TUNNELING TECHNOLOGY FOR FUTURE HIGHWAYS

Research, Development, and Technology

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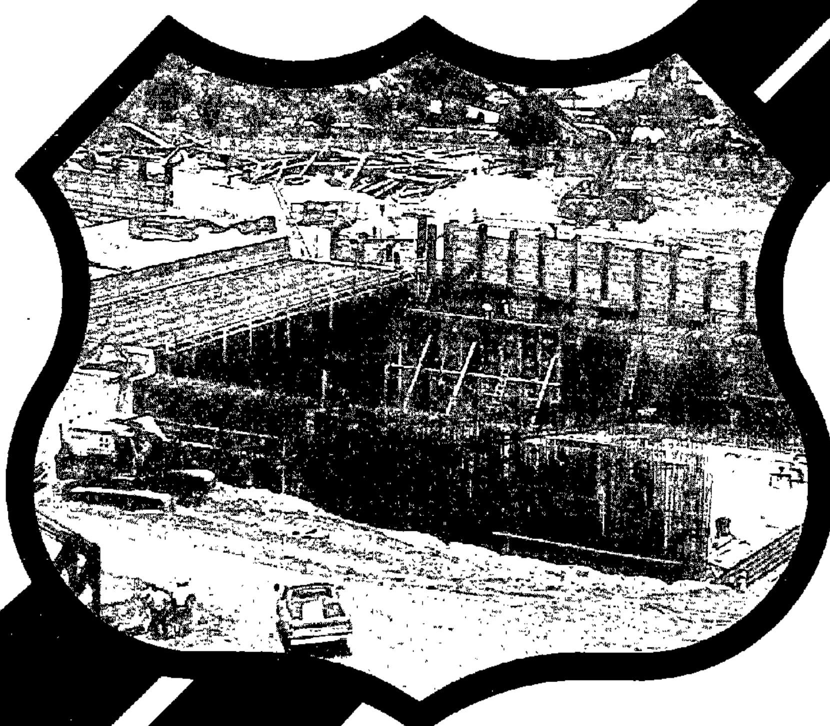

FOREWORD

This report summarizes and gives an overview of a comprehensive research program. It will be of interest to State, Federal and consulting engineers responsible for planning design and construction of tunnels.

The research described in this report was done as part of the Federal Highway Administration FCP Program. Results are being integrated into FCP Project 5B "Tunneling Technology for Future Highways."

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

Richard E. Hay, Director
Office of Engineering
and Highway Operations
Research and Development
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16. Abstract

This report gives an overview of research conducted for FCP Project 5B, Tunneling Technology for Future Highways. That project was aimed at research including state-of-the-art tunneling techniques unknown in the United States although accepted by other countries, and more experimental tunneling techniques not yet generally accepted. Specific research studies dealt with cut-and-cover tunnels, site investigation, earth movements, environmental criteria, and supporting activities (research conferences, information exchange, etc.).

The report summarized research on: costs, classical ground control techniques, slurry walls, tie backs, anchors and grouting for cut-and-cover tunnels; planning of site investigations, direct mechanical measurement (pressuremeters, cone penetrometers, vanes, piezometers) of soil properties, and indirect measurement by sensing techniques (aerial photography, acoustic, seismic, and electromagnetic systems); prediction and control of ground movements including phenomenological study and development of lining techniques; guidelines for the environment including air movement and pollution, tunnel lighting, traffic operation, driver behavior, safety and fire hazards.

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TABLE OF CONTENTS

SUMMARY

This report summarizes the USDOT, Federal Highway Administration's tunneling research activities between 1971 and 1982. It describes the assumptions that led to the project definition, discusses the objectives and scope of the project, reviews the project organization and the results of the research contracts, summarizes the research reports and evaluates the overall achievement of the project.

This report concludes that the state-of-the-art was significantly advanced in spite of the severe constraint of limited availability of funds. The writers recommend a continued and increased effort to implement the research results. They also recommend increasing training activities on all levels within the States and Federal Government and in private industry to diffuse innovative design ideas to working units involved in tunnel design and construction.

This report suggests continuing with the implementation and disseminating information on the research results.

INTRODUCTION

The roots of the Federal Highway Administration's tunneling research program can be traced back to the 1968 report prepared by the Rapid Excavation Committee of the National Research Council, National Academy of Science and National Academy of Engineering (B-1). * This committee recommended that a substantial federally funded research program should be launched immediately with the goal of reducing the cost and improving the speed and technical capability of underground excavation. Their recommendation was based on projections showing sharp increases in underground excavation in response to growing construction needs and environmental concerns.

Although the committee's report referred generally to all types of underground excavation, the recommendation was particularly relevant to the Department of Transportation in view of the projected growth of transportation tunnel construction. This was especially significant in urban areas where tunneling is an attractive alternative for providing new space for transportation purposes while maintaining environmental standards and preserving the surface land for other purposes.

Various agencies of the Federal Government reacted favorably to the recommendations of the National Research Council and initiated tunneling research activities shortly after 1968. To avoid duplication in these research activities, the Federal Council for Science and Technology established the Interagency Committee on Excavation Technology (ICET) in February 1971 with the goal of coordinating Federal research activities. The FHWA actively participated in promoting ICET and adhered to the concept of interagency cooperation.

The Department of Transportation (DOT) prepared the ground for its research and development effort in 1971 with a study (B-2) designed to provide a program which could justify itself on the basis of cost savings. This program would also solve socio-economic problems associated with construction of transportation tunnels in the 1970's and 1980's. The DOT study surveyed the state-of-the-art of underground excavation technology, identified the areas that could be improved, and recommended a funding level for research and development (R&D).

Justification of the DOT Research and Development program was based on projections that demand for transportation tunnels would increase from two to three times during the 1970's and double again in the 1980's. To perform a cost/benefit analysis, the study referred to the findings of the Organization of Economic Cooperation and Development (OECD) Advisory Conference on Tunneling, Report on Tunneling Demand (B-3). This Report estimated the total cost of transportation tunneling for the decade of the 70's would be $4.5 billion with about one fourth or $1.1 billion applied specifically to highway tunnels.

Based on the \$4.5 billion construction estimate and an assumed savings of 30%, the study recommended that the DOT R&D program be established with an annual funding level of \$10 million (1969 base year) to be spent over a decade with appropriate start-up and termination gradients. The coordinated program was actually agreed upon and set up by the participating administrations in 1973. (See Figure III-1.)

The responsibilities for the R & D program in tunneling were divided among four DOT agencies: the Office of the Secretary (OST) which was to coordinate overall tunneling activities and evaluate new concepts; Urban Mass Transportation Administration (UMTA) which had primary responsibility for underground rail systems design, legal relations, and muck removal, transportation and utilization; the Federal Railroad Administration (FRA) which concentrated mainly on improving tunnel lining and excavation techniques; and the Federal Highway Administration (FHWA) which was primarily responsible for site investigation, tunnel instrumentation, and cut-and-cover tunneling. Each participating administration was responsible also for carrying out research aimed at solving modal problems specific to that administration, with the Office of the Secretary responsible for coordinating such research and solving inter-modal problems.

The annual funding level of each Agency to be presented to Congress had not been agreed upon. It was estimated that the FHWA would bear approximately one quarter of all tunneling construction costs; therefore, it would have been reasonable to allocate that proportion of the annual \$10 million research estimate for FHWA tunneling research. However, this concept was not emphasized because the DOT wished to keep the program flexible and adaptable to the human resources within the three Administrations and because each Administration had to justify its own annual research program separately to Congress. Thus, the Administrations' long term funding was uncertain and their shares of the research budget varied from year to year. This will be analyzed in greater detail in subsequent Sections.

The FHWA research was divided into four tasks:

1. Cut-and-cover tunneling
2. Site investigation
3. Ground movement, prediction and control
4. Highway environmental criteria for tunnels.

This program was brought to public attention in 1974 during the Second Rapid Excavation and Tunneling Conference (RETC) organized by the American Institute of Mining, Metallurgical and Petroleum Engineers and the American Society of Civil Engineers (ASCE) (C-5-14).* Internally, FHWA administered this program as Project 5B, Tunneling Technology for Future Highways integrated in FHWA's Federally Coordinated Program (FCP) of Research and Development.

The first phase of the FHWA program was carried out from 1973 to 1976. During 1976 and 1977, organizational changes within the DOT led to the redistribution of the research responsibilities. However, this reorganization affected the FHWA program in only a minor way. In 1978, the FHWA program was slightly redefined to yield five tasks in place of the original four. These were:

1. Cut-and-cover tunneling
2. Site investigation
3. Tunnel construction and evaluation
4. Highway environmental criteria for tunnels
5. Support activities

The program continued in this form with decreasing levels of funding that ended in FY1982. Only the FHWA program will be dealt with in this report.

* References are coded according to Appendix. For example, (B-1) is No. 1 in Appendix B. References listed in Appendix C are arranged also by Task number. For example, (C-5-14) is No. 14 under the heading Task 5 in Appendix C.

I. PROJECT OBJECTIVES AND SCOPE

1. Project Organization

The research program was managed by a Project Manager under the Office of Research, Structures and Applied Mechanics Division. The task and contract managers were in the Structures and Applied Mechanics Division, Materials Division, Traffic Systems Division and the Environmental Division of the Office of Research. These Divisons were reorganized in 1982; however, this reorganization did not affect the tunneling research project.

The research program was carried out primarily under administrative contracts. Two in-house research studies contributed some data and computer program input to two of these contracts. Eight HP & R studies also supported the research program using State and Federal funds. Their principal achievement was collection and interpretation of data on highway tunnels used by researchers under administrative contracts (C-4-15,16,17,18,19,20,21,22).

The Office of Development, Implementation Division, was responsible for disseminating the results and it assigned an implementation Manager to this project. The primary tool of the Implementation Division was the organization of seminars and conferences, which usually were organized under pooled funds from participating agencies. The implementation effort also used administrative contracts to carry out its aims.

The Office of Engineering, Bridge Division, also contributed substantially to the research effort. It played a guiding role in identifying technical problems and in commenting on program development and orientation.

2. Formulation and Testing of Research Objectives

First, the research objectives were formulated within the FHWA. Later, they received wide publicity and were commented on by various groups of professionals. The interactions between project staff and various groups of professionals helped to formulate the objectives in more and more detail.

Both the objectives and research results were tested systematically at the following meetings:

- Interagency Committee on Excavation Technology (ICET) monthly meetings between 1971 and 1977 which included representatives of every Federal Agency involved in tunneling research;
- DOT-Industry Council Meetings held biannually in 1975 and 1976 with invited leaders of the tunneling industry who reviewed and commented on the results:
- FHWA Offices of Research and Development; Annual Federally Coordinated Program (FCP), Progress Review Conferences;
- Rapid Excavation and Tunneling Conferences sponsored by the American Institute of Mining, Metallurgical & Petroleum Engineers and the American Society of Civil Engineers;
- DOT-Transportation Tunneling Program Review (1975, 1976 and 1977);
- American Society of Civil Engineers, co-sponsored conferences,

specialty sessions;

- Annual Transportation Research Board (TRB) meetings;
- TRB special Critique Committee April 6-7, 1981 in Washington, D.C.;
- U.S. National Committee on Tunneling Technology under the auspices of the National Academy of Sciences and the National Academy of Engineering;
- U.S. National Committee for Rock Mechanics under the auspices of the National Academy of Sciences and the National Academy of Engineering.

3. Project Objectives

The objectives of Project 5B, Tunneling Technology for Future Highways, remained practically unchanged for the decade extending from 1973 to 1982. These objectives encompassed a broad range of research aimed at improving the design, construction, operation and maintenance of underground transportation facilities. Details are given in Appendix A.

Although the primary objective was to minimize the costs of constructing, operating and maintaining these underground facilities, the secondary objectives extended to environmental concerns, safety and aesthetic aspects of the tunnel environment and even to improving the quality of surface environment by rerouting traffic underground. This broad statement of the objectives allowed FHWA to participate in the DOT coordinated research program and to pursue research objectives identified by the operating offices of the FHWA.

4. Scope

In 1973, the scope of the program included the development of theories, instruments, new materials, improved construction techniques, design methods and the introduction of new concepts for improving the tunnel environment. It was intended also to demonstrate the results and to encourage the industry to implement the findings. The January 1980 project description emphasized finding solutions to technical problems identified by the operating offices of both FHWA and UMTA and disseminating the research results by presentations to State and Federal officials, industry representatives and interested engineers and designers at national and international conferences.

5. Historical Overview

In the late 1960's and early 1970's it was estimated that transportation tunnel construction would significantly increase in the 1970's and beyond. On the basis of FHWA estimates, the DOT R&D Program Plan predicted 21.7 miles of highway tunnels would be built in the 1970's. This would have represented about 70 lane miles at an approximate cost of $1.1 billion in 1969 currency. It was also estimated that about 50% of all highway tunnels would be built in an urban environment by the cut-and-cover technique.

This forecast and DOT's Program Plan (B-2), estimating that a well structured, adequately supported research program could reduce tunneling costs by 30% and increase the tunneling rate by 100%, justified the development of the FHWA program.

The FHWA research program was structured to support the Federal Aid Vehicular Tunnel Construction Projects and the DOT research objectives. FHWA was responsive to the needs of and intended to benefit from the research results obtained by the other Administrations within DOT. It was not intended to become a complete, independent tunneling research program, in spite of its broad objectives.

Those tasks which were directly responsive to the DOT's objectives were as follows:

1) Cut-and-Cover Tunneling
2) Site Investigation
3) Ground movements, Prediction and Control, which later was modified to read Tunnel Construction and Evaluation.

Another task supported special highway use and national objectives:

4) Highway Environmental Criteria for Tunnels; addressed modal problems in highway tunnels.

It might have been expected that the composition and funding level of the FHWA tasks were influenced by organizational changes within DOT and the evolving of the Federal Aid Vehicular Tunnel Construction Projects. However, such a relationship cannot be identified with any certainty after the initial formulation of the R & D Program.

The DOT coordinated research program started in 1973 and the Agencies' actual expenditures were as follows until FY 1977 in thousands of Dollars:

	Fiscal Years				
Agency	1973	1974	1975	1976	1977
OST	470	1015	940	992	540
UMTA	290	340	1066	1295	2036
FRA	800	500	0	400	0
FHWA	190	614	2080	2196	1803
Totals	1750	2469	4086	4883	4379

Each Agency justified its annual program budget on the basis of its own specific modal needs as well as the common objectives of the coordinated program. Variations in the construction program, specific needs and the manpower available to manage the research effort affected actual research spending. Thus, the actual funding share of the agencies was not related to the significance of their share of the research tasks, neither in relative nor absolute terms.

For example, FRA, which initially had major responsibilities in excavation and tunnel lining research, funded its research program neither in proportion to the requirements of these two significant research tasks nor in proportion to the effort of the other agencies. In FY 1975, FRA started phasing out tunneling research and, in FY 1977, it stopped funding it entirely. Parallel with this FRA phasing out, the OST began to assume research responsibilities in these areas in 1975. In 1977, OST's programs were reduced in scope and its tunneling research activities were transferred to UMTA. On December 10, 1977, the Office of the Assistant Secretary for Systems Development and Technology was abolished and OST stopped funding directly any tunneling research activity.

Following the reorganization of the DOT tunneling research program in 1977 with only FHWA and UMTA carrying out tunneling research, UMTA increased its program funding to an annual average of about $3 million, keeping the original DOT objectives. However, UMTA's research still focused on material handling, ground control and stabilization, tunnel instrumentation and, modal problems. Excavation research had low priority in this program and the average annual funding level stopped much below the planned $10 million. In 1980, the UMTA program was again redirected. The new UMTA objectives addressed modal problems only to reduce the cost of maintaining and rehabilitating existing rail systems, including subway tunnels.

It is not the objective of this report to analyze the results of the DOT program and the performance of the various agencies in the coordinated research program. However, it seems clear that:

- the total funding (about $43 million) was much less than the $111 million recommended in the DOT program, particularly if one considers the high inflation rate in that period and that the $111 million was estimated in constant 1969 currency.
- the excavation and tunnel lining research was disproportionately underfunded.

In 1976/77, FHWA could not increase its participation in the DOT tunneling research program. FHWA's 5B project culminated in 1976, when it reached its maximum funding level. Subsequently, the funding steadily declined until FY1982 when the project was phased out. In fact, probably the only cost effective course was to continue with the original plans and complete the ongoing research with the available funds.

The Federal-Aid Vehicular Tunnel Construction Projects did not reach the anticipated volume either in the 1970's. Therefore, the underlying assumptions, which justified the project in 1969 and 1971 had to be reconsidered. The 1970's were not active years for highway tunnel construction. Using data supplied by the Office of Engineering of the FHWA and proportionally adjusting for construction which started earlier than January 1, 1970 and ended after December 31, 1979, the following can be established for the decade of the 1970's:

- 7.8 miles of highway tunnels were built (36% of projections) under the Federal Aid Program. They represented about 24 lane miles (34% of projections) and the bid price in current Dollars was about $447.9 million. This figure does not include any adjustment for inflation, quantity variations, changes in orders, etc.

The distribution of the tunneling types and their percentage participation in the totals are as follows:

Type of Tunnel	Tunnel Miles Tot. Length Basis(%)	Lane Miles Lane Length Basis(%)	Million Dollars Bid, Current Basis(%)
Cut-and-Cover	1.12(14%)	6.05 (25%)	95.99 (22%)
Trench	1.99(26%)	5.11 (21%)	135.82 (30%)
Rock Tunnel*	4.73(60%)	13.00 (54%)	216.09 (48%)
Total	7.84(100%)	24.17 (100%)	447.90 (100%)

*Includes other than rock tunneling, i.e. soft ground tunneling in faults and overburden.

The unit costs of tunneling ranged as follows:

Type of Tunnel	Bid $Million/Mile of Tunnel	Factor
Cut-and-Cover	20 - 148	7.4
Trench	62 - 84	1.3
Rock Tunnel	25 - 101	4.0
Average	57	

The broad range of unit costs illustrates that the geometrical requirements and the solution of geotechnical and urban problems were usually more significant in determining the unit costs of tunneling than inflation which, according to the ENR construction index, increased the construction costs only by 2.16 times from 1970 to 1979. In other words, the bid price for the same job in 1979 would have been slightly more than double the 1970 bid price, but the unit price of rock tunneling varied by a factor of four and the unit price of cut-and-cover tunneling varied in the range of 7.4.

6. Task Objectives and Scope

Task objectives and scope were specific for the short term. Study objectives and scope evolved with available research results.

6.1 Cut-and-Cover-Tunneling

The initial objectives aimed at improving design techniques, construction technology and materials. The environmental concern was explicit when the research focused on protecting existing structures (buildings, utilities, etc.) in the vicinity of construction and on reducing disturbance to the environment (noise, vibration, dust, traffic interruption or accessibility to commercial areas) and to increase the rate of construction or, at least to restore the street to its normal business and traffic as quickly as possible. Acknowledging earlier progress, the January 1980 reviewed project documentation emphasized better ground stabilization and reinforcement techniques, grouting and construction optimization which had been recommended by earlier studies.

6.2 Site Investigation

Overruns were common in highway tunnel construction projects in the 1950's and 1960's. In the early 1970's, the FHWA operating offices estimated that one unforeseen condition was encountered in every two miles of highway tunnel, resulting in cardinal change orders and significant increases in costs. The reasons for these overruns were identified as deficient site investigations. Often time and budget constraints or unwillingness to modify established practices limited the scope, quality and quantity of the application of various site investigation techniques. The principal initial objective of this task was to develop more accurate and sensitive site investigation systems capable of generating a complete set of continuous, reliable data along the proposed tunnel alignment for engineers and contractors. Although, the Task objectives did not change in the January 1980 project documentation, the scope of the Task evolved based on recommendations of earlier studies. The scope specified the development of accurate subsurface investigation technology, including long distance guided horizontal and vertical penetrations.

6.3 Ground Movements, Prediction and Control (after 1978: Tunnel Construction Evaluation)

The initial objective focused on analytical techniques for estimating earth movements and evaluating stability during and after tunneling. The objective also included instrumentation and monitoring the construction of new highway tunnels. The modified program extended these research objectives to include determining analytically the effects of tunnel excavation methodology on ground movements, displacements and earth pressures and predicting the relationship between exploratory techniques, design support and selection of construction procedures. Later project documentation indicates an intention to consider the design verification of support systems and the determination of design requirements for highway tunnels, and also earthquake and disaster mitigation. However, this work could not be completed because funds were unavailable.

6.4 Highway Environmental Criteria for Tunnels

This task concentrated on finding solutions to modal problems of highway tunnels. The objectives extended from making the highway tunnels more acceptable and safe for the traveling public to improving the environment by limiting air pollution, managing land use around highway tunnels and studying behavioral aspects.

These objectives remained practically unchanged, although the scope evolved and became more specific in the later part of the program when the recommendations of earlier studies became available. The January 1980 scope statement emphasized optimization of traffic flow for the design and operation of highway tunnels and called for development of inatruments, techniques and procedures for detecting and dealing with potentially dangerous conditions in highway tunnels.

6.5 Supporting Activities

This task was defined later in 1978 although elements of it appeared in the program in 1974 under Task 2. The statement elaborates on two objectives; the first is a coordinating function among the DOT Administrations and the second defines a relationship with national and international organizations to marshal execution of studies of common interest using pooled funds. It also proposes using conferences, partially sponsored by FHWA funds, to disseminate information on FHWA program results.

II. TECHNICAL ACCOMPLISHMENTS

The reviewed FHWA research reports fall into three categories:
- those summarizing the state of the art;
- those discussing fully developed, tried techniques which have been used abroad but have not been widely applied in the United States;
- those proposing techniques and methods which have not been accepted fully by the profession as state-of-the-art.

In the two latter cases, full acceptance by the profession would require testing of the techniques in the American labor and legal environments to gain experience and to create references. This was done to some extent in certain cases by the implementation work performed under this project. As time has passed, experience also has accumulated from other sources which should be taken into account. However, additional testing may be required for other cases. This additional testing under various physical conditions would raise the confidence levels of the owners, engineers and contractors so that they would accept the proposed techniques as state-of-the-art and thereby facilitate their routine application. In this endeavor, success depends on the quality of the engineering and construction workmanship.

In general terms, the design engineer's role in society is to search for, evaluate, plan, and provide the most economical and safe design alternative for the clients and the public. These reports can help the engineer to identify all the alternatives. They provide a checklist of available methods and techniques, a critical evaluation of the problems, guidelines for optimizing tunnel construction, and valuable references presenting past experience. The state-of-the-art reports are essentially reference works. The other reports may be used also with judgement in design and construction engineering. However, all these reports should be exploited skillfully. As it has been stated often, engineering is an art and not an exact science. Therefore, it is not recommended that the reviewed reports be used as cookbooks or that the information be applied without any other considerations. It should be noted also that the reports may contain errors.

1. Cut-and-Cover Tunneling

Because it was anticipated that a large proportion of highway tunnels would be constructed using the cut-and-cover technique, Project 5B promoted a broad-based research program in cut-and-cover tunneling. The first study provided a review of the existing state-of-the-art in cut-and-cover tunneling practices and an analysis of the environmental and technical problems with recommendations for further research (C-1-1,2).

The research can be grouped according to the following subject areas:

1. Cost and systems analysis
2. Classical ground control techniques and theories
3. Prefabricated elements and slurry trench wall construction techniques
4. Tiebacks and anchors
5. Grouting

1.1 Cost and Systems Analysis

Optimization of cut-and-cover tunneling was the subject of a workshop sponsored jointly by the Office of the Secretary of Transportation (OST) and the FHWA. The proceedings of this workshop (C-1-4) compare various aspects of traditional sheeting systems with precast and cast-in-place diaphragm walls. Because more than one half of the cost of a tunnel constructed using cut-and-cover techniques is related to the cost of the wall, this discussion of the advantages of diaphragm walls is extremely relevant for system planners. The advantages are: 1) that diaphragm walls are more watertight than conventional sheeting; 2) can be used as both temporary retaining wall and permanent structures; 3) involve less earth movement during construction and excavation; 4) usually construction of diaphragm walls is more compatible with an urban environment than classical techniques, such as soldier piles and lagging.

The cost effectiveness of various methods in cut-and-cover tunneling was analyzed in detail in a large study carried out by Jacobs Associates, the results of which are given in a three-volume report (C-1-11, 12, 13). The object of this study was to consider, compare and evaluate the factors involved in cut-and-cover, tunneling, to identify those factors which significantly affect the cost of cut-and-cover tunnel design. The first volume describes the study situations, the methods and design criteria used and discusses methods of cost analysis. The test situations included three types of structures: highway tunnels, underground rapid transit line tunnels, and rapid transit stations. Each of these was considered for two different urban sites having different ground water conditions and for three depths of excavation: 30 ft (9.1 m), 50 ft (15.2 m) and 70 ft (21.3 m). For each site, three types of ground support system were evaluated: Soldier piles and lagging, cast-in-place concrete walls, and precast concrete panel walls.

Methods of cost estimation using a proprietary computer program are discussed and costs associated with various combinations of conditions and construction methods are compared in detailed discussion and summarized in tables. The second volume of this report expanded the design and other criteria given in Volume 1 to include three more urban sites yielding a total of 176 different construction situations. Construction costs for different types of cut-and-cover construction are compared in a manner similar to that used by contractors in competitive bidding. The examples given can be used to approximate the cost of jobs which vary in conditions or requirements from those studied.

The third volume contains complete cost analyses for 15 of the 176 study situations giving unit cost of labor, equipment and material. This information could be used to develop a unit price cost estimate for a particular cut-and-cover situation. A supplemental volume (C-1-16) includes basic data for all situations considered in the study.

The advantages of using slurry walls as both temporary and permanent earth support in construction of an underground transit station were explored using examples of nine urban sites selected from San Francisco, Boston, and Washington, D.C. transit systems(C-1-20). The study concluded that, although the slurry wall technique is generally more costly than classical methods and can not be expected to solve all deep foundation problems, it often can be justified on a cost basis by tangible savings in areas where the existence of a water table and the need for building underpinning increase the cost of classical construction methods. Also, it may be the method of choice on the basis of intangible considerations when other methods would endanger historic sites or have other unfavorable environmental impacts during construction.

The cost effectiveness of the slurry wall technique was demonstrated in a redesign of the Federal Center Station of the Washington, D.C. Metro System, using slurry walls as permanent earth support (C-1-20). In the actual completed project, slurry walls were used as temporary support measures resulting in a savings of $2.3 million. This report stated that using slurry walls as permanent earth support could have saved another $2 million without sacrificing any of the aesthetics of the design.

1.2 Ground Control Technique and Theories

The area of ground control was explored comprehensively in a three-volume report prepared by Goldberg-Zoino & Associates (C-1-5,6,7). Volume 1 of this series is actually a summary of the findings of the researchers. It provides a convenient reference for the design engineer and contractor. The second and third volumes of this series survey the state-of-the-art of ground control, including such techniques as sheet pile walls, soldier piles and lagging, underpinning, ground freezing, and grouting.

Volume 2 (C-1-6) concentrates on those factors affecting the design of the ground support wall, including earth pressure, lateral resistance, ground water, and bearing capacity of the soil. It also devotes considerable attention to displacements of ground and structures adjacent to an excavation. Volume 2 provides the basic theoretical knowledge and design framework needed by the engineer to approach a project involving deep excavation and underpinning.

Volume 3 of this series describes specific techniques in use for supporting walls of open excavations and underpinning neighboring buildings. The applicability of each technique is discussed and, wherever possible, the merits of the various techniques for given situations are compared. In general, these comparisons deal only with variables, such as soil type, wall type and support method, but some general guidelines are supplied regarding cost also. The specific construction methods included in this volume are: soldier piles, steel sheet piles, concrete diaphragm walls, tiebacks, underpinning, grouting and freezing.

In a later study (C-1-8) following the above research, the same firm investigated the outlook for developing improved support systems. The recommendations fall into three categories: Improving existing construction techniques, improving analytical methods to aid design and development of new construction techniques.

In the first category, the authors, recommend either increasing stiffness of the support wall by using a diaphragm wall or decreasing the spacing of bracing or tiebacks. In the second category, analytical techniques used to evaluate wall stability and movements are discussed and compared as to their applicability under various conditions. The concepts explored include: cofferdam type analysis to predict wall stability, predicting ground movement below the excavation base and predicting time-dependent lateral ground movements based on primary consolidation and soil swelling characteristics. The recommendations include in situ monitoring of support systems to provide an improved data base for future analytical developments and an extensive, long term research effort to investigate more fully the complex behavior of tie-back systems. The finite element analysis is considered promising in this respect.

Although the third category is new construction techniques, the methods described are not necessarily completely new but are new in respect to the applications recommended. For example, a hybrid technique comprised of standard tiebacks combined with internal bracing is outlined to reduce wall displacement. Several different combinations of these techniques are described in detail together with their advantages and specific applications. Several methods to reduce displacement are suggested, including tiebacks, ice walls, vertical soil reinforcing, and pressurized wells in cohesive soils.

The problem of groundwater control in open and confined excavations was investigated under a contract performed by Goldberg-Zoino & Associates, Inc. (C-1-21, 22, 23, 24), with the aid of subcontractors Ground/Water Technology, Inc. and Jacobs Associates. The findings of the study can be divided into three parts; the knowledge needed for proper design and installation of groundwater control systems, choice of the proper method to suit the particular need, and recommendations for future research.

In approaching the groundwater control problem, the first step was to summarize the groundwater control systems then in use for both cut-and-cover and bored tunnels in urban areas. This part of the contract was reported in Volume 1 (C-1-21) which discussed and compared eight methods: dewatering, recharge of water bearing layers or aquifers, cutoff walls and trenches, grouting, freezing, compressed air, slurry and earth pressure balance shields and electro-osmosis.

Volume 2 (C-1-22) concentrates on methods of keeping tunnels dry for the life of the structure. It includes discussions of such methods as impervious concrete, various types of waterproofing membranes, sealing tunnel lining segments, grouting of soil and rock and sealing sunken tube tunnels. It provides data necessary to evaluate their applicability in a well organized format. Also advantages and disadvantages of the methods are tabulated for ready reference. This volume concluded by stating that, in general, the methods available at that time were adequate for groundwater control but that research could be helpful in studying some of the newer construction materials available, for example those used as membranes and gaskets.

Volume 3 (C-1-23) contains guidelines for implementing various groundwater control methods under varying site conditions. An executive summary of all the findings is found in a separate report (C-1-24).

1.3 Prefabricated Elements and Slurry Trench Walls

Prefabricated structural elements include any element which is manufactured before it is used in a structure as opposed to cast-in-place members. The aim of the engineer and the contractor is to manufacture these elements under favorable conditions by using industrial techniques and to deliver and install them efficiently at the lowest cost possible. Prefabricated structural members may be made of steel, such as rolled sections used as soldier piles in temporary retaining walls, or reinforced concrete segments for tunnel lining. This type of prefabrication has been employed for some time. The primary interest in such members for cut-and-cover tunneling is to provide immediate ground support by simplifying the operations and reducing the costs. For this purpose, the feasibility of larger and more sophisticated structural elements and new installation techniques could also be considered.

The most recently developed prefabricated elements are precast concrete panels which are inserted in the ground in a slurry trench before any excavation takes place in the tunnel itself. These panels, progressively braced or anchored, provide an immediate temporary ground support on the sides of a cut-and-cover excavation and they can be also left in place to form the final tunnel wall. This has the obvious advantage of combining two steps in one and saving the cost of building a separate temporary support wall. Moreover, once it is in place the wall is an instantaneous and effective ground support, unlike cast-in-place concrete which requires weeks to be fully effective. An additional advantage is that this technique usually decreases the need for underpinning of adjacent buildings along the excavation. Under certain ground conditions, the groundwater control can also be easily achieved.

During the last 35 years, the slurry trench method of constructing tunnel walls has been used widely in European countries and Japan, particularly for tunneling in urban areas. In these countries, the possible higher cost of implementation is considered to be offset by savings in eliminating underpinning nearby buildings and environmental advantages, such as less disruption to traffic and commerce during construction.

Application of the technique in this country has been slow for several reasons. In the first place, contractors unfamiliar with the technique are reluctant to experiment with a new method requiring considerable investment in training of personnel, when the exact amount of the savings cannot be precisely defined or guaranteed. The contractors perceive a prohibitive risk. Secondly, the method requires large numbers of skilled laborers and, in most instances, there are not enough cut-and-cover projects of the type requiring this technique to fully occupy such a large labor force. The studies carried out under this task investigated the current state of application of this technique and explored the ways in which it can be improved and applied more effectively.

One two-volume report (C-1-14,15), prepared by The Consulting Engineers Group, Inc., thoroughly surveyed the use of prefabricated elements for cut-and-cover tunneling here and abroad. It explored the types of excavations which can benefit most from application of this technique and the materials which can be used most effectively. The first volume can be used as a handbook to obtain background information on applying all types of prefabricated structural members to cut-and-cover tunneling. The advantages of plant vs. site fabrication, properties of various structural materials, shapes, and design considerations, including load factors and design stresses, were described.

The slurry wall method, in particular, was investigated in detail, including comparisons of various application techniques, structural materials, and slurry materials. For example, the use of drilled-in tangent or overlapping cast-in-place piles is compared with slurry wall construction and the latter was found to hold most promise. One of the chief reasons was the speed of this process, compared to standard methods. However, it was found that the choice of shape of the structural members used or even whether precast members are combined with cast-in-place members has little effect on further reducing the time required. This is because the slowest step in the slurry wall process is excavating the trench. This can be speeded somewhat by using additional equipment, but in general provides no significant time savings.

Among all the materials investigated, precast concrete elements were judged to result in lower costs and shorter construction time and prestressing the precast elements usually provides additional advantages. The choice of methods depends always on the site conditions.

For vertical walls the best ideas were:
- continuous interlocking sheet piles 4 ft to 8 ft wide (1.2 m - 2.4 m)
- king piles at 8- to 12-ft (2.4 m - 3.6 m) intervals with precast or cast-in-place elements between.

For horizontal elements in situations where backfill is not required, the recommendations were:

- precast, prestressed sections, in a wide variety of shapes; (i) to span the full width of the tunnel if the street can be closed for several weeks;

(ii) to apply modified Vierendiel or precast post-tensioned segmental sections, if the street must remain open;

- steel trusses
- concrete trusses.

If backfill is required, precast concrete arches were recommended.

Technical feasibility and benefits associated with the use of precast structural elements were explored in three case studies described in Volume 2 of the report discussed above (C-1-15) and in a study carried out by Chi Associates, Inc. (C-1-20) which assessed the advantages of the slurry wall technique for constructing an underground transportation station for the Washington, D.C. Metro. The former study was carried out for three actual sites: a station for the Chicago Mass Transit System, a shallow highway tunnel through suburban Minneapolis, and a deep highway tunnel connecting Portsmouth and Norfolk, Virginia. These sites were chosen because they represent differing physical and environmental conditions and because, in each case, some preliminary work already had been done using conventional methods which could serve for comparison. For each case, a structural system using prefabricated components was selected and detailed designs were made. Cost estimates for the proposed solutions were compared with those for more conventional construction methods and the duration of construction required was found using an idealized Critical Path Method.

Each of these sites was described in detail, including discussions of various options in materials and methods as well as comparisons of time and cost with conventional methods. Overall, it was found that structural cost savings of from 7 to 13 percent were possible with accompanying savings in time. A dramatic difference in the amount of surface disruption incurred was predicted in the first site, the only one in which such disruption was an important factor.

The second report (C-1-20) was somewhat similar to the first in that it dealt with the use of slurry walls at an actual site. However, only slurry wall technique using precast concrete elements was considered. In this case, a complete design was supplied for a project which already had been completed and which had actually used slurry wall technique as temporary excavation ground control at an acknowledged savings of $2 million. However, the design developed in this study used the slurry wall both for temporary ground control and as part of the permanent structure.

The report concluded that an additional savings of $2 million could have been realized by such a design. It was pointed out, however, that slurry walls are not appropriate for solving all deep foundation problems but can permit considerable savings in situations where costly dewatering and underpinning of adjacent structures would be otherwise required. Other less tangible advantages of slurry wall technique, such as less disruption of traffic or preservation of historic sites, can also contribute to making this technique an attractive alternative.

The Department of Civil Engineering of Duke University (C-1-3) carried out a study considering various aspects of the interaction of the slurry wall with the adjacent soil. Analytical models were developed to aid in understanding the physical mechanisms involved in this interaction so that eventually the performance of slurry walls can be predicted with greater confidence. Analytical methods for modeling slurry wall construction, including finite element analysis, were reviewed and evaluated and a research program to improve slurry trench technology was proposed.

1.4 Tiebacks and Anchors

Tiebacks are construction elements which consist of tendons which transfer loads to the ground via ground anchors. They can be used for both temporary and permanent support and can be applied routinely to both rock and most noncohesive soils. However, soft to medium cohesive soils are usually less appropriate because of their lower long-term holding capacities. This method has decided potential for cut-and-cover tunneling for use with temporary retaining walls as well as for permanent support of completed tunnel walls.

1.4.1 Tiebacks

Tiebacks are a fairly recent development and have been used only in the last 20 years in Europe and since the 1970's in the United States. They have not found general acceptance because a number of problems remain to be solved. These problems are related to: determining the holding properties of various soils, the immediate and long term capacity of the tieback, protecting the tieback itself from corrosion in long-term use, predicting how tiebacks can maintain their loads without excessive movement under various geotechnical conditions.

The first step towards answering these questions and making tiebacks a more effective construction tool was to summarize the current state-of-the-art. This was accomplished in a study completed by the Schnabel Foundation Company (C-1-32,33). This survey reported all kinds of applications of tiebacks in Europe and the United States, including retaining walls, tunnels, dams, harbor quays, and landslide stabilization. The report examined in detail the following aspects of tieback application:

- load-holding characteristics of soils
- corrosion protection of tieback elements
- testing long term tieback performance.

In considering use of tiebacks in noncohesive soils, the study found that tiebacks are routinely installed and have satisfactory long-term performance in soils having a standard penetration resistance greater than 10 blows per foot. Tiebacks perform less well in soft to medium cohesive soils; however, their performance can be improved by installing tiebacks at a steeper angle. In evaluatating suitability of such soft soils for tieback installation, the best indications are soil strength, Atterberg limits, natural water content, and experience in similar soil.

In soil with a high organic content, normally consolidated clays, and cohesive soils having an unconfined compressive strength less than 1.0 ton/sq ft (96 kPa), tiebacks may be susceptible to creep. However, tiebacks in soils with strengths above this limit will not experience significant loss of load capacity or move excessively over a long period.

To fully evaluate load holding characteristics of tiebacks in soils having a standard penetration resistance of less than 10 blows per foot, a tieback test program was recommended. Testing arrangements and equipment were outlined and a sample testing program was developed, including performance testing, creep testing and proof testing. Performance testing measures the load applied to a tieback and its movement as the load is applied or removed. A proof test measures the total movement of the tieback.

The study reported that most permanent tiebacks can be protected by applying portland cement grout along the length of the anchor and placing a grease-filled tube or heat shrinkage sleeve over the unbonded portion. Such grout protected tiebacks must be electrically insulated from the structure they support and the tendon must be protected by at least 0.5 in.(12.7 mm) of grout. In particularly corrosive environments, the tendon should be completely encapsulated in a plastic or steel tube.

1.4.2 Anchors

Ground anchors aid in supporting natural and man-made structures, such as rock blocks, retaining walls and precast concrete elements. The anchor itself is a structural element which has its bearing in the soil mass. The application of a force through the tendon mobilizes the shear strength in the soil mass surrounding the anchor. The capacity of the anchor depends on the available and mobilized shear strength of the soil and may change with time. Ground anchors can be temporary, lasting less than 6 months, semi-permanent, or permanent, lasting longer than 18 months. The most promising applications of ground anchors for cut-and-cover tunneling is for support of various kinds of retaining walls. As no generally accepted design guidelines exist in this field and to obtain as thorough coverage as possible, three internationally prominent contractors received contracts to describe their own methods for design and installation of permanent ground anchors. These contractors were Soletanche and Rodio, Inc. (C-1-25), Nicholson Construction Co. (C-1-26) and Stump/Vibroflotation (C-1-27).

Each of these contractors reported on their experience with ground anchors including the soil criteria acceptable for application, structural design and recommendations for placement, methods of placement, including drilling and grouting methods, and advice for maintenance and monitoring anchors after installation. The successful application of permanent ground anchors to actual projects was illustrated by three case histories in both the Soletanche and Nicholson reports and one case history in the Stump/Vibroflotation report.

In addition to the information above, the Soletanche report included a detailed discussion of a specific type of ground anchor developed by them called the "Injections Repetees en Pression" or IRP anchor. This anchor was developed for use in soil or rock formations with poor mechanical characteristics, such as clayey-silty alluvium, soft limestone, or Karstic rock. It achieves a satisfactory anchor bond by improving the soil characteristics along the sealed length using cement pressure grouting which is injected in a series of ascending stages along the anchor length. This method has the advantage of permitting regrouting later, if necessary. The Soletanche report included also computer programs used to optimize a ground anchor support system.

1.5 Grouting

Grouting is the injection of a fluid under pressure into soil voids where it later hardens, thus performing the following functions: consolidation and strengthening of the soil mass and inhibiting movement of ground water. The first research contract in this field consisted of a thorough survey of the state-of-the-art of grouting and was performed by Halliburton Services. The first volume of the report on this contract (C-1-9) was based on published and unpublished documents, interviews with construction personnel in the grouting business and site visits, both in Europe and the United States, and the authors' personal experiences. This report covers all aspects of grouting from theory to current practices and recommendations for improving techniques.

The second volume (C-1-10) is a design and operations manual which gives guidelines for soil grouting operations beginning with selection of the particular chemical grout, continuing to the design of the injection pattern and including methods of evaluating the completed treatment. Three general grouting techniques relevant to excavation and tunneling in an urban environment are described: permeation, void filling, and compaction. Details on six types of application are supplied. These are: groundwater control, sand stabilization, soil strengthening, backpacking tunnel liners, leak repairs, and tieback anchorages.

1.5.1 Grout Composition

The next contract on chemical grouting focused on the search for more economical grouts not directly dependent on petroleum. This contract, performed by Soletanche and Rodio, Inc. (C-1-17,18), first examined the products then on the market and classified them based on their major component. The categories were: aqueous solutions, colloidal solutions in water, non-aqueous systems, emulsions (non-aqueous), reaction with the ground or ground water, and combined systems. Then the grout materials identified were evaluated on the basis of injectability, permeability, setting time, strength of pure grout, strength of grouted soil, durability, and toxicity. Finally, seven waterproofing grouts and five consolidation grouts were selected for in-depth examination.

Those materials chosen were analyzed further in terms of their performance on previous tests and were retested further in the laboratory. The results were presented in a ratings table showing the advantages and disadvantages of the grout materials. The report concluded that, apart from the chemical composition of the grout, the fundamental characteristic which differentiates one from another is viscosity. Waterproofing grouts are usually dilute and hence of low viscosity but consolidation grouts are diluted less and are more viscous.

The study found that there is available a series of grouts of decreasing viscosity suitable for a wide range of application in soils. The recommendations were:

- Coarse ground - Bingham-type materials, with cement or clay in suspension
- Average soil particle size - Somewhat viscous colloidal solutions (silica or lignochrome gels, organic or inorganic colloids)
- Very fine ground - Pure non-colloidal solutions (organic monomers in aqueous solution).

The Soletanche study concluded that some widely used grouts could be further improved; for example, the silicate derivatives could be made more durable. Also, the lignochromes could be made less toxic by decreasing the percentage of potassium dichromate by 10 percent and furans could be made suitable for use in a basic medium by adding resorcin. Further improvements could be obtained by combining existing products and research on new systems. Emphasis should be placed on consolidation grouts because a wide range of waterproofing grouts is already available. In developing improved consolidation grouts retaining long-term strength should be the principal criterion.

1.5.2 Grouting Techniques

Grouting techniques were investigated and reviewed by the Hayward Baker Company in a four-volume report (C-1-28,29,30,31). The first volume of this report presents the results of a laboratory and field research program which studied innovative methods for design and control of chemical grouting in soils. Both consolidation and waterproofing grouts were considered and both mixing and injection methods were investigated. Grouting was evaluated using site exploration tests, such as the standard penetration test, cone penetrometer, and borehole pressuremeter. Also, undisturbed sampling was done and test pits were used for sample collection for laboratory testing and evaluation.

The second volume of this report deals with testing procedures for grouted soils, the effects due to sampling and determining the groutability of soil. Over 300 unconfined compression tests and over 30 creep tests were conducted on specimens grouted in the laboratory to investigate the influence of preparation and testing methods on the magnitude and reproducibility of the determined strength and deformation characteristics. Groutability of soils using various chemical grouts was investigated by performing several series of permeability tests both under low and high gradients and considering linear, cylindrical and spherical flow regimes. Although a large number of inferences could be drawn and useful observations were made, no general conclusions could be reached because of the large number of variables which had often conflicting influences.

The third volume of this report concentrated on improving the effectiveness of subsurface grouting by a more detailed design of the injection geometry and a better time, space and pressure injection sequencing. Quality control tools are also discussed. Six actual case histories illustrate the recommended procedures. The fourth volume of this report summarizes the findings of the researchers.

2. Site Investigation

The principal aim of this task was to advance the state-of-the-art by providing better information for the tunnel design engineer and for the contractor planning the construction program. In particular, it was intended to provide continuous data on the geological formation and structure, geotechnical parameters and water conditions along the planned tunnel alignment. This information and a proper interpretation of the data allow an optimization of the design and construction planning. However, if the data are incomplete, discontinuous or incorrectly interpreted, suprises may be encountered during construction and these surprises usually result in losses for the owner, the contractor or both. The frequency and magnitude of these losses depend on the geology, the degree to which an optimum site investigation program was carried out and the capacity of the contractor to handle the surprises at the site.

Although definite losses can be associated with an incomplete or erroneous site investigation program, they are difficult to quantify. Also, losses depend to some extent on contractual arrangements, legal intepretation of problems and, therefore, any problem often leads to costly court procedures. Consequently, the results of research under this task were not expected to make a direct measureable impact on tunneling costs. Due to the nature of this task, the results should have an indirect impact in early stages of design and construction planning and the improvements should be noticed by the reduced frequency and diminished magnitude of technical and contractual problems during construction. To be more specific, the results should help:

- optimizing the design (most economical safe design)
- facilitating construction planning for contractors
- reducing the number of unexpected problems encountered during construction resulting in fewer delays, order changes and claims.

The research reports can by grouped into the following categories:

2.1 planning and optimizing site investigation programs, including horizontal, long distance penetration in soils and rocks;

2.2 measuring soil characteristics, water pressures, and states of stress by direct mechanical methods;

2.3 sensing soil and rock characteristics in the ground by various indirect techniques.

It is important to emphasize that applying the research results requires specialized knowledge and more time spent on program planning and data interpretation than required by earlier, less sophisticated techniques.

2.1 Planning and Optimizing Site Investigation Programs.

The first contract addressing this problem was carried out by Fenix and Scisson, Inc. (C-2-1). This study had four aims:

1. Survey and evaluate the subsurface investigation techniques available at that time;
2. Investigate interactions of subsurface investigation system elements;

3. Produce a value analysis model for predicting the relative value of various site investigation techniques;

4. Determine feasibility of horizontal long-hole drilling.

The first goal of the study was met by a survey which considered all site investigation techniques having possible application for highway tunnels located within 500 ft (152 m) of the surface. These were analyzed and divided into categories based on tested capability and potential.

In the first category, those techniques were considered which had limited applicability in their present state of development. They included passive microwave, ultraviolet and luminescence sensing methods and gravitational and temperature borehole logging. Techniques which were considered proven methods but little used and with poor potential for application included: magnetic, electromagnetic, gravity, and radiometric surface geophysical; spontaneous potential, gamma ray, and neutron borehole logs; laboratory unconfined compressive strength tests for soil; and laboratory uniaxial shear and tensile strength tests; triaxial shear strength and creep tests for rock.

Techniques with proven capabilities and good potential were identified also, despite the fact that they were little used. These included: color photography, infrared photography, and side-looking airborne radar remote sensing. Also in this category, but with good potential only in a few selected tunnelng problems were: visual or photographic borehole logging and conventional resistivity, focusing electrode, induction, formation density and caliper borehole logs. Those techniques which were partially developed and needed additional experience for a broader acceptance included: thermal infrared, multispectral photography, multispectral scanning infrared and radiometry remote sensing methods, acoustic holography, horizontal drilling and sonic borehole logging. Details of all methods mentioned are included in an Appendix which explains the principles, equipment, procedures, capabilities and applicability of each system.

The second goal of this study was approached by analyzing the various available site investigation methods from the standpoint of tunneling problems and design requirements. The researchers concluded after studying case histories that little information was available on how site investigation data was actually used in tunnel design and that there are few cases in which the predicted conditions were ever compared to those actually encountered. Based on available data, however, researchers concluded cost overruns in tunneling projects can often be traced directly either to insufficient subsurface information, incorrect interpretation of the information provided, or to management's decision not to follow the investigator's recommendations.

A value analysis model was prepared satisfying the third goal of the study. This consisted of a 41-step flow diagram capable of identifying the system (or method) having the greatest benefit/cost ratio for a given problem. A set of forms was developed also for use with the value analysis model to aid the user in applying the model to a particular project.

In the fourth portion of the study, the state-of-the-art of horizontal long-hole drilling was evaluated and found to be technically feasible.

However, the researchers stipulated that this method may not be economically feasible if extended over distances of one mile (1.6 km) unless ground conditions are favorable.

Closely related to the research just discussed was a study, carried out by Foster-Miller Associates, Inc., focusing on the feasibility of using long range horizontal boreholes to replace pilot tunnels. This study was reported in three volumes (C-2-5,6,7). The first volume determined the horizontal penetration capabilities of available drilling equipment to be a maximum of 5000 ft (1524 m). This was judged to offer an order of magnitude cost reduction over pilot tunneling.

Four techniques were identified as suitable for such long range drilling. These are: diamond wireline core drilling, rotary drilling, down-hole motor drilling, and down-hole percussive drilling. Penetration capabilities in terms of hole width and length and costs are supplied.

The second volume of this study (C-2-6) presents a model for estimating the time and cost associated with drilling long horizontal holes using each of the four methods described above. An appendix applies the model to a specific example of a 5000-ft (1524-m) hole in rock comprised of 59% medium rock, 30% hard rock and 11% soft rock. Another appendix repeats the procedure for rock of a different profile.

The third volume of this study evaluates the potential for improving horizontal drilling. Two recommendations were made to improve core drilling:

- using a down-hole motor for steering;
- improving rod handling.

To improve rotary drilling, the researchers recommended:

- using a wireline survey tool;
- improving rod handling equipment;
- carrying out a rolling cutter core bit test program.

One new piece of equipment with potential for this type of drilling is a remote steering tool for rotary drilling.

The feasibility of horizontal boring and exploration in soils as an alternative to vertical boring was assessed by the Massachusetts Institute of Technology (C-2-8). The first part of this study concerned development of methods for penetrating from 2000 ft to 3000 ft (610 m to 915 m). Two recently developed methods, the thruster and mandrel systems, were evaluated. The mandrel system, developed by Titan Contractors, was shown capable of drilling a 3-in. diameter washover pipe from 1400 ft to 1700 ft (426 m to 518 m) with longer horizontal holes possible. However, improvements are required in the return of cuttings and hydraulic fracturing to achieve significant increases in range.

The thruster system developed by CONOCO and DRILCO Industrial were found capable of cutting at least a 3.5-in. (9-cm) diameter hole up to 800 ft (244 m) in soft coal. However, improvements in bit wear, cuttings transport, hydraulic line loss and variable anchor pressure are needed to achieve any significant increase in horizontal penetration distance.

The second part of this study dealt with exploration capabilities of horizontal boreholes. Preliminary designs were developed for down-hole seismic (geophysical) sensing and contact sensing. These approaches were evaluated by investigating wave attenuation characteristics and hole disturbance. The third and final portion of the MIT study compared the cost effectiveness of horizontal boring with vertical boring and surface geophysics. The researchers concluded that shallow tunnels (less than 75 to 100 ft (23 - 30 m) are best explored using vertical techniques. However, horizontal boring can be cost effective for deeper tunnels or in environmentally sensitive areas, such as parks and densely settled neighborhoods, where vertical access is difficult.

2.2 Direct Methods

These research results can help design engineers to estimate representative parameters needed for designing tunnels. Several methods were evaluated to provide various parameters for design engineers. In this respect, particular attention was paid to the direct measurement of the in situ state of stress in soils, because advanced finite element computer programs require knowledge of the initial state of stress in the soil as input data. Computer technology is far ahead of the available measuring techniques and the output of these computer programs is very sensitive to the input data. Therefore, to make these computer programs more useful engineering tools, it is necessary to improve the input data providing various parameters including the in situ state of stress. The evaluation of the various proposed measuring techniques is intended to serve this purpose.

2.2.1 State of Stress in Soils

Determining the in situ state of stress in soils is a difficult problem often requiring extensive and subtle evaluation. Under simple conditions, such as a uniform, normally consolidated soil under a horizontal ground surface, the state of stress can be determined from theoretical considerations. In other cases, however, it should be measured in the field or in the laboratory. Both types of measurement provide limited data. These tests usually can measure only single components of the stress tensor or only a stress ratio.

A contract carried out by the Illinois Institute of Technology (IIT) Research Institute (C-2-3) set out to summarize and evaluate current methods of measuring in situ state of stress in soils and recommend steps for future development. All known methods of determining in situ stresses in soil were summarized. Five of these were explored in greater detail with regard to their capabilities and suitabilities for various geotechnical conditions. These methods are: acoustic velocity, borehole pressuremeter, borehole stress probe, hydraulic fracturing, and anisotropic vane shear.

Recommendations for additional development were made on three levels. The first, most immediate need was the development of an in situ stress gauge capable of determining the two-dimensional stress tensor in the plane normal to its axis. Second, for medium range development, researchers recommended development of fabric analysis as an effective soil mechanics tool. Finally, on the long range, the report proposed the development of a method using electroparamagnetic resonance for determining stress in soils.

2.2.2 Self-Boring Pressuremeter

One of the most promising methods for measuring in situ lateral stress in soils is the self-boring pressuremeter test (SBPT). Though based on the same principles as the conventional and widely used Menard pressuremeter, this device has a cutting head so that the soil is tested when the hole is cut, thereby avoiding the disturbance associated with predrilling the hole. The SBPT has the potential of measuring horizontal stress in situ and makes it possible to determine the ratio of the horizontal and vertical normal effective stresses. To investigate whether the SBPT could live up to this potential, a contract was awarded to the Massachusetts Institute of Technology Department of Civil Engineering (C-2-15).

The objectives of the MIT contract were to perform self-boring pressuremeter tests using two different SBPT devices, compare the results, and present and evaluate methods of deriving soil parameters from the data obtained. Boston Blue clay was chosen for these tests because it is one of the best known and widely tested clay deposits in the world and is highly suitable for SBPT testing. The devices tested were the Camkometer, developed by Cambridge University, England, and the PAFSOR developed in France by the Department of Highways.

During the program 14 tests were made with the Camkometer and 20 with the PAFSOR. Both devices were found to yield good results for the horizontal stress in the upper medium to stiff clay layers, using the Marsland-Randolph graphical iteration method of analysis. The initial pressure was often far too low, however. It was recommended that this device be applied to measuring other parameters as well in various clay deposits, but difficulties were encountered in measuring undrained shear strength in the deeper soft clay layers. In fact, the derived peak strengths in a soft clay were too high by a factor of two or more. Most tests gave reasonable estimates of undrained shear modulus (G_{50}) however.

Further testing of the PAFSOR and Camkometer self boring pressuremeters was carried out in cohesive deposits at seven sites in Italy, Iran and Norway in the course of a contract performed by the University of Turin, Italy, for MIT in Cambridge, MA (C-2-24). Among the soil characteristics investigated were: undrained strength, horizontal stress, and limiting pressure. Many of the tests yielded promising results; however, it was concluded because of the multitude of variables involved, additional research is needed before all the parameters can be determined with confidence using SBPT.

2.2.3 Other In Situ Testing Methods

Other in situ testing methods to measure various soil parameters applicable to tunnel design in soft ground were analyzed in a contract performed by Soil Systems, Inc. (C-2-16). These methods were: bore hole shear strength (BHS), bore hole earth settlement (BESA) and bore hole electronic earth penetrometer (BEEP). These methods were in varying stages of development at the time the contract was carried out but all were found to be promising practical methods of obtaining soil engineering data in a bored hole.

The first method, the BHS, was already in commercial use, thus, permitting examination of how effective this method is for solving engineering problems. Discussion included such applications as landslide failure analysis, earth anchor design, friction pile design, and foundation design. The study concluded that the main limitation of this technique was the difficulty in mobilizing the cohesion in moderately cohesive to highly cohesive soils. Of the two other methods, BEEP was closer to being manufacturable, lacking only some added instrument research. The BESA technique was found to require additional applied research and correlation testing.

Soil Testing Services, Inc. (C-2-17) reported on research conducted using the Menard pressuremeter, a testing device capable of providing design parameters for nearly all soil and soft rock formations. Specific situations were discussed including silty soils, brittle soil formations, interbedded sand, silt or clay, and fill. Among the conditions found to affect pressuremeter test results were: variations in pressure increments, temperature of the test liquid, ratio of bore hole to probe size, probe size changes, and the encounter of soft clay. Nine case histories were reviewed to illustrate the typical use of the method and the conditions where the pressuremeter was an effective measuring device.

Three other types of in situ soil testing devices were evaluated in a study carried out by the Civil Enineering Department of the Massachusetts Institute of Technology (C-2-18) using several MIT case histories and literature information. These methods were: the field vane, Dutch cone penetrometer, and piezometer probe. Each method was analyzed and specific recommendations were made for their use. In comparing the three techniques, the report states that the field vane test has the advantage of simplicity because it is self-contained and does not require electronic support equipment. Also, it is the only device that easily measures clay sensitivity. Although the field vane test does require empirical correlations for interpretation, data from this test, when corrected using Bjerrum's relationship with plasticity index, provides more reliable estimates (+-25%) of shear strength in medium to soft saturated cohesive soils than any other reasonably simple in situ test.

The electrical Dutch cone test was found to give somewhat less reliable estimates of the undrained shear strength (cu)(+-35%) in clays than the field vane test; however, it is much better suited for investigating soil variability, because it yields continuous profiles rapidly and economically.

Also, the Dutch cone test is applicable in all kinds of soils even in granular deposits. Thus, the researchers feel that this device is highly cost effective and very versatile and should be used more widely in the United States. Additional information on the Dutch cone penetrometer was supplied by a study carried out by Woodward-Clyde Consultants (C-2-21). This study provides applied research data from five case histories using this device and demonstrates further the usefulness and possible limitations of the Dutch cone technique.

Concerning the piezometer, the researchers found that this device is ideal for detecting thin sand or clay layers within an otherwise homogeneous deposit. Also, the piezometer is a relatively rapid and inexpensive method for assessing variations in coefficient of consolidation throughout a deposit, though no absolute values could be obtained with the technology available at that time.

Another in situ investigative tool, the Begemann type static cone penetrometer was studied by CH2M Hill, Inc. (C-2-20). The selected Begemann cone penetrometer measures both point resistance and skin friction resistance. This study included discussions of applications, methods of interpretation, accuracy and limitations based on the researcher's experience with the technique. The report supplied examples from five case histories. The uses of the penetrometer included: subsurface investigations, soil classification, settlement analyses, and pile capacity analyses. The advantages reported were:

- lower cost - one third to one half that of drilled test borings;
- speed - three times faster than conventional boring (up to 400 ft (122 m) in 8 hours);
- fewer conventional borings needed - aids development of most cost-effective and timely field exploration.

Disadvantages of the static penetrometer were mentioned also. These were:

- gives no samples of subsurface material;
- does not indicate ground water conditions;
- interpretation of probe data in ϕ=C soils requires subjectivity.
- cannot be used in all materials.

Researchers concluded that, although the static penetrometer can not be used as the only tool in a site investigation program, it does allow the geotechnical engineer to develop subsurface information more economically than with conventional soil test borings alone.

Still another method of determining the state of stress in soils was developed and reported on by Soils Systems, Inc. (C-2-22). The technique, known as a blade stress sensor method, was designed with the idea that disturbance during testing or measuring is inevitable. The device measures soil normal stress using a three-bladed stepped vane with nine pressure cells. The vane exerts disturbance on the soil in discrete increments and determines the pressure as a function of disturbance. Then, the pressure at zero disturbance can be determined by extrapolation. The effectiveness of this device was demonstrated by laboratory testing and the accuracy of the technique was shown by comparing field results with those obtained using standard pressuremeters. In two sites, one in expansive clay and one in loess, results using the blade stress sensor agreed closely with those found using standard pressuremeters. Also, the blade stress sensor was found to be more precise and easier to use.

In summary, the research on state-of-stress in soils and design parameters measured by direct methods advanced the state-of-the-art both by raising the confidence level in techniques developed earlier and not widely used, and by initiating research on devices using new principles. However, these latter items will need further development and experience to gain broad acceptance by the profession.

2.3 Sensing Techniques

Sensing of geologic features significant for tunnel designers can be carried out either from the air or from the ground. The first group uses airborne equipment, both airplanes and satellites, to define critical geologic features related to the tunnel location. The techniques used include black-and-white, color, and color infrared photography, side-looking radar, and multispectra and thermal scanner systems. The second ground-based group includes techniques which are used from the surface or within boreholes or pilot tunnels, such as acoustic, electric, resistivity, magnetic and electromagnetic survey systems. Engineers interpret the collected data to predict changes in subsurface conditions inside the ground mass where visual observation is impossible.

2.3.1 Airborne or Remote Sensing

The potential for aerial remote sensing techniques was assessed in a study carried out by Earth Satellite Corporation (Earthsat) (C-2-9). Field tests were carried out at two sites representing two substantially different environments, one in West Virginia and the other in Nevada. The study concluded that aerial techniques are of greatest value when combined with conventional site investigation techniques. In particular, the results of a remote sensing site investigation program can help in planning a detailed, complete site investigation program. Color and black-and-white photography could be the prime sources of information to determine the regional geology and the structural geology of the projected tunnel alignment. These and other remote sensing techniques also can prove valuable for answering questions about the average characteristics of the materials and for estimating probable water conditions.

Of the remote sensing techniques evaluated at the two sites, only color infrared photography was of little value. Radar imagery confirmed some previously detected linear features and added detail to the knowledge of the regional geology. Visible and near-visible multispectral scanner data was of little value at the West Virginia site because of the limited number of outcrops and the presence of lichens which masked most rock surfaces. Heavy lichen cover interfered also with the 8-10 micrometer and 10-12 micrometer bands of thermal imagery. Aeromagnetic data correlated well with features identified in photographs, supporting the hypothesis that these features are faults. Finally low-sun-angle photography revealed numerous linear features, some of which had been identified as faults using other sensors.

In another contract performed by Earth Satellite Corporation (C-2-12), airborne magnetic sensors were used to search for buried sand and gravel. This method is based on the observation that sand and rock layers have different electrical characteristics than the neighboring ground and this, in turn, creates contrast for the passage of electromagnetic waves. Findings were promising with best results achieved by three systems which use very low frequency radio signals (VLF range). These systems were; E-Phase, INPUT, and Dighem.

2.3.2 Ground-Based Sensing

Acoustic sensing techniques suitable for use in soil were investigated by Telcom, Inc. (C-2-2). The primary objective of this effort was to use acoustic sensing to map the soil-rock interface or to identify the location of rock boulders in a soil matrix between boreholes. The secondary objective was to evaluate the potential of acoustic techniques for predicting variations of soil properties between boreholes. The most promising technique for these purposes was found to be a pulse compression or chirp method similar to that used in radar to improve resolution. This method was shown to be feasible and further research was recommended.

The field capability of acoustical surveying was explored by Holosonics, Inc. (C-2-4) at a site in Washington, D.C. The system used involved surveying a total of 244 ft (74.4 m) using four short boreholes. Data from the survey were recorded directly in digital code on perforated paper tape, thereby reducing data handling time. As the tunnel progressed, predictions from the survey were compared with the observed geology and with the geological mapping done by the owner's engineering staff using other methods. Correlations between predicted and observed features was impressive, both in the results formulated by Holosonics and those obtained by a later independent study of the raw computer data. Especially impressive was the ability of the technique to detect a large zone of blocky ground located some 200 to 250 ft (61 m - 76 m) from the borehole.

Acoustic emission techniques can be used to predict ground stability by detecting noises generated by soil and rock movement. This application of acoustic monitoring was investigated by the Department of Civil Engineering and Physics of Drexel University using laboratory and field testing (C-2-26). Results indicate that acoustic emissions can be interpreted to show both current soil and rock movement as well as the stress history of these materials.

The potential of this method was demonstrated using an acoustic signal in the 1 kHz to 30 kHz range to predict a small tunnel-roof failure a day and a half before it occurred. An attempt was made to determine if any specific frequencies could be related to potential instabilities so that background noise could be filtered out. However, after analysis of thousands of recorded signals, no specific bands could be associated only with field movements. Thus, acoustical monitoring can be carried out only when there is no construction activity in the neighborhood.

Tunneling in rock is expensive and a sensing system capable of predicting unforeseen problems would be extremely valuable. For this reason a contract was awarded to ENSCO, Inc. (C-2-10,11) to explore this possibility. The first volume of this report (C-2-10) determined that a borehole-sensing system capable of yielding complete data on subsurface conditions has extremely high cost/benefit potential. This finding is especially significant in view of the rapidly increasing costs of driving pilot tunnels.

A prototype system was designed to take electromagnetic radar, pulsed acoustical, and multi-spaced array resistivity measurements. The sensors were placed along a long horizontal borehole and data were stored on magnetic tape for reduction and analysis later at a computer center. A prototype system was designed including instrumentation, methods of application, interpretation of data, corrective measures, and suggestions for future research.

FHWA invited 14 organizations to evaluate the effectiveness of their site investigation techniques at the site of the proposed Forest Glen Metro Station in Maryland in 1977 and early 1978 (C-2-23). Acoustic, seismic, and electromagnetic survey techniques of site investigation were investigated during the field research experiments. Nine of the invited 14 organizations submitted written reports which provided evaluations and predictions of the geologic structure using their probes and data processing techniques. Results of these experiments indicated that, in general, the higher frequencies of acoustical waves result in greater detectability and resolution of rock discontinuities but shorter distance of rock penetration. However, a higher energy source may improve penetration distance. Of the five acoustic and seismic systems tested, two were recommended for further development. These were the cross-hole acoustic system of ENSCO, Inc. and the down-hole and cross-hole system of Holosonics, Inc.

Concerning the electromagnetic techniques, the most significant improvement needed, according to the survey, was provision of azimuthal directivity around the borehole to avoid superposition of all reflections from the 360 degree omnidirectional field of view. Also, the effective radius should be enlarged and the behavior of electrical properties of rock masses in the frequency range from 10^6 to 10^9 Hz should be further investigated. Of the three systems compared, two were found to be worth further development. The first was the ground probing radar system of ENSCO, Inc. which had an effective penetration range between 5 and 20 ft(1.5 -6 m). The second which was deemed extremely promising was the method of Southwest Research Institute which effectively penetrated up to 60 ft(18.3 m).

As geophysical probing techniques continue to improve, it is becoming possible to determine detailed information not only at specific points, such as boreholes, but also extending as far as 50 ft (15.2 m) beyond. With better interpretation of the data, moreover, it may be possible to provide a more graphic, but still accurate image of the underground environment. A study carried out by the Lawrence Livermore National Laboratory (C-2-25) applied some of the more sophisticated techniques of data interpretation developed in other disciplines to interpretation of geophysical data. Both electromagnetic and seismic techniques were investigated for imaging such structures as bridge piers, grout injection areas, and a strip mine. Results indicated that mathematical procedures are, in certain situations, capable of producing a clear visual image of subsurface geophysical structure.

Although most underground sensing systems are used to study naturally occurring features, acoustic surveys can be used also to evaluate construction materials, such as tremie concrete. In a study conducted by Holosonics, Inc. and Sigma Industrial Systems (C-2-14), acoustic transmitters were installed in PVC pipes which had been inserted during concrete placement. Using methods developed in preliminary laboratory testing, the researchers performed through-transmission surveys on a tremie concrete seal of an Interstate Highway bridge between Portland, OR, and Vancouver, WA. The surveys were able to detect significant velocity variations which could be attributed probably to "washing" of the concrete during placement. However, the surveys indicated that the pier had cured in a generally homogeneous fashion and contained no major voids in the areas surveyed. This experiment indicates the potential for acoustic evaluation of materials, such as the tremie concrete construction.

2.3.3 Combination Device

In summary, research on ground-based sensing aimed at reducing the cost of site investigation for highway tunnels, making the data base more complete, and extending the range of observations in the radial direction by sensing along the axis of the borehole or pilot tunnel. This part of the research went through several stages of development. The most advanced version of a combination probe sensing device was still under development at the time this report was written.

The Mobility Systems and Equipment Company of Los Angeles, California, designed and built a Mobile Underground Site Evaluation System (MUSE) in 1981 and 1982. MUSE was first utilized in 1982 to support a field test at the Cumberland Gap tunnel test site near Middlesboro, KY. Southwest Research Institute conducted the tests from a 1004-ft (306-m) long horizontal borehole using their own combination probe sensing device developed for the FHWA in September 1982.

The combination probe sensing device includes the following equipment:

- a shallow resistivity device designed to measure resistivities of the borehole wall material with high resolution. Capable of detecting about 0.5-ft (0.15-m) thick layers. This method indicates the layer thicknesses along the borehole;
- a deep resistivity device is designed to probe the resistivity of the materials around the borehole in a radius of 50 ft (15 m). This device can detect significant cavities within this radius;
- a VHF radar system consisting of an energy source and transmitting and receiving antennae separated by 2.9 ft (0.9 m). The transmitting antenna has some directivity in the azimuthal plane around the borehole axis. The probe is designed to detect the reflections of a transmitted electromagnetic pulse produced by electromagnetic discontinuities, usually representing geotechnical discontinuities, in the ground. At each borehole position, the time variation

of the received signal is recorded for 500 nanoseconds for each angular position (45 degree increment) of the transmitting antenna;

- a seismic probe consisting of two transmitters and three receivers hydraulically stamped against the borehole wall. The probe measures the seismic velocity directly from the signal propagation between source and receiver through the ground and records the reflected waves from the depth.

The data obtained in the Cumberland Gap test are being processed at the writing of this report and the final report is expected to be available in 1984. No conclusions can be drawn at this time; however, it is clear that:

- the proposed technology has a great potential;
- more experience is required to fully develop this potential.

More specifically, additional experience is required: to correlate geophysical data with the ground material classification and design parameters used by tunnel engineers; to interpret the "signatures" of materials; to establish the geometry of weak planes, cavities, and all major discontinuities, such as faults in the ground, in a graphic form drawn to scale; and to estimate water conditions in the future tunnel and stability of the excavated surfaces. Most importantly, additional experience is essential to increase the confidence level of engineers in this method.

3. Ground Movements, Prediction and Control (Tunnel Construction and Evaluation)

The major aim of this task was to approach the tunnel lining design problem from the phenomenological and analytical sides and to a lesser degree to improve on tunnel-lining materials and lining techniques. For this reason, FHWA encouraged the States to instrument tunnels under construction and the FHWA jointly funded tunnel instrumentation by State DOT's and other Federal Agencies.

The case studies of tunnel instrumentation in Colorado and California were intended to provide a data basis for analyzing the interaction between ground and tunnel linings. Ground pressure depends on the material around the tunnel and the in situ state of stress in the ground, water pressure, the excavation method, initial unsupported ground movements, flexibility and allowable deformation of the primary and final lining and supported ground movements leading to an equilibrium state. Various theories were used to interpret movement and deformation data and correlate them with ground pressure theories on tunnel lining.

The reports can be classified in three categories which combine areas of research covered by both the initial and revised assignments of Task 3. These categories are:

1. Phenomenological studies, including testing of materials and instrumentation and observations of the tunnel;
2. Interpretation of these observations, including various theoretical studies;
3. Development of lining materials and improved tunnel lining techniques.

3.1 Phenomenological Studies

The earliest work on this subject was carried out in 1977 as part of a program studying the response of tunnels to earthquakes. This research performed by Tor L. Brekke (C-3-1) began by designing instrumentation programs at four levels of sophistication, with each succeeding level including also all the features of the lower levels. The first and most basic monitoring system involves thorough cataloging and mapping of defects in the tunnel lining and support system and installation of tape extensometer measuring points with institution of regular readings, at least once a year.

The second level is designed to provide information on dynamic tunnel motion compared with free-field rock or soil mass reponse. Instrumentation at this level includes three, and possibly four triaxial accelerometers equipped with central recording capabilities. Level three monitoring employs one triaxial and two biaxial accelerometers making it possible to determine the relative displacemnt and strain between the crown and springlines. The fourth, most advanced monitoring system recommended, uses an array of seven biaxial accelerometers to measure the total response of the tunnel.

It was recommended that the first two of these monitoring systems be applied to instrumenting three California tunnels: the Loleta Railroad Tunnel, No. 40, the Caldecott Tunnels, and the San Fernando Railroad Tunnel, No. 25. In each location, the complete geological environment of the site is discussed in conjunction with the criteria for choosing the particular site.

The instrumentation of the Caldecott Tunnels was carried out in a contract performed by the California Department of Conservation, Division of Mines and Geology (C-3-9). Instrumentation equivalent to Level 3 described above was installed. This included: tape extensometers, triaxial accelerometer and biaxial accelerometers. The data collected by these instruments was stored on magnetic tape to be evaluated under the next phase of this contract.

The overall approach to the investigating the structural stability of tunnels was outlined in a series of reports prepared by Delon Hampton & Associates, Chartered (C-3-3,4,5,6). The studies leading to these reports began by considering the geotechnical problem specific to tunneling, settings for various tunneling problems (for example, soft ground, rock, weathered rock, and mixed face), approaches to exploring and identifying problems and specific procedures for site investigation.

The second volume of these reports (C-3-4) concentrates on in situ site investigation techniques in soil, rock and transition materials. Each method is assessed from the standpoint of its operating principles, potential for contributing useful information, and drawbacks, if any. Specific modifications of individual techniques are included in the discussion. Also, discussed in this volume are classification systems for soils and rocks and correlations between various laboratory and field tests. Three classes of correlations are identified: Class I correlations - parameters determined in the laboratory; Class II correlations - field tests; Class III - correlations between field tests and laboratory tests.

The third volume of these reports(C-3-5) considers the use of geotechnical parameters in the design and construction of tunnels. For tunneling in soft ground, the study found the tunnel design parameters to be: soil profile, position of groundwater, shear strength, modulus of subgrade reaction and coefficient of lateral earth pressure, Poisson's ratio, and unit weight. Most of the design methods, however, assumed linear elastic behavior, which, strictly speaking, is not valid. For this reason, the study recommends development of nonlinear, inelastic procedures to relate more closely to actual linear and ground responses. Also, the study concluded that, wherever the potential for cost savings exists, the currently used methods of liner design should be verified using instrumented test sections to monitor response of both ground and liner.

The behavior of rock during tunneling is strongly influenced by discontinuities in the rock mass. Nevertheless, the study reported that no currently available theoretical approach could be applied to predicting behavior. The study recommended systematizing and improving the accumulated experience in rock tunnel design and construction using rock type, rock classification systems, and rock behavior descriptions. A number of such classification systems are described.

The parameters needed for an analytical design of tunnel liners are:

- depth of cover;
- unit weight of the ground surrounding the tunnel;
- coefficient of lateral earth pressure;
- position of water table;
- modulus of subgrade reaction.

These parameters were compared and rated on a scale of 1 to 5, relative to their importance in various tunneling situations.

The study concludes with a review of current practices of tunnel liner design focusing on design of several actual tunnels, including: the Washington Metropolitan Area Mass Transit Authority (WMATA), Bay Area Rapid Transit (BART), Chicago Urban Transportation District (CUTD), and Maryland Mass Transit Administration (MTA) systems. The designs and geotechnical backgrounds of these tunnels are considered and analyzed with respect to the effectiveness or drawbacks of the design criteria used. It was concluded that the most influential parameters during tunnel construction are: ground water conditions, soil type and stratigraphy, soil strength characteristics, boulder conditions, rock mass quality, joint characteristics, and intact rock properties. Effective site investigation should be directed toward determining these parameters.

The fourth volume (C-3-6) of these reports highlighted the benefits and lessons learned during construction of actual tunnels around the world, among which were tunnels in New York, Maryland, Colorado, and California, Osaka, Japan, and Helsinki, Finland. The survey studied effective construction procedures, such as predrainage, chemical grouting, ground freezing and basic tunneling problems in rock, such as predicting rock conditions, squeezing and swelling conditions, loosening and crushed rock conditions. Some effective construction procedures for problem tunnels in rock were described also. For example, using a tunnel boring machine in competent rock can be advantageous in reducing labor, overbreak and support costs.

Among other construction procedures analyzed was the rock bolt system which is effective in improving stand-up time during tunneling and which provides temporary and permanent support but cannot be used in badly broken rock formations. Another method, shotcrete lining, is useful in loosening rock; however, its effectiveness may be influenced by the geometry of the critical rock wedges, configuration of the tunnel surface, the presence of water and adhesion problems on the rock surfaces. The New Austrian Tunneling Method (NATM) has the major advantage of adapting readily to varying ground conditions and flexibility of changing tunnel cross-section. However, it requires a well trained field staff and experienced crews.

The Eisenhower tunnel located on Interstate 70 outside Denver, CO, was instrumented to supply basic data to be used in selecting appropriate tunneling methods and support-lining systems. This project, carried out by the Bureau of Reclamation (C-3-10), involved a wide range of studies including: geological investigations, determinations of in situ stress and deformation modulus, rock movement monitoring, steel support instrumentation, lining instrumentation, multiple drift stress measurements, laboratory core tests, and petrographic studies. Unfortunately, almost every step of this study encountered some problems which adversely affected the date. In some cases the test equipment was destroyed completely. Some of these problems might have been eliminated by involving the contractor, perhaps by assigning one of the contractor's engineers to assist in installing and monitoring the instruments.

Although no firm conclusions could be derived, some helpful correlations were noted. The steel support and lining system reactions were generally compatible and tended to follow tension and compression trends in the rock. The stress field measured in the rock at one station was approximately three times that at another station. Correspondingly, the maximum loads and percent strain of steel supports were also over three times higher at the first station. This was confirmed again by laboratory tests showing the first station to have slightly poorer rock properties.

3.2 Interpretation of Observations

Some valuable insights into the ability of instrumentation to predict conditions in flawed rock were derived from a reanalysis of the data obtained in the Straight Creek Tunnel under the continental divide in Colorado. The data was obtained from a pilot tunnel driven during the period from 1963 to 1965 and was analyzed at that time. However, because it was found that the results included a lot of spurious data caused by unrecognized instrument malfunction, the data was examined again in 1982 by Terrametrics, Inc. (C-3-8). The original data was first screened and then reprocessed completely and reorganized into a consistent and useable format which incorporated about 40% of the original data.

The Terrametrics study concluded that measurements of rock deformation and support loading are most crucial for support system design. Support loading was found to be a discontinuous process, with peak loads measured soon after excavation but of short duration. Reloading may reoccur repeatedly in response to a variety of geologic and construction influences. The study concluded also that load stabilization is an equilibrium condition and is easily disturbed, for example by construction activities like timber repairs and "relieving". One of the major causes of disturbance, however, appears to be transients initiated when the tunnel face intersects geologic discontinuities. Such transients were found to propagate many hundreds of feet along the tunnel disrupting support equilibrium.

The steel rib support system of the second Eisenhower Tunnel was monitored and analyzed by E.J. Cording (C-3-11). Forty-five ribs were instrumented with strain gauges to measure strain and 57 were equipped with tape extensometer points by the Colorado Department of Highways to measure lateral convergence. Three ribs out of the 45 instrumented were selected for detailed study. Because construction procedures for this bore were well defined and recorded, it was possible to make detailed comparisons between lining behavior and construction procedures. Results agreed well also with known geological conditions.

The study recommends reducing the data to a manageable level, eliminating irrelevant data and making the residual data more readable. The authors also recommend assessing potential instrument errors at the site. Further studies of data should consider time-rate buildup of stress and deformation in the lining and the influence of ground and support conditions on bending moments in the ribs. It is noted also that future studies would benefit greatly from summarizing significant aspects of tunnel performance, both from instrumentation data and general observations.

The following specific recommendations were made to improve future studies:

1. Primary emphasis on measuring ground movement using extensometers and inclinometers. Place instruments prior to excavation of main tunnels to obtain complete history of ground movement.
2. For deep tunnels, install instruments from within, possibly from small pilot tunnels driven adjacent to or within the perimeter of the future main tunnel.
3. Secondary emphasis on measuring lining strains and distortions.
4. Use easy to read, and the most durable instruments to assure valid readings over the long term.
5. Reduce and evaluate data as the tunnel is excavated to allow time for corrections and adjustments if necessary.
6. Maintain close coordination with construction personnel.

An important area of concern in planning tunnels is the potential damage that could be caused by earthquakes. The first contract, performed by Purdue University (C-3-2), addressed specifically this possibility. It developed a methodology for analysis and design of a cavity and ground support system under seismic loading conditions. An inference model was developed to estimate the degree of confidence in the inferred values of the physical parameters. Also, an uncertainty analysis was introduced to deduce the statistical characteristics of the output from the analytical model. Computer programs were designed to apply these models for evaluating the effects of four types of stress on the rock media: underground waterflow, excavation, seismic perturbation, and displacement of the rock media on the liner. In general, this method combined information obtained from site investigation with an uncertainty analysis to provide a realistic and reliable simulation of the geologic environment.

In a contract sponsored jointly by the FHWA and the National Science Foundation, URS/John A. Blume & Associates, Engineers carried out a thorough review of the state-of-the-art of earthquake engineering of transportation tunnels and other underground structures (C-3-7). This review, which included study of past performance of 127 underground openings during earthquakes, indicates that, in general, such structures are less severely affected than surface structures at the same location. The most important factors affecting stability of tunnels during seismic motion are: peak ground motion parameters, earthquake duration, type of support, ground conditions, and in situ stresses.

The review found also that current procedures used for seismic design of underground structures vary greatly depending on the type of structure, ground conditions and the past experience of the designer. Procedures for subaqueous tunnels are fairly well formulated; however, those for tunnels in soil and rock are less defined. Also, numerical procedures for analyzing dynamic stresses are not completely compatible with current static design procedures for underground structures. The following research activities were recommended:

1. Systematic reconnaissance of underground structures following major earthquakes;
2. Placement of instrumentation for recording seismic motion in tunnels;
3. Analytical studies of seismic motion;
4. Further development of seismic design procedures for structures in soil and rock.

3.3 Materials

Research directed towards developing new materials for tunnel support and lining was carried out by the Bureau of Reclamation (C-3-12). This contract was sponsored jointly by the FHWA, the Bureau of Reclamation, the Bureau of Mines, and the Federal Railroad Administration. The effort concentrated on polymer-impregnated concrete or PIC which is a conventional precast concrete which has been impregnated with a liquid monomer. Subsequently, the monomer is converted to a polymer by thermal-catalytic or radiation methods. The polymer is a solid plastic which fills voids and microfractures within the concrete, resulting in a new composite material. PIC has greatly increased strength, a higher modulus of elasticity and reduced permeability.

The research carried out under this contract built upon years of previous research on PIC materials. The load-bearing capacity of PIC was compared with that of standard concrete tunnel lining sections in a full scale mockup of a tunnel segment 8 ft (2.4m) high with an internal diameter of 8 ft (2.4cm). PIC compared favorably with standard concrete. PIC withstood 404 psi [2.8×10^6 Pa] compared to 245 psi [1.7×10^6 Pa] for standard concrete; however, failure was brittle and sudden whereas the standard concrete failure was more gradual.

Other tests were conducted to determine effects of joint configuration, to analyze heat transfer and the effects of fire and elevated temperature, and to investigate the surface burning characteristics. Cost of PIC linings was evaluated and found to be competitive with conventional concrete for tunnels 20 or more feet (6.1 m) in diameter. Most cost savings resulted from the reduced cost of precasting the thinner PIC segments and installing the lightweight support.

4. Highway Environmental Criteria for Tunnels

The aim of this task was to provide guidelines to designers to handle special, highway-tunnel related environmental and safety problems. The research activities can be grouped in the following categories:

- air movement and pollution
- tunnel lighting
- traffic operations
- driver behavior
- safety and fire hazard.

Dealing with and reducing the adverse environmental impact of highway tunnels, such as air pollution, noise, fire hazards, and accidents, obviously costs extra money. This money is not strictly speaking, tunneling costs but is aimed at increasing the public acceptance of highway tunnels and the travelers' safety and comfort. Most of the goals have been met by this task; however, at present, some of the studies on tunnel lighting and driver behavior, and fire hazards in highway tunnels have not yet been published.

4.1 Air Movement and Pollution

The enclosed atmosphere of highway tunnels magnifies the hazards from exhaust pollutants. In certain cases, because of the limited exposure periods as travelers pass through short tunnels, most of these air impurities pose negligible dangers. In other cases, in long highway tunnels, they pose a significant threat to health. In a contract performed by Mine Safety Appliance Research Corporation (C-4-1) these dangerous pollutants were identified as carbon monoxide, hydrocarbons, nitrogen oxides and particulates (which include organic and inorganic compounds from exhaust emissions and particulates from tire abrasion, salt, and dust). A literature survey was carried out to determine the short term and long term effects of these pollutants.

The second part of this contract reviewed methods of eliminating dangerous pollutants from tunnel atmospheres. After a literature search, the researchers evaluated the most promising methods in the laboratory, including methods such as catalytic combustion, adsorption, wet scrubbing and electrostatic precipitation. Laboratory experiments showed that hopcalite at 225-250 degrees F (107-121 degrees C) can eliminate carbon monoxide from air, but this method seems to be impractical on a large scale.

Nitrogen oxide and some noxious hydrocarbons can be removed by adsorption on activated carbon at ambient temperatures, but more work is needed to make such a process cost efficient. A large proportion of particulates can be removed by electrostatic precipitation, filtration, and wet scrubbing. The contractor recommended that carbon monoxide continue to be monitored and that the levels detected be used as the primary indicator of tunnel ventilation rates. Also, smoke meters should be installed in tunnels, particularly those having heavy diesel traffic.

A more up-to-date assessment of the problems of tunnel air pollutants was carried out by Science Applications, Inc. (C-4-4,5,6,7). The first study of this series described highway tunnel design techniques and ventilation systems then in use. It was concluded that there were no systematic methods of selecting the optimum air quality management from the vast number of options available and that not enough research had been directed at evaluating the impact of external conditions, such as topography, meteorology, exhaust and inlet locations, and ambient air quality.

The aerodynamic factors affecting air quality in highway tunnels were studied and a computer model known as TUNVEN was developed for calculating quasi-steady-state longitudinal air velocities and pollutant concentrations (C-4-5). This model was used to calculate tunnel air quality using varying ventilation systems, traffic conditions, tunnel lengths and other parameters. From this information, guidelines were developed for choosing an appropriate ventilation system and air quality management plan. Another computer program called DUCT was devised to analyze air flow along ventilation ducts and a finite-step model was developed. The DUCT program provides numerical solutions for inflow semi-transverse ventilation systems and examples for its application are given. A users manual for applying the TUNVEN and DUCT programs to actual ventilation problems is included as a separate report (C-4-7). In the course of this comprehensive study, a heat balance for highway tunnels was given and used to investigate temperature and humidity effects. Also, conditions necessary for fog formation were determined and the incidence and control of fires was discussed.

Intermittent cut-and-cover highway tunnels commonly found in urban areas present different problems from longer tunnels. First, these tunnels have no mechanical ventilation; thus they rely on effective design to achieve optimal air flow. The effects of such conditions as traffic density and meteorology on air flow patterns were investigated by the Jet Propulsion Laboratory of the California Institute of Technology (C-4-3). A 3% scale model named the Highway Intermittent Tunnel Simulator (HITS) was built for this study. Then, using sulfur hexafluoride tracer gas, quantitative data were obtained on air flow patterns of vehicle exhaust emissions while the percent of cover was varied from 50% to 80%. It was established that neither moderate buoyancy nor winds along the highway tunnel significantly affected emission flow patterns. In the 50% covered sections, the amount of emissions remaining in the tunnels can be lowered by varying the configuration of the center divider.

The air quality in and about passively ventilated intermittently covered highways was investigated by the Jet Propulsion Laboratory in a later study (C-4-13) using the HITS facility to simulate carefully run field tests at tunnel sites near downtown Los Angeles, CA. This report presents the estimates of traffic-induced air flow speeds in various tunnel sections. This study also provided information about air flow and pollution dispersion patterns in and around one or multiple highway tunnels for various geometric configurations and wind and meteorologic conditions. The researchers verified: the ambient air quality at the portals, the model's prediction of induced air flow along the tunnels and the pollution dispersion characteristics of the air flow along and outside the tunnels. The results obtained using HITS facility will be reserved for future studies on partially covered, depressed highways as they are designed.

4.2 Other Environmental Aspects

A major effort to clarify the socioeconomic impact of urban transportation tunnels and to help assess the effects of highway tunnel projects was carried out by Abt Associates Inc. (C-4-8,9,10,11). To evaluate the effects of tunnel construction on the environment, the tunneling effort was divided into 189 separate tasks. Effects of these tasks were examined under eight categories: air quality, noise, vibrations, water quality, visual quality, traffic, barrier and land use. An Impact Assessment System (IAS) was developed which can be applied on a general level early in project preparation without any quantitative estimates. Later, it can be used also to estimate the magnitude of impacts, and to assess the importance of impacts using input from affected groups. This offers decision makers a logical well organized basis for making their choices.

The potential problem of fire in highway tunnels was explored in a study by Sverdrup & Parcel and Associates, Inc. (C-4-12). This study investigated how to reduce the risk, damage, and fatalities from tunnel fires. Information obtained from major domestic highway tunnel operators was tabulated and compared and their recommendations were evaluated. The danger associated with transporting hazardous substances through highway tunnels was considered also and a risk analysis for unrestricted transit of such materials was performed and applied to the 35 tunnels included in the study. This encompassed qualitative assessment of the effects of traffic, tunnel design, and operations on this risk.

The Sverdrup & Parcel study concluded by making a comprehensive list of design and operating recommendations for prevention, detection, alarm, notification, control, extinguishment, and suppression of fires. Among the specific recommendations for limiting the danger of fires in highway tunnels are:

1. Prohibit transit of explosive or potentially explosive materials.
2. Strictly control transit of any hazardous materials.
3. Monitor tunnels 24 hours a day, preferably from an on-site control room.
4. Alarm systems should include telephones in every tunnel, with a direct line from the control room to a fire station. The alarm system should include also a two-way radio communication net inside and outside the tunnel.

Specific recommendations were made also for limiting fatalities in highway tunnel fires. These included using a ventilating system capable of being used both to extract smoke and for providing an emergency exit for motorists trapped in a tunnel fire area.

5. Supporting Activities

FHWA contributed with other Federal Agencies to the support of two national committees organized under the National Research Council, National Academy of Sciences and National Academy of Engineering; the U.S. National Committee on Tunneling Technology and the U.S. National Committee for Rock Mechanics. Both Committees performed significant work as indicated by their publications during the period they received some FHWA funds (C-5-1 to C-5-11). They also provided a forum for dissemination of the FHWA research results.

FHWA supported various professional organizations with research funds, promoted international cooperation and exchange of information with various foreign countries and participated in numerous conferences. This support represented a concentrated effort to advance tunneling research, gain data and experience from researchers not involved in the FHWA program, and inform the technical community about the advances in the state-of-the-art and U.S. and foreign achievements in the field.

The FHWA co-sponsored an Engineering Foundation Conference on Subsurface Exploration for Underground Excavation and Heavy Construction in Henniker, New Hampshire in 1974 (C-5-12). Subsequently the American Society of Civil Engineers (ASCE) both on Local and National levels sponsored seminars and conferences focusing on the FHWA research results. The reports on these conferences are discussed in the Section dealing with implementation.

Another example of research carried out by professional societies and partially funded by the FHWA was a study investigating potential for using underground rights-of-way for locating utility plants in urban areas (C-5-15). This was carried out by the American Public Works Association and the American Society of Civil Engineers. This study resulted in a manual designed to aid State and local agencies in improving utility accommodation policies in cooperation with utility companies. The recommended practices can be summarized:

- enable legislation to establish rights of local agencies to control use of the right-of-way;
- provide adequate staff and budget to protect streets and highways;
- establish and implement adequate permit, inspection, and pavement restoration controls;
- provide accurate information to field excavation forces to allow safe work and to protect existing utility plants.

During the entire research program, the FHWA established and maintained information exchange programs with foreign institutions which benefitted the FHWA program. The Centre d'Etudes des Tunnels in Bron, France, the Building Research Establishment and the Transport and Road Research Laboratory under the Department of Environment in the United Kingdom were particularly cooperative in exchanging information. Some of the direct benefits of these activites are summarized under the implementation results, Section IV.

The Office of International Programs, Department of Transportation (DOT) encouraged the FHWA to participate in research in Yugoslavia. In Ljubljana, Yugoslavia, a cooperative research study started in 1975 on Computer Oriented Stress-Strain-Time Relationships for soils in tunnel engineering (C-5-16,17). This study was funded 50% from allocated PL-480 funds and the other 50% was sponsored by a Yugoslav institution. The study, which was completed in January 1980, summarized the state-of-the-art of stress-strain relationships in the early 1970's and emphasized time-dependent characteristics of these relationships. When the English text became available in 1980, some updating of the report would have been required, particularly on the plasticity modeling of soil behaviors, but this was not undertaken because the Yugoslav researcher's priority at that time deviated from the needs of the FHWA tunneling project. DOT deposited the report with NTIS, but it was not published as an FHWA research report.

FHWA researchers, contract, and project managers used the DOT tunneling research review conferences (C-5-13), Rapid Excavation and Tunneling Conferences (RETC) (C-5-14), the Annual Transportation Research Board Meetings in January of each year, and XVth World Congress of Permanent International Association of Road Congresses as forums to present the research program, discuss the research developments, disseminate information and to obtain feed-back from the users.

The attendance of the above conferences and meetings, the participation in the semi-annual DOT Industry Council Meetings, and the participation in the monthly meetings of the Interagency Committee on Excavation Technology (ICET) provided an additional forum for discussion of the FHWA research program and coordination with other agencies. ICET, until its dissolution in 1978, also provided a forum for coordinating the research activities of the U.S. Federal Agencies involved in tunneling research (C-5-18,19).

6. HP&R Studies (Highway Planning and Research)

The HP&R research was financed with State and Federal Funds, administrated by State Departments of Transportation and was performed either by those Departments' personnel or associated State Universities or research institutes. Most of this research was carried out in support of Task 4. The reports can be grouped in two categories: tunnel ventilation and traffic flow.

6.1. Tunnel Ventilation

The California Business and Transportation Agency, Department of Public Works, Division of Highways, Bridge Department, carried out a literature survey on tunnel ventilation in 1969 (C-4-15). This survey included methods of ventilating tunnels, eliminating or disposing of contaminants, and evaluating physiological effects of pollutants, particularly carbon monoxide.

Tunnel ventilation was the subject of two research projects carried out by the Colorado Department of Transportation (C-4-16,17). The first of these was aimed at determining the pollution concentration in existing Colorado tunnels and predicting how long a tunnel must be to require mechanical ventilation. The Eisenhower tunnel under the Continental Divide was intended to be a major source of data but, because of delays in completing this tunnel, data was collected from various shorter tunnels in Colorado instead.

The study concluded that high altitude did not seem to increase concentrations of pollutants in tunnels having fewer than 2400 vehicles per hour. Also, results indicate that pollutants are most likely to be concentrated in cavities or along the rough uneven walls of unlined tunnels where traffic is slow and not particularly heavy. The average value of carbon monoxide detected was 8.2 ppm and the average hydrocarbon and nitrogen oxide concentrations were 4 ppm and 0.17 respectively. These levels have no noticeable effect on humans and, in fact, concentrations of 75 ppm of CO, 37.5 ppm of NO, 10 ppm of NO_2 and 6 ppm of HCHO are considered allowable for periods of several hours.

The study indicated that, even at high altitudes of about 5000 ft (1,524 m) and above, tunnels less than 2000 ft (610 m) long vent well if traffic is less than 1500 vehicles per hour. However, combination of increased length and heavier traffic may require some type of mechanical ventilation. The highest level of pollution is generated in a tunnel when vehicles are stopped and engines idle. Vehicles in motion at about 40 mph (64 km/h) induce a wind of about 7 mph (11 km/h) which contributes significantly to dispersion of pollutants.

The second Colorado DOT research study (C-4-17), completed in September 1981, investigated the ventilation system at the Eisenhower Memorial Tunnel. It was designed to determine the most energy efficient means of operating this tunnel at an elevation of 11,000 ft (3,353 m) above sea level. The 8,940-ft (2,275-m) long tunnel has a fully transverse ventilation system built in. Four natural ventilation mechanisms are also involved in changing the air in the tunnel: piston effect, barometric pressure differentials, chimney effect, and outside wind effect. Of these, only the piston was found to be a reliable means of ventilation.

A balanced mode of operation in which equal supply and exhaust flows are provided for each ventilation section, was found to be the most efficient means of operation. Unbalanced operation is inefficient because it tends to interfere with natural ventilation provided by the piston effect. This study showed how power consumption could be reduced by using lower fan speeds.

In performing this study, the TUNVEN computer model (C-4-7) was applied and found to be an excellent tool for aerodynamics design and analysis of tunnels. Its use resulted in finding a seasonal variation in airflow caused by icing the flues. Also, the TUNVEN model indicated that emission rates of newer automobiles may be much higher than originally projected, at least at high altitudes.

The Tennessee Department of Transportation sponsored a study on natural ventilation of a planned tunnel under Overton Park in Memphis which was carried out by the University of Tennessee Space Institute (C-4-21). This study was concerned mainly with the effects of the number and distribution of open and covered sections of a tunnel, on pollutant concentrations within the tunnel and near the open sections. A steady state induced velocity model and mass balances for the closed and open sections were used to develop a steady state model to calculate concentration distributions of pollutants throughout the tunnel system.

6.2 Traffic Flow

The Maryland State Highway Administration sponsored a three-part study of traffic flow carried out by the Department of Civil Engineering of the University of Maryland (C-4-18,19,20). The objective of this study was to investigate traffic flow on restricted facilities, develop a model to describe the traffic flow, and recommend methods of improving traffic. The facility chosen and investigated in the first volume was the Baltimore Harbor Tunnel, a link between major interstate highways which is extremely important to the Northeast Corridor.

The following four subsystems were studied: the tunnel itself, the ramp area, the merging area and finally the queuing area. Data were collected for four days in February and March 1973 and analysis revealed the major bottleneck to be inside the tunnel at the foot of the upgrade. Conventional regression analysis was used to compare various theoretical approaches to traffic flow.

In the second part of the research study (C-4-19), the Howard Iteration technique was applied to various traffic control alternatives. Five different control alternatives were tested: no control (normal operation), and four cycles with lengths ranging between 2 and 4 minutes of a traffic signal located upstream of the tunnel entrance. Results indicate that the Howard Iteration method can be used successfully to evaluate traffic control alternatives. The 2-minute cycle apparently is the best for this facility but a shorter 1 1/2-minute cycle should be tested also.

The third part of the research on the Baltimore Harbor Tunnel dealt with evaluating the pretimed traffic control system (C-4-20). It was found that using pretimed control could increase flow rates. In fact, left lane flows in the Harbor Tunnel were increased by 7 percent at the bottleneck area at the foot of the upgrade. Also, pretimed control improved the quality of flow throughout the tunnel; speeds were 56 percent higher during heavy flows using the 2-minute cycle than using no control. Although some disadvantages of this system were pointed out, the basic concept was deemed sound and further research on different cycles in this facility and on other facilities was recommended.

The Pennsylvania Department of Transportaiton engaged the services of the Franklin Institute Research Laboratory (C-4-22) to test the installed experimental lighting system in the underpass on I-276 in Philadelphia, PA. The lighting system used five levels of illumination of low pressure sodium vapor lamps. The objective was to determine the effect of various levels of illumination on traffic operations. In particular, to evaluate traffic accidents, vehicle velocity maintenance, braking habits of drivers and drivers' subjective responses to new lighting conditions. The results indicated that: (1) new lighting conditions decreased velocity variability and brake applications at portals; (ii) a decrease of internal lighting level resulted in smoother, safer traffic flows; (iii) increase of light intensity of monochromatic lamps inside the tunnel did not have an adverse effect on drivers; (iv) IES recommendations appeared to be better than those of AASHO; (v) six months after accident data revealed a reduction in accidents at the portals and inside the tunnel.

III. SUMMARY OF RESULTS AND PROJECT OUTPUTS.

The literature reviews, references and data presented in the reports should be useful to anybody interested in the subject. The research can be summarized and evaluated from the following points of view:

- researcher
- engineer
- contractor
- owners of future highway tunnels
- cost and benefits

The researcher can profit from practically every report. Therefore, the researchers' interest is not analyzed further in this summary.

The engineer, in his normal work, should evaluate various alternatives before recommending a particular design. The great majority of reports could serve just this purpose, to help the engineer to identify and use certain ideas which can lead to different alternatives. In this respect, the engineer could profit from using most of the reports selectively with judgement.

The contractors and owners would be interested primarily in the overviews and systems studies. In this respect the following reports may be particularly valuable: C-1-1,4,5,6,7,8,9,11,12,13,17,19,20,24,25,32,34,35, and 36; C-2-1,5,21,23, and 27; C-3-1; C-4-1,6,8, and 12.

The FHWA tunneling research project (5B) started in FY1973, the funding peaked in FY1976 and the project was phased out in FY1983. The annual fundings are presented in Table III-1 for the research, implementation and HP&R studies. A breakdown of expenditures by Task is shown in Table III-2 and Figure III-1 shows the funding in graphical form.

The total funding of about $12 million achieved the following broad results:

1. Cut-and-cover tunneling and retaining walls:
   - development of ground control ideas, a new data basis for and theoretical treatment of ground control design.
   - transfer of ground control techniques from foreign countries.

2. Site investigation:
   - rationalizing site investigation planning
   - development of new mechanical measuring devices and transfer of certain techniques from foreign countries;
   - development of mechanical (acoustic and seismic) and electromagnetic sensing (radar, etc.) techniques and data processing in site investigation to permit a better evaluation of the ground materials and tunnel design.

3. Ground movements, prediction and control:
   - improving the field observation data base for transportation tunnels and interpretation of the physical phenomena affecting

earth pressure on the tunnel lining and deformation of the tunnel lining. This is expected to lead to improved design methods.

4. Highway environmental criteria for tunnels:
   - development of design guidelines to improve the environmental conditions in and near highway tunnels, increase safety and drivers' comfort at the approaches of and within highway tunnels and to reduce pollution and fire hazards in and near highway tunnels.

Most of the benefits are not as apparent as the DOT Program Plan anticipated. One should be cautious in evaluating the benefits of a research program. In many cases, the benefits are not quantifiable at all because it would be speculative and highly questionable to work out the cost of a hypothetical case, that is a tunnel built without the benefit of this research program, and compare it with the cost of a finished project. The hypothetical case cannot be designed to the same detail as an actual adopted design, because nobody would pay to do it. The cost of surprises during construction cannot be evaluated in such a hypothetical case either, nor can the assumptions entering into the hypothetical case be verified because it will never be constructed. Thus, we are left trying to compare two cases without a common denominator.

The cost benefits (savings) of a new technology cannot be determined by a bidding process on various alternatives including an alternative using the new technology. Even if all the alternatives were designed and worked out to the same degree of detail and released for bidding, the new technology alternative would not necessarily receive the lowest bid. In general, given a choice, the bidders would select the alternative with which they are most familiar, feel most comfortable, perceive the highest potential for profit and the lowest risk. Reasons for this are numerous, such as the available skill of the contractor's personnel, project organization, past experience, a legal analysis of anticipated future problems, and the financial risk. During bid evaluation, it would be difficult to evaluate the contractor's strategy for making money with the particular alternative. Moreover; a knowledge of this strategy usually does not influence the evaluation of bids. For this reason, the selection of the lowest bid usually does not result in the lowest possible cost project. For the same reason, therefore, bidding results cannot prove the advantages and cost effectiveness of the new technology.

Often, the project preparation costs increase when new technology is considered in the design stage. Most of the research results require new or additional skills and the engineer needs specially trained personnel to appreciate the innovation and to apply it successfully. The knowledge required to do this exceeds the routine experience of many civil engineers. Therefore, the engineering firm should maintain some specialized staff or consultants to examine the applicability of research results to particular projects. Although this would definitely improve project quality, it would complicate project engineering and increase the project preparation cost. It is not certain that either the owner, the engineer or the contractor would see any immediate benefit in this extra spending; therefore, they would be inclined to avoid it.

The research results, as usual in the engineering profession, must be applied selectively, not generally. For example, the applicability of horizontal site investigation systems should be weighed against the cost effectiveness of vertical penetration and sensing site investigation systems. Similarly, the application of prefabricated panels in a slurry trench may not always be the least expensive, environmentally most compatible construction technique for urban cut-and-cover tunnels. The viability and cost effectiveness of each technique depend strongly on the geotechnical and environmental factors and on the skills of the engineers. Geographical factors, labor and legal considerations may also enter into consideration. No two tunnel projects are identical. The right solution for one tunnel may not be the optimum solution for another.

Engineers work with alternatives and, in this sense, these research results increase the number of alternatives available. Some of the research results demand new labor skills not obviously available on the labor market. One must compare cautiously those alternatives which involve either labor or machine intensive techniques, particularly when the choice is between specialized, skilled labor for precision work and unskilled labor. This comparison cannot be made on a cost basis alone because some of the benefits or risks are not readily apparent and quantifiable. For example, specialized skilled labor should be continuously employed but unskilled or common labor can be hired any time. Computer models are particularly misleading where judgement is needed. This statement is particularly relevant today when computer models have gained such wide acceptance in engineering work. It has been repeated often, that "with poor assumptions a man can make more mistakes with a computer in a minute than he could in a lifetime of common sense." This suggests handling cautiously the computer-generated numbers when comparing various alternatives. Despite the fact that computers are valuable new tools, good judgement is still required.

Some additional comments on this research program:

1. None of the reports, even the state-of-the-art reports, intends to provide an encyclopedia of engineering knowledge of the particular subject. Each report expresses the views and reflects the skills and experience of the writer, consequently all these reports are subjective.

2. Fund constraints limited the achievements of Project 5B. Highway tunnels are major structures. As shown in Section I, the average cost of highway tunnels between 1970 and 1979 was $57 million per mile based on bid prices. In contrast, spending on research activities was proportionally small. To put this in perspective, one may consider that 2.7% of the total bid prices of a decade of Federal Aid Vehicular Tunnel Projects was spent on tunneling research in Project 5B. This represents only 21% of the average cost of a one mile-long tunnel. In this light, the achievements of Project 5B can be considered reasonable.

3. Time constraints also limited the appreciation of the accrued benefits of Project 5B. Highway tunnels are constructed following a long project preparation cycle, often exceeding a decade. There was insufficient time to fully apply the research results in actual construction projects.

Table III-1
Project 5B
Annual* Funding of Research
Implementation and HP&R Activities
(1971-1984)

FY	Funding, Thousands of $			
	Research	Implementation	HP&R	Total
1971	82	-	18	100
1972	44	-	52	96
1973	190	-	50	240
1974	614	-	71	685
1975	2080	-	46	2126
1976**	2196	105	60	2361
1977	1803	100	48	1951
1978	1505	95	-	1600
1979	1000	160	9	1169
1980	632	135	10	777
1981	612	60	12	684
1982	76	-	5	81
1983	23	50	-	73
1984	-	25	-	25
Total	10,857	730	381	11,968

* Detailed breakdown for every fiscal year and for every contract was not available in the Project File. Some of the data had to be estimated from five year totals, a few yearly records and from available contract costs in that period.

** 1976 includes FY1976 and FY1976 funds. The total represents a 15-month period from July 1, 1975 to September 30, 1976. This was the year of the transition from the old July 1 starting date to the October 1 starting date of the fiscal year.

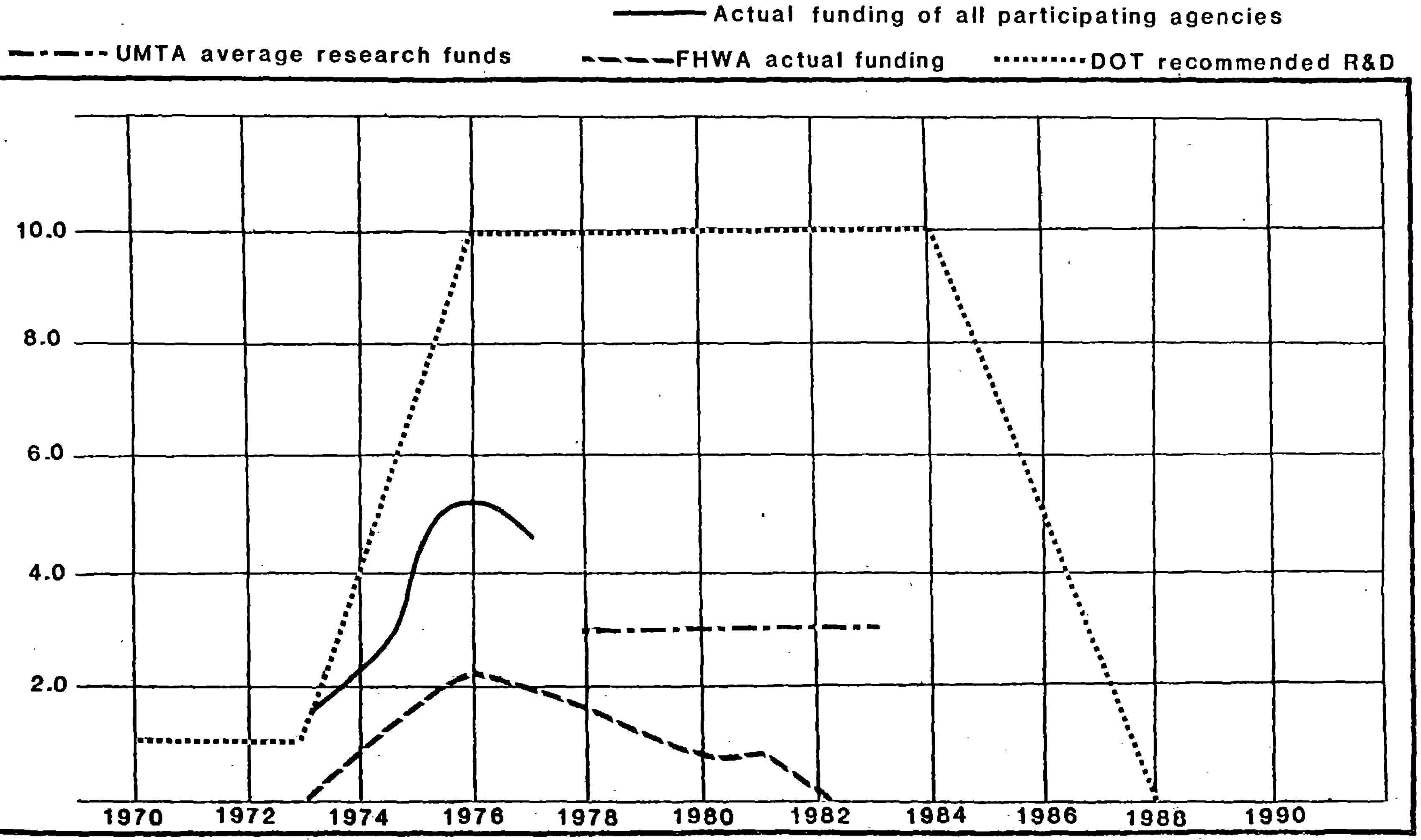
Table III-2
Total* Funding of Research
Implementation and HP&R Activities

Item	Funding, Thousands of $ Subtotals of Current Expenditures	% of Total Expenditures
Task 1	2,459	20.5
Task 2	4,381	36.6
Task 3	2,022	16.9
Task 4	1,757	14.7
Task 5	238	2.0
Implementation	730	6.1
HP&R	381	3.2
Total	11,968	100

* Detailed breakdown for every contract and every task was not available in the Project File. Some of the data had to be estimated from project totals and inferred from Table III-1.

Figure III-1
Projected and Actual Funding of the Tunneling R&D Program

Participating Agencies
DOT: US Dept. of Transportation
FRA: Federal Railroad Admin.
FHWA: Federal Highway Admin
UMTA: Urban Mass Transportation Admin.



IV. STATUS OF PROJECT IMPLEMENTATION AND TECHNOLOGY TRANSFER

The Office of Implementation made significant efforts to disseminate the research results. In particular, results of implementation can be summarized:

- research information was published and distributed;
- a study of slurry trench wall construction technique was made in European countries;
- seminars and conferences were co-sponsored in the United States;
- field evaluation of instruments and slurry walls as an integral part of underground structures was carried out.

1. Completed Implementation Projects

As part of a world survey of current Research and Development on Roads and Road Transport, organized by the International Road Federation, the Federal Highway Administration took part in a study of various applications of the slurry trench wall technique in Europe. The study team visited five western European countries, inspecting sites of completed or ongoing diaphram wall projects and conferring with designers. A total of 26 projects were visited and the findings were summarized in a report (C-1-34).

The study group found that slurry trench or diaphragm wall techniques were being applied widely on transportation projects in Europe. The conclusions were:

1. The advantages of the slurry wall method make it an effective, economical technique for routine underground construction projects as well as for projects having unique difficulties.
2. The high volume of slurry trench work being done implies a construction industry with considerable experience and the capacity to perform high quality construction of diaphragm walls.
3. This perfected construction technique has evolved gradually over years of application.
4. Considerable design expertise is available on the staffs of owners, consultants, and contractors.

The observers found that this construction technique required no special skills that were not already available to American contractors; however, a considerable amount of experience is needed to routinely perform high quality work under a variety of conditions. Thus, diaphragm work is usually done by specialty subcontractors or experienced prime contractors. The construction procedure varied very little from one project to another. The clamshell grab bucket was used for excavating the trench on all of the projects visited. Buckets ranged in standard sizes from 18 to 60 inches (46-152 cm) wide and, in some instances, the width of the slurry wall was dictated by the width of the available bucket. Hence, if the original design called for a 21-in (53-cm) wall, it would be modified to 24 in (61-cm) so that a standard width bucket could be used.

Both cast-in-place tremie concrete and precast concrete panels are used, with the choice dependent on the economics or physical limitations of the site and, to some extent, on the preference of the contractor. Several effective applications of this technique to highway construction were described. One was in constructing retaining walls for depressed sections of highway through highly developed areas and the other was in cut-and-cover highway tunneling under a park area.

To bring the advantages of the slurry trench wall technique to the attention of engineers, architects and contractors in the United States, the FHWA sponsored a two-day symposium in Cambridge, MA, in August 1977 (C-1-35). Twenty speakers addressed various aspects of slurry wall construction, ranging from reports of applications in Europe and assessment of the current status of the technique in the United States to future research planned for this construction method. A substantial amount of technical information was presented by designers, research engineers, and contractors. This portion of the symposium dealt with topics such as site conditions, geotechnical aspects, deformations and earth pressures, and construction procedures. Specific examples of slurry wall construction were supplied related to projects in Baltimore, MD, Washington, D.C., the United Kingdom and Japan.

1.1 Instrument Evaluation

A manual for interpreting the quasi-static Dutch Cone penetration test was prepared in 1977 by John H. Schmertmann (C-2-27), University of Florida under an FHWA contract. It is designed to: (i) aid in evaluating the ground stratigraphy, the types, layering, uniformity, continuity, permeability and strength of the soils encountered; (ii) estimate the need and geometry for removal of poor soil materials; (iii) evaluate the results of soil stabilizations. The manual is organized according to the purpose for performing the cone penetration test; for example, applications for preliminary design, compaction control, pile design, estimating shear strength, or estimating settlements.

Under each of the categories, are guidelines for applying cone penetration data and sample applications are supplied to illustrate the procedures. Step by step directions are given for adapting instructions and evaluating the results. The method is designed for use by geotechnical engineers familiar with the fundamentals of soil mechanics and foundation engineering. A 43-minute video tape called "Introduction to the Dutch Cone Penetration Test" also was prepared under this contract.

The French Self-Boring Pressuremeters, PAF 68 and PAF 72 were evaluated by the California Department of Transportation under an FHWA direct task order contract (C-2-28). The primary tasks of this investigation were to conduct expansion tests with the two devices at three California sites and evaluate the operation, design, and construction characteristics of the two probes. During the project, two other sites were added, Teton Dam in Idaho and Saugus, Massachusetts. The evaluation included comparing results obtained with laboratory tests and with other in situ devices, such as the Cambridge self-boring pressuremeter.

The PAF probes were easily adapted to the American drill rigs used in the project and calibration and testing proceeded with no difficulty. The PAF 72 pressuremeter proved to be the sturdiest instrument capable of withstanding rough handling in the field. However, the Cambridge pressuremeter was the most sensitive probe tested and, thus, is recommended equally with the PAF 72. However, it was noted that the PAF 72 monitoring system was mechanically based and was somewhat simpler to operate than the electromechanically based Cambridge probe. Also, investigators state that the appropriateness of self-boring probes for particular field exploration must be considered. For example, if the subsoil layers have already been delineated by other methods, self-boring probes could be used in specified layers only.

In addition to detailed instructions for carrying out field tests with the self-boring probes, computer programs using the BASIC language were written to reduce and plot data. Also, a new graphical method of applying pressure and volume corrections was proposed. Computer reduction of data required from one to two hours per test and the graphical method two to three hours, compared to between four to six hours using a completely manual method.

The recommendations based on this study were:

1. Calibration and testing procedures for the PAF probes should be standardized.
2. Transducers and pore pressure cells, such as those in the Cambridge probe, should be incorporated in the PAF 72.
3. Repeatability of test data should be studied more thoroughly.
4. The most recently developed PAF, PAF 76, should be evaluated.
5. The effect of the remaining degree of soil disturbance on soil parameters should be studied further, along with the effects of cutter geometry and strain rates adopted.
6. Hardened steel should replace mild steel in PAF cutting shoes.

The use of electrical resistivity was emphasized in a handbook of geophysical cavity-locating methods prepared by Environmental Exploration under an FHWA contract (C-2-29). This includes aerial remote sensing, surface techniques and subsurface techniques. First, the various cavity-locating techniques were reviewed and summarized. Then, the electrical resistivity technique was examined in detail, including a brief explanation of working principles and capabilities of various methods, such as the monopole and dipole technique.

Field procedures for the two most successful resistivity techniques used for cavity location, the tri-potential earth resistivity method (TEM) and the Logn monopole method are supplied. The Logn configuration is an asymmetrical version of the Schlumberger dipole configuration. Like the Schlumberger array, the Logn array, developed in 1954, takes advantage of measuring changes in the potential gradient. This report includes a discussion of data reduction and interpretation methods and sample forms for recording data obtained by these methods. Data interpretation is illustrated using sample data obtained using the two techniques at a test site in West Virginia. The relationship of the interpreted data to the cavities actually existing is discussed. The handbook concludes with computer programs written in FORTRAN language useful for reducing resistivity survey data and sample data listings.

1.2 Conferences and Seminars

Two conferences on site exploration sponsored by the FHWA were held in 1978. The first, a conference on site exploration in rock for underground design and construction, was held in Alexandria, VA, from March 29 to 30, 1978 (C-5-30). This conference dealt exclusively with results of a field research study carried out on a proposed underground subway station site of the Washington Metropolitan Area Transit Authority (WMATA) in Forest Glen, MD. This research study involved 14 different organizations and 12 different concepts of subsurface site investigation. Each researcher conducted a field study in deep vertical boreholes drilled at the site. Each used his own probes and processed and evaluated the resulting data independently. The results of these studies also were published later in a summary research report (C-2-23) in 1982 but the conference served to provide an initial (1978) evaluation of the various site exploration techniques used and the results obtained.

The second conference, a symposium on site exploration in soft ground using in situ techniques, was held also in Alexandria, VA, from May 1 to 3 (C-5-31). The objective of this symposium was to relate methods of in situ measurements to more conventional procedures to obtain properties and to consider the alternatives available to geotechnical engineers. Among the topics considered were site exploration needs and a comparison of techniques. The techniques discussed included classical and self-boring pressuremeters as well as other devices, such as the vane shear and static penetronometers.

The benefits and implementation of tunnel instrumentation were the subjects of a seminar held March 24 to 25, 1980, in New Orleans, LA (C-3-14). This seminar was directed towards decision makers in transportation agencies responsible for engineering and construction of tunnels in an effort to acquaint them with the benefits of better tunnel instrumentation. The four half-day sessions included papers given by invited speakers as well as presentations and discussions by panelists. The first session presented the reasons why tunnel instrumentation is an essential part of tunnel construction. The second session described technical methods and how to plan a tunnel insrumentation program. This included a panel discussion on the subject of contractual relations. Finally, in session three, four speakers presented case histories which demonstrated the application and benefits derived from tunnel instrumentation. These case histories included tunnels in soil and rock drilled for a number of underground transportation facilities around the country as well as for some other purposes. The seminar closed with summaries of the previous sessions.

2. Ongoing Implementation

An interchange on Interstate Route 75 being built in Atlanta, GA, offered the opportunity to document the applicability of the slurry wall construction technique to highway construction. The design calls for two 80-ft (24-m) deep slurry walls to be constructed with an internal bracing system consisting of walers and intermittent concrete struts. Under an FHWA contract, Chi Associates, Inc. (C-1-35) will prepare a detailed report which will cover the design and construction evaluation of the project and discuss the reasoning leading to the selection of the slurry wall method rather than the conventional soldier pile and lagging method. Engineers from the FHWA, Georgia DOT, and the contractor will supply information and the entire construction procedure will be documented using photographs, design drawings and plans. Among the other topics to be included in the final report are: site investigation pertinent to the wall design, dimensions and properties of the wall and the lateral support system, and problems encountered during construction.

This Atlanta project was not completed at the time this report was written, therefore a complete evaluation remains pending.

3. Evaluation

The widespread adoption of the research results by the construction industry is behind schedule. The original DOT R&D Program Plan (B-2) assumed a three-year lag between R&D expenditures and construction implementation. In fact, during the past decade, the assumption of a 10-year lag probably would have not been too short. Usually, the design and construction cycle of highway tunnels exceeds a decade. In most cases, tunnels designed in the 1960's were delayed over a decade and many of them were not constructed at all. Environmental concern, public challenges of the highway construction projects, economic slowdown, evolution of traffic following the 1973-1974 oil crisis unfavorably influenced the progress of the Federal Aid Vehiclular Tunnel Construction Program.

New ideas and various alternatives should be evaluated in the feasibilitiy and early design stages of the project cycle. At this time, advanced site investigation techniques can be planned and their results easily incorporated in the design. Also, the engineer can evaluate comfortably the various construction techniques and adopt the most economical, safe design for the tunnel. The environmental, safety, and tunnel operation aspects also can best be considered in these early stages.

Later in the project cycle, small changes in the design may trigger a chain reaction requiring reconsideration of all aspects of the highway tunnel design. Therefore, following a design change, a major engineering input is required to ascertain the feasibility and completeness of the modified design. Theoretically, it might have been possible to incorporate some of the research results in some of the delayed tunnel construction projects, however:

- a study would have been required to identify those projects where design changes could be incorporated with a reasonable cost savings or other intangible benefit;
- it was not evident then that enough time was available. Thus, any attempt to introduce design changes would have been conceived as an attempt to delay the proposed project;
- introducing design changes would have required additional funds not available under Project 5B for extra engineering;
- the owners were not convinced that these proposed design changes would benefit them;
- the owners would have resisted any suggestion of design modifications on the basis of scheduling, legal, organizational and fiscal problems.

In view of the long project preparation cycle of highway tunnels, delays in construction and various other problems discussed above, no formal adoption or deployment of the research results was detectable during the 1970's. However, the conferences and seminars may have encouraged engineers to consider some of the research results in their work not only in highway tunnel design, but also in designing retaining walls for highways or excavations for buildings or underground rapid transit systems. An indication supporting this statement is the interest shown in recent civil engineering literature in the ideas expressed in the earlier FHWA research reports.

Design engineers must evaluate various alternatives in their routine work and will apply the research results of this project depending on their needs, available funds for engineering and the design firm's experience and technical capability. In a final analysis, however, only the owners of highway tunnels can significantly influence the future implementation of the results. They can select the design firm with sufficient technical capacity and experience to study all the alternatives. Therefore, the States' Departments of Transportation should play an active role in implementation.

To avoid any misunderstanding, further implementing these research results would necessarily increase the engineering effort of project preparation. This would increase correspondingly the costs of engineering. This increased quality and quantity of the engineering effort would reduce the average total project costs though it may not affect every individual project cost. In many cases, the benefit of using advanced site investigation techniques may be a reduction of surprises during construction, hardly quantifiable as a cost benefit. However, these site investigation techniques can reduce the risk in project implementation, and thus, they can reduce the physical contingency requirements of the projects. In a final analysis, they can reduce the owner's outlay of funds for the project. Environmental benefits, enhanced safety and drivers' comfort also are difficult to quantify.

These cases illustrate the complex nature of the benefits derived from Project 5B. It would be too simplistic to present them as quantifiable. The owners of future highway projects should use value judgement in project preparation and require the engineers to perform high quality design work. This will benefit the owners in the long run and could contribute to the implementation of Project 5B.

V. PLANS AND RECOMMENDATIONS FOR RELATED FUTURE RESEARCH

From purely the research point of view, practically every item investigated could be updated or studied further to refine and improve it. Similarly, the implementation effort could be justifiably increased adding new useful studies and demonstration projects to the ongoing Atlanta, GA, slurry wall study. However, as project 5B is completed, it is now more appropriate to reconsider priorities and to apply the lessons learned during the past decade.

1. Objectives

In selecting new construction research objectives, the major constraints are the availability of sufficient funds and the time frame of execution. It would be futile and a waste of public funds to define expensive objectives even with high benefit/cost ratios, if completion of the research program is not assured. This eliminates most construction-related objectives in a low or moderately funded research program. Development and repeated full scale repeated testing of construction-related projects would absorb large amounts of funds comparable to the highway tunnel construction costs.

This point may be well illustrated by the magnitude of actual money spent on cut-and-cover tunneling research under Project 5B. The $2.5 million spent led to reports on state-of-the-art reviews, theoretical treatment of ground control, data analysis and transfer of foreign technology to the United States. It was impossible however, to develop any new technology, finance laboratory tests, help develop new equipment and techniques or fully fund any full scale construction testing. A research program addressing these objectives would have required funding levels exceeding the funds available by one or two orders of magnitude.

Another factor to consider is the time frame of execution, particularly if testing is repeated several times. European and Japanese contractors have found that field testing evolutionary improvements in tunnel construction techniques requires a decade or more. This observation is compatible with the long project cycle of highway tunnels. Under current conditions, it is not realistic to specify long range research objectives connected with tunnel construction.

2. Recommendations

With limited funds provided, the following options might be considered:

1. Investigate Innovative Ideas
2. Complete Promising Research
3. Improve Techniques and Devices
4. Disseminate Information
5. Continue Implementation
6. Special Courses
7. Incentives to Universities

2.1 Investigate Innovative Ideas

Under small contracts, funds could be used to develop new, innovative ideas on a pre-feasibility level. These contracts would be directed at the following objectives:

- rewarding engineers with innovative ideas to keep interest alive in the tunneling community;
- stimulating debate and discussion in the tunneling community;
- preparing the foundation of new future research projects, to be launched either by the FHWA or other government agency or even to be considered by private industry for rapid development.

2.2 Complete Promising Research

The unfinished, currently not implementable research studies of Project 5B could be advanced to a stage where their implementation would be justified. These subjects are:

- blade device to measure state-of-stress in soils;
- devices to measure various mechanical characteristics of soils;
- improving performance of acoustic and electromagnetic sensing devices in single horizontal long boreholes and between vertical boreholes. In particular improving directional sensing techniques and interpreting data, collecting "signatures" on rock quality and detecting large discontinuities in the geologic formation;
- initiate several new comparative sensing and interpretation competitions similar to those known as Forest Glen site experiments under Project 5B. These tests should be performed both between vertical holes and in horizontal holes similar to those of the Cumberland Gap experiment;
- continue to monitor tunnel instruments installed and monitored under 5B (second Eisenhower). If needed, additional instruments should be installed and in situ and laboratory tests executed to complete the previous work and to permit valid conclusions on the long term characteristics of soil-structure interaction;
- continue tunnel operations studies, observations on air pollution and safety problems in and near highway tunnels. Driver behavior, hazardous cargo, traffic flow and lighting problems could be further investigated to update existing guidelines.

2.3 Improve Techniques and Devices

In response to FHWA Operating Offices, observations and State DOT engineers' comments. FHWA may consider funding small contracts to improve on existing site investigation and tunnel operations monitoring devices and techniques. The identified problems should be investigated for success potential and, if justified, relatively short term contracts for achieving the objectives should be fully funded.

2.4 Disseminate Information

The FHWA support to seminars and the dissemination of information in research reports were reasonably successful under Project 5B and it would be justifiable to continue, or even expand this undertaking. FHWA may contact and encourage the authors of earlier research reports to present short articles on their earlier findings in the Proceedings of the appropriate ASCE Divisions as updated versions of the original reports. FHWA may consider also a partial funding of the writing by a standard Purchase Order of approximately $5,000 to the principal author, once the article is published. This approach would not only serve to inform the Society but would also stimulate updating of the earlier research results at a low cost and generate discussion of the subject in the same Proceedings.

2.5 Continue Implementation

Implementation of the research results should continue and FHWA may consider co-sponsoring specialty conferences with ASCE, provided ASCE invites a substantial number of the researchers who participated in Project 5B and gives them the opportunity to present papers on their subjects.

2.6 Special Courses

Along a different line, it may be useful to influence directly the owners of future highway tunnel projects by developing special courses for administrators and engineers of State DOTs. The first series of courses should be executive summaries and the second series should be detailed technical courses. The courses could be organized and delivered either in Washington, D.C., in connection with the TRB meetings in January, or be offered at a university during the summer.

2.7 Incentives to Universities

A major recurrent problem in implementing new technology in highway tunnel design and construction is the small number of engineers who are really masters of the design method. When an idea gets to the drawing board it has to be expressed in a set of assumptions, numbers, performance requirements and geometries. Those who are only superficially familiar with an idea hesitate to make decisions and tend to reject an idea rather than take responsibility. This can be corrected at the university level.

At present, universities tend to offer general, well attended, popular courses. Specialized courses without special financial support only invite expensive failures, because they do not attract students. Even on a graduate level, students do not want to specialize too much because they do not know what subjects they will need in their future employment. Therefore, to prepare a pool of specialized engineers, FHWA may consider one of the following; scholarships to interested students, grants to faculty members, or some other incentive to universities willing to offer courses in special design and construction subjects. Seminars cannot substitute for such courses because students learning the step by step application of a method will gain deeper understanding of that method than an engineer attending a seminar who only obtains a superficial knowledge of the subject and has no application experience.

3. Conclusion

Perhaps the most important result of Project 5B is the stimulation of interest in highway tunnel construction and tunnel research. Urban and rural highway tunnel construction with or without Federal aid will continue in the future because the need is there. Consequently, it would be beneficial and prudent to continue tunnel related research to support these construction plans and take advantage of the achievements of Project 5B.

APPENDIX A

ORIGINAL PROJECT OBJECTIVES AND SCOPE

Objective

To provide a new dimension of space for transportation facilities by (1) improving tunnel design and construction technology, (2) reducing the costs and adverse environmental impact of construction, and (3) reducing the cost of maintenance and operation of a safe and attractive tunnel environment.

Scope

The project is directed toward finding satisfactory solutions to technical problems which have been identified by the operating offices of the Federal Highway Administration (FHWA) and Urban Mass Transportation Administration (UMTA). Research studies are conducted to address the identified problems. Dissemination of the research results includes presentation at State, Federal, Industrial, National and International Conferences.

Close coordination of the tunneling research project is maintained with UMTA and also with the private sector through the American Society of Civil Engineers (ASCE), the U.S. National Committee on Rock Mechanics (USNC/RM) and the U.S. National Committee on Tunneling Technology (USNC/TT). Representatives of all of the organizations are active as a part of the DOT Tunneling and Underground Construction Council which reviews the transportation tunneling research projects through DOT Tunnel Research Review Conferences.

Emphasis is placed on obtaining research results at the earliest possible time to be used in current construction projects. The research effort is structured to be responsive to the need for reducing tunneling costs while supporting improved transportation. The FHWA research program includes the development of theories, instruments, new materials, improved technology, design methods, phenomenological studies, environmental and economic analyses, and the introduction of new concepts for improving the highway tunnel environment. The research is followed by demonstrations of the results and the encouragement of industry to implement the findings.

The FHWA research project has been organized into research tasks and each task subdivided into studies. The research tasks are: Cut-and-Cover Tunneling; Site Investigation; Tunnel Construction Evaluation; Highway Environmental Criteria for Tunnels, and Supporting Activities.

TASK 1. CUT-AND-COVER TUNNELING

Objective

To improve cut-and-cover tunneling technology by improving both design and construction criteria and techniques; to provide better protection for existing structures in the vicinity of construction; to reduce construction costs and environmental disruption during construction of cut-and-cover tunnels; and to develop better ground stabilization and reinforcement techniques in order to reduce disturbances during construction of cut-and-cover tunnels.

Scope

This task includes research on all aspects of the design and construction of cut-and-cover tunnels. The following technical problems are being studied:

1. New and more efficient construction techniques.
2. Improved chemical grouting techniques and materials.
3. New techniques for ground reinforcement and new ground support systems.
4. Ground water control during and after construction.
5. Systems analysis for optimizing construction planning and management for excavation, bracing, dewatering, ground control, and fabrication of cut-and-cover tunnels.

TASK 2. SITE INVESTIGATION

Objective

To develop more accurate and sensitive techniques of site investigation for (1) selecting the optimum location of tunnels, (2) choosing safe and efficient excavation techniques, (3) predicting earth movements during and after tunneling, and (4) providing a basis on which to stipulate realistic tunnel lining requirements.

Scope

1. Remote sensing of subsurface characteristics from above ground surface.

2. Indirect subsurface investigations involving acoustic, seismic, electrical and electromagnetic techniques. All these indirect subsurface investigation techniques can be applied in situ from the ground surface through other vertical or horizontal boreholes, at the face of tunnel excavation or in pilot tunnels.

3. Direct subsurface investigations involving in situ testing probes designed to measure the in situ state of stress, the shear strength of the ground mass, and the stress-strain-time characteristices of the ground mass material.

4. Development of subsurface investigation technology including long distance guided horizontal and vertical penetrators, and continuous sampling of ground materials in their undisturbed state.

5. Laboratory determination of stress history of ground materials and the constitutive relationships required for computer code modeling.

TASK 3. TUNNEL CONSTRUCTION EVALUATION

Objective

Develop more accurate and sensitive techniques:

1. To evaluate the interaction between the support systems and ground.

2. To determine the effects of tunnel excavation methodology on ground movements, displacements and earth pressures.

3. To predict the relationship between exploratory techniques, design support, and selection of construction procedure.

Scope

The task includes research on all aspects to evaluate the technique of tunnel construction. The following subjects are to be considered:

1. Design verification of support system.

2. Numerical techniques for tunnel design.

3. Design requirements for highway tunnels.

4. Earthquake and disaster mitigation.

5. Instrumentation and interpretation of data from current tunneling projects.

6. Determination of the effects of new exploration techniques on construction methodology.

TASK 4. HIGHWAY ENVIRONMENTAL CRITERIA FOR TUNNELS

Objective

To make the use of highway tunnels more acceptable and attractive to the traveling public by enhancing safety and comfort, improving quality of the highway tunnel environment, assuring continuity of traffic flow, reducing pollution effects, and reducing costs of operation and maintenance. Safety conditions and traffic flow within highway tunnels will be enhanced by applying the findings of studies on motorist behavior in transition zones and within tunnels.

Scope

This task addresses problems related to highway tunnel design and operation to optimize traffic flow; to enhance health, comfort, and safety of users and thereby increase tunnel attractiveness to and acceptance by the users; and to improve social, economic, environmental, and related consequences in the vicinity of highway tunnels. Factors considered include visual guidance esthetics, air quality, noise, maintenance requirements, and costs. Transition problems at portals and particular environmental problems and related engineering problems for very long, short, intermittent, and deep tunnels are being evaluated.

Problems will be evaluated under present conditions, and recommendations will be made for solutions. Instruments and procedures will be developed for detecting potentially unfavorable or dangerous conditions in highway tunnels, and techniques will be developed to deal efficiently with those problems. The focal point of this task is to develop environmental design criteria for highway tunnels to ensure that problems identified will be addressed.

TASK 5. SUPPORTING ACTIVITIES

Objective

The objectives of this task are twofold. First, to coordinate the FHWA research program with other Federal agencies doing research in tunneling and underground construction and to integrate the program with other DOT agencies through the tunneling and construction council, and second, to review and test technical objectives against cost effectiveness, contracting constraints, and environmental considerations; to determine the influence of energy and materials shortages; and to identify specific technological advancement needs with design and construction requirements.

Scope

To provide the FHWA Technical and Financial share of multi-agency support for the U.S. National Committees on Tunneling Technology and Rock Mechanics, U.S. and international tunneling research activities, and the National Research Council on Tunneling. To interact with national, State, and foreign agencies and industry for devising ways and means to cost effectively design, construct, maintain and operate highway tunnels.

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I. Publications of the U.S. National Committee on Tunneling Technology (partially supported by FHWA research funds)

1. "Legal, Economic, and Energy Considerations in the Use of Underground Space (1974). NTIS Order No. PB 236 755/AS.

2. "Better Contracting for Underground Construction" (1974) NTIS Order No. PB 236 973/AS.

3. "Standardization and Metric Conversion for Tunneling, Underground Construction, and Mining." (1075). NTIS Order No. PB 243 754.

4. "Executive Presentation - Recommendations on Better Contracting for Underground Construction" (1976).

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6. "Better Management of Major Underground Construction Projects" (1978).

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9. "Tunneling Technology Newsletter" (available from the USNC/TT Secretariat)
"Better Contracting for Underground Construction " - March 1976 (Issue No. 13)
"A Selected, Annotated Reading List on Tunneling" - December 1977 (Issue No. 20)
"Catalog of Tunnels - Existing, Under Construction, and Planned" - March 1980 (Issue No. 29)
"Films on Tunneling" - December 1981 (Issue No. 36)

II. Publications of the U.S. National Committee for Rock Mechanics (partially supported by FHWA research funds)

10."Advances in Rock Mechanics:
Vol.IA.
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Vol.III. Proceedings of the Third Congress of the International Society for Rock Mechanics."

11. Proceedings of the Symposia on Rock Mechanics cosponsored by various professional organizations, such as ASCE, AIME, and the hosting Universities.

III. Miscellaneous Publications (partially supported by FHWA research funds

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

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

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

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

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

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

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

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