the excavation and backfilling operations only
Dewatering	Major effect
Underpinning of Structures	Major effect
Traffic Decking	No effect
Utility Support	In most cases, a small effect
Excavation	Major effect
Concrete	In wet or compressible ground, may give rise to extra costs for ground preparation and steel placement
Backfill	Affects cost if excavated material is unsuitable for backfilling
Restoration	Little effect

Fill Demand

Fill demand represents a cost quantity that can vary considerably from one transit system to the next and for various projects within the area of a given transit system. Fill demand as defined in this study affects only the muck disposal work item. If there is no demand for the muck to be removed during construction, the contractor may be obliged to pay for its disposal as well as for the haulage costs.

On the other hand, if the material is of desirable quality for land fill (gravel of sand), the contractor may be able to dispose of the material at a profit.

Architectural Requirements

The basic design, form, and shape of a rapid transit station structure can significantly affect the cost of its construction. Special architectural requirements that change otherwise economic structural designs or functional plans for visual and aesthetic reasons will add to the construction costs. Likewise, experimental or unique designs may require that special construction techniques be developed. However, this may be justified in many cases by aesthetic standards, if not by cost. Lack of uniformity in design of stations may also add significantly to the total cost of constructing the rapid transit system.

The measurement of the effect of architectural requirements upon the unit work events is the added costs to the concrete structure portion of the construction and, to a lesser extent, to the excavation and backfill.

Weather

General Discussion. The term "weather," as it influence underground construction, may be defined as "a weather condition that produces an additional cost to the construction work." These increases may stem from a constraint on a unit work event or from the movement of materials to the site. The effect of weather is measured in terms of the time/cost schedule of the various unit work events that are affected.

Decisions Related to Weather. Decisions involving weather relate to construction that is particularly exposed to the effects of the weather, e.g., cut-and-cover work. When the construction schedule is determined, seasonal conditions are taken into consideration wherever possible: excavation and, as a rule, backfilling operations should be scheduled for the dry, rather than the wet periods; concreting, particularly of horizontal slabs, should be scheduled to avoid very cold or very hot periods of the year.

Effect on Work Events. Interaction of weather with unit events is as follows:

Work Event	Effect
Modification of Utilities	Since most utilities are under ground, a major portion of the cost of relocation is the excavation, backfilling, and other items of the work that are fully exposed to the influence of weather. Thus, weather has a major effect on the event.
Dewatering	Slight effect on installation schedule; virtually no effect otherwise
Underpinning of Existing Structures	Little effect
Traffic Decking	Some effect on the construction schedule; little effect otherwise
Utility Support	Little effect
Excavation	The effect depends on the soil type and the method of excavation used. For instance, where excavation can be done from the surface, i.e., by backhoe or drag-line, inclement weather will have little effect on excavation, other than the normal slowdown that rain or snow produces on any outside work. However, if the excavation operation is performed from within the excavation itself (as is normal when decking is involved), and if the soil consists of fine sands, silts, most types of clays, or mixtures thereof, heavy rain or snow can cause the excavation and muck transportation equipment to become bogged down, and the excavation can be slowed down considerably. Given adequate drainage, coarse sands and gravels will not be affected.
Concrete	When concrete is placed, the temperature must stay within specified limits. If temperatures are low, heating of concrete aggregates and water before mixing may be required. After the concrete is

Work Event	Effect
	placed, it may be necessary to protect it against freezing by covering with insulating material, enclosing the space over it, or using braziers or other hot-air devices. Because concrete strength is attained more slowly at low temperatures, delay in the removal of support framework may be required. If temperatures are high, the cooling of both the mixing water and aggregates before they are placed on the mixer may be called for. Rain and snow may raise the percentage of water in the concrete and increase the difficulty of surface finishing, thereby preventing concrete from being placed in horizontal slabs. Since there can be a great deal of variation both in the weather and in the nature of the concrete structure, it is not possible to predict the influence the weather will have on this event.
Backfilling	Precipitation can strongly influence backfilling. The compaction of some backfill materials, such as sandy silts of certain graduation, is sensitive to the amount of moisture in the material, and either too much or too little moisture makes compaction difficult, if not impossible. (Pure granular material is not sensitive to moisture.) Since precipitation directly affects the amount of backfill moisture, it affects the placement and compaction costs.
Restoration	All types of restoration, except the restoration of the interior of an existing structure, are affected by the weather.

SENSITIVITY FACTORS – INSTITUTIONAL CONTROLS

Whereas the physical controls influence the cost of individual work elements in each construction segment, the institutional controls influence the basic overall project costs through their effect on schedule/time, direct cost, productivity of labor, and project financing. In some cases, the exact influence exerted on these cost elements can be quantified; in others, the influence is more generalized and is understood as a tendency rather than as a quantity.

Project Schedule

The project schedule is specified in the contract documents and is generally established by attempting to optimize the construction time for the estimated labor and fixed costs for the project. Any project schedule must fit within the framework of the entire system schedule, and insufficient planning and coordination of contractors can result in delays and additional cost to the owners.

System-Wide Labor Agreement

A system-wide labor agreement establishes an organization of all contractors and unions involved in the construction of the rapid transit system for the purpose of handling grievances and minimizing labor disputes. The agreement may call for a project relations officer from the owner-engineer staff whose function is to provide communication services, through periodic meetings and other means, to all contracting parties involved. The relations officer will serve as a mediator to solve grievances or potential labor conflicts. If a settlement fails at this level, the agreement may provide for further mediation through a panel of the owner-engineers. If mediation is unsuccessful, arbitration through a federal mediation and conciliation service may be necessary.

In a rapid transit project with a number of interfacing contracts, all possible slowdowns or strikes must be minimized. The system-wide labor agreement, such as described above, provides the vehicle for eliminating possible delays.

It should be noted that such an agreement will not void the normal collective bargaining agreements between the contractors and unions. Also the project can still suffer the effects of strikes by suppliers of materials and by transportation groups that are not engaged directly in the construction of the projects. As a rule, however, these effects are likely to be small compared with those that are possible in the construction contracts. The effects of construction strikes and slowdowns on construction schedules and system implementation are assessed on a statistical basis, and the costs due to these strikes and slowdowns may be distributed over the whole system through the overall influence on schedule/time.

Owner Lease/Purchase, Work Area

Work areas in the immediate vicinity of the construction are required for storage of construction equipment and materials, parking for workers, and the project field office. Negotiations for leasing or acquisition of these work areas by the owner before the contract is awarded ensure against schedule delays and excessive costs that may occur if the item becomes a contractor responsibility.

Rights-of-Way

Acquisition of the transit rights-of-way requires considerable lead time, and the owner must schedule this task in such a way as to avoid (1) possible costly schedule delays to the construction, and (2) claims that may arise because the contractor lacked adequate access to the work area.

Entry Permits

Entry permits must be obtained for any structures or properties to which the contractor must have access for support or any other modification required by the underground construction. Acquisition of entry permits by the owner, rather than the contractor, minimizes the potential effect of this institutional control on the project schedule/time.

Building Permits

In some metropolitan areas, e.g., Washington, D.C., time-consuming procedures are required for the many permits and licenses that are needed. In such cases, the contractor allows both schedule time and manpower for this task. Owner acquisition of at least some of the more involved permits and licenses reduces such cost and risks, particularly where blanket coverage can be obtained for several contracts from the same authorities. In addition to its possible influence on project schedule, the obtaining of building permits by the contractor can increase the direct project costs.

Owner-Purchased Material and Equipment

System-wide purchases of equipment and materials by the owner, rather than smaller purchases by individual contracts, offer three major benefits:

- They can help keep the project on schedule, particularly if several supply subcontracts are involved and if the product or products are not manufactured on a regular basis, as is the case with tunnel liners. (If the specifications require a particular lining design, the time required for mobilization by the contractor or manufacturer for lining production will probably be more extensive than that allowed for by an optimized schedule, and hence, delays to the schedule may occur.)
- They can result in substantial cost savings. These savings (which are estimated to be as high as 25 percent) stem from the increased efficiency from production of larger numbers of standardized items, (e.g., liner segments) the spreading of overhead and mobilization costs, and minimizing of escalation costs.
- They relieve the contractor of the need to purchase these items, the capital outlay for which may be considerable.

Safety

Safety programs, with or without owner-purchased insurance, are established in the project specifications and define the requirements for safe working conditions and procedures, as well as the routine procedures for meetings and reportings, that are needed to ensure compliance with the specifications. Safety in a project can reduce productivity losses due to accidents. The effect of safety programs on the cost of the project is evaluated by studying the number and severity of accidents and their impact on productivity (via increased labor costs). Where compressed air working is a requirement, the owner has a choice of providing compressed air facilities for the contractor or making the contractor responsible for the provisions. The difference in cost between the two approaches depends on the number of compressed air projects.

Owner-Purchased Insurance

Insurance purchases on a system-wide basis allow cost savings by relieving the contractor of this financial outlay, by providing bulk-purchase savings, and by permitting handback of premiums to the owner.

Labor Productivity

Productivity is the amount of work accomplished for a given amount of labor. Wide variations in labor productivity experienced in different geographic areas have a major impact on direct costs.

Advance Payments

Owner-advanced mobilization payment is, in effect, a method of accelerating payment to the contractor for large early expenditures on construction plant and equipment. Such payments relieve the contractor of the burden of such financing, and these savings should accrue to the owner.

Cash Flow

Because of the difference between the owner's and contractor's credit ratings and borrowing capacities, an owner's financing or interest charge may be 2-3 percent less than those of a contractor. Therefore, for the sake of economy, it behooves an owner to relieve the contractor of as much financial burden as is compatible with an efficient approach to construction.

Size and Mix of Contracts

With respect to direct cost, the cost of the contract is the important factor. Normally, specifications limit prospective bidders to those who can provide proof of experience of successfully accomplishing projects of a similar type and magnitude. Specifications also require proof of bonding capacity to handle the size of contract being bid. Experience with the BART system projects indicated that the number of eligible bidders is substantially reduced for every $10,000,000 increment in project value. Thus, as the size of the project is increased through certain value levels, the degree of competition decreases. It is generally not considered practical to split the construction into units less than stations or less than the line section between stations. As both these units may range in value from $7,000,000 to $25,000,000, it may be concluded that if interfaces, working areas, schedules, etc., are taken into consideration, the single station or line unit may prove to be the most practical economic size.

SUMMARY

Through investigation of the study projects, sensitivity controls to actual construction were defined and are of two types: physical and institutional.

Physical controls include utility density, traffic conditions, existing structures, ground conditions, architectural requirements and weather.

Institutional controls consist of the overall project schedule, the presence (or lack) of a system-wide labor agreement, lease/purchase of work areas, rights-of-way, entry permits to existing buildings that are affected by construction, and building permits. Additional institutional controls related to finance include acquisition of transit system materials and equipment, advance payments to contractors, cash flow of funds, safety and owner purchase of insurance, labor productivity, and the size and mix of contracts.

These controls are used later in the report to structure the generalized models.