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OWNER-ENGINEER RISK SHARING IN URBAN UNDERGROUND CONSTRUCTION

by

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Department of Civil Engineering

and

Stanford University
Department of Civil Engineering

Final Report
February 1981

U. S. Department of Transportation
Urban Mass Transportation Administration
Office of Technical Assistance
Office of Systems Engineering
Washington, D. C. 20590

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16. Abstract

Previous research, funded by U.S. Dept. of Transportation and carried out at M.I.T., has shown that where owners will share in construction risks, contractors will bid lower prices for construction. This research investigated whether owner-engineer risk allocation would result in reduced design conservatism.

The study found that non-technical, institutional variables have a significant impact on design conservatism. As might be predicted, this impact was greatest where site geology was relatively favorable and least in unfavorable rock conditions (where conservative design is needed for good technical reasons).

Where rock tunnels are being designed and built in good geotechnical conditions, this study predicts potential direct cost savings of almost 30% by reallocation of design risks.

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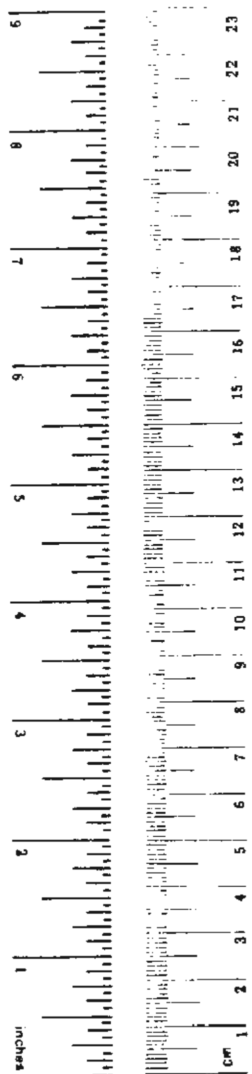
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

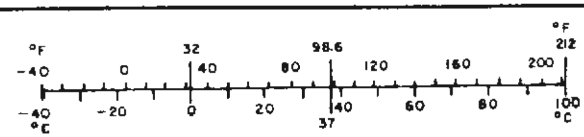
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2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

*1 in. = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

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



EXECUTIVE SUMMARY

OWNER-ENGINEER RISK SHARING IN URBAN UNDERGROUND CONSTRUCTION

SUMMARY OF RESEARCH APPROACH, RESULTS AND CONCLUSIONS

BACKGROUND

Previous research, funded by the U.S. Dept. of Transportation, Urban Mass Transportation Administration (UMTA), has shown that if a construction buyer is willing and able to reallocate and share in the risks associated with the construction of urban underground projects, then contractors will lower their bid prices to reflect this reduction in risk. Furthermore, a study carried out by the authors, along with Professor David Ashley of MIT, was able to develop a methodology for quantifying the savings which a buyer could expect to realize by sharing in construction risks. Sharing in the risks of construction — especially uncontrollable risks such as geological uncertainty or material price inflation — can now be assessed on a case by case basis by any construction buyer using this approach. However, the team which designs and builds facilities such as subways has another key participant — the project designer. The research described in this abstract was aimed at analysing the desirability of reallocating design risks, in order to secure less conservative, but still adequately safe designs for underground facilities such as subways.

APPROACH

The approach taken in this study was similar to the approach used in the owner-contractor risk sharing work. Based on case studies and interviews with all of the parties involved in several major ongoing rail transit projects, a model was developed to show the risks which impacted a designer's decision making on initial and final support design, construction methods specified or implied, and groundwater control procedures to be used for a rail transit tunnel. The model took the form of an "influence diagram" using circles to show state variables, rectangles to show decision variables, and connecting lines to show their interrelationship. The model was found to contain several non-technical or institutional variables which could impact the designer's technical decisions. Such variables included the contractual liability imposed on the design firm, and the degree of integration between design and construction (U.S. practice separates these functions completely). A workshop was then organized by the research team, at which three experienced tunnel designers designed a hypothetical tunnel in a given geological formation, with various assumed values of these nontechnical variables. The variables found to have the greatest impact were then analyzed in greater depth to determine how they influenced conservatism, and a sensitivity analysis was then conducted in some detail with a representative expert, Mr Harry Sutcliffe, to determine which institutional variables affected design decisions most significantly, and to quantify their cost impact by costing out the designs specified under all of the configurations of the institutional variables.

RESULTS AND CONCLUSIONS

The study found that non-technical variables do have a significant effect on design decisions, and hence on the cost of construction for subway tunnels in rock. Specifically, the variables found to have the greatest impact on design decision-making were:

1) Integration of design and construction; where designers had some knowledge of, or input to selecting, the construction contractor they were willing to specify less costly lining designs. Under a design-construct mode, significant savings were possible.

2) Design criteria; where requirements for water tightness or unbalanced loadings were decreased, designers were able to design less costly linings.

3) Liability of design firms; where owners required narrow form indemnification, or reduced coverage limits, and where owners were willing to assume resposibility for information provided, designers were willing to adopt lower cost construction procedures and lining designs.

There was also some interaction between these variables, with two or more being required to change in order to induce design changes for certain ground conditions.

In addition, the extent of savings from less conservative design depended on the quality of the rock (as measured by RQD, etc.). The savings were largest for favorable ground conditions and smallest for poor ground. The implication is that the designer would truly need the conservative design in bad ground, even with the most favorable risk allocation. In good rock, on the other hand, part of the cost of current designs is truly due to overdesign as a result of excessive liability being placed on the designer. This is the situation in which large savings are possible if owners will restucture, and share in, the project risks.

Consideration was given to the costs of maintenance and to expected failure costs in order to assess the trade-offs between capital costs and life cycle operating and maintenance costs. Since we could find no data on any transit tunnel failure in the U.S. and since all of the designers assured us that they were using lining thicknesses far in excess of structural requirements (to control leakage, or for other reasons) we determined that the expected cost of failures was negligible under current design levels. The costs of pumping water were considered in trade-offs on lining thickness, and in evaluating the use of shotcrete. In some cases no trade-off existed, since lower cost shotcrete linings were also expected to have less water infiltration under low head conditions.

It would be appropriate to stress the limitations of this research and to suggest areas in which it could be augmented. The research focused on the design phase of subway tunnels in rock, under prevailing U.S. practice. Changes in the risk allocation structure were departures from this starting point. It might be appropriate to conduct case studies and research on the design-construct mode of contracting, as is practised in some European countries, to assess its feasibility and cost savings in U.S. practice.

ACKNOWLEDGEMENTS

This report represents the culmination of over five years of research on risk allocation between owners, contractors and designers in underground construction. The ability to proceed with this line of research long enough to become familiar with the roles and responsibilities of all parties under existing arrangements, and then to explore the effects of reallocating risk among project participants, derives from the long term support and encouragement of several individuals in the Department of Transportation. Russel McFarland, in the Office of the Secretary of D.O.T., was the prime mover in starting out the research on owner-contractor risk sharing. Bob Thibodeau, our contract monitor at the Transportation Systems Center in Cambridge, provided us with all of the help and support a research contractor could wish for in the implementation of that early work. Subsequently, Gilbert Butler, in the Office of Rail and Construction Technology at U.M.T.A., supported this work on owner-designer risk sharing. He has my warmest thanks for his friendship and encouragement over the last several years. His openness to new ideas, and his practical critiques have greatly enhanced the quality of this research.

A number of unusually gifted and dedicated graduate students at the Massachusetts Institute of Technology have done much of the creative thinking and hard work which led to this report. Michael Dziekan and Gary Atkinson helped conceive, and carried out the data collection and analysis for, the owner-contractor risk sharing study; Benedikt Bjarnason and Mohamad al-Momen did background research for this report; Photios Ioannou and Nabil Qaddumi helped conceive, and executed, the workshop and experiment upon which this report is based. Nabil also prepared first drafts for most of this report. Supervising their work was truly a learning experience, and I consider it to have been a privelege.

Some equally gifted and dedicated faculty members at M.I.T. have provided input to this study. Bob Logcher, who codirected this research, provided essential input to the original proposal which got the effort started; he provided helpful critique and input at all stages of the research; and he contributed his razor-sharp analytical skills to the resolution of methodological problems at every stage. David Ashley was also associated with this project from the beginning. He directed the data gathering and analysis for the owner-contractor study, and assisted in the design of the experiment for this study. These two friends and colleagues have my deep respect and appreciation for their collaboration in this effort.

To the geotechnical engineers and tunnel contractors who provided so generously of their time and experience, this document is a distillation -- in all its imperfections -- of your collective experience, and of your insights into the relationship between risk and decision-making in urban underground construction; your names are listed in Appendix A. I hope you will excuse me for singling out

Harry Sutcliffe of Bechtel for special mention. Harry provided many man-months of his time -- as thesis advisor, experimental subject, and as critic. His contribution was pivotal to the success of the study.

My move from M.I.T. to Stanford in the middle of 1980 created some challenging problems for the contracting officers of Stanford, M.I.T. and U.M.T.A. To their credit, the project was able to keep going with no interruptions. George Prendergast and Francis Conroy at M.I.T., Deborah Kiest and Rita Kuhn at Stanford, and Thomas Mara at D.O.T., thank you for your patience and ingenuity in keeping the funds flowing so smoothly.

Finally, many hands have created, and revised, and revised, and revised... this text. Terry Demeris at M.I.T., Karen Carpenter and Beth Doench at Stanford, have all left their imprint on the report. Thank you.

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CHAPTER 1

INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

Implementation of U.S. mass transit projects in the recent past has been characterized by poor cost and schedule performance. In fact, U.S. rail transit systems (subways) have been estimated to cost three to five times as much as comparable European systems, even when allowances are made for differences in project and industry characteristics [Dallaire (1976:37-42)]. According to a Stanford University study (1977), the cost of underground transportation facilities in the United States is currently growing faster than the Consumer Price Index (CPI).

As these costs continue to soar, U.S. rapid transit systems are becoming unaffordable. It is, therefore, essential to control and cut the costs of underground construction.

1.2 CAUSES OF THE PROBLEM

Interviews with the different parties involved in underground construction in the U.S. (i.e., owners, engineers, contractors—and researchers) indicate that U.S. subway projects are so costly because the delivery process is complex and inefficient. This opinion is supported by several recent journal and magazine articles. They all agree that there are many costs in the delivery process that do not necessarily result in increased quality or economy in the finished product, and that these costs should be identified and pruned.

However, when it comes to diagnosing the specific causes for having underground facilities that are more costly to build than their counterparts in Europe and elsewhere, a spectrum of opinions is provided by the different participants in the industry.

Two distinct viewpoints emerge on the causes of the problem:

1. The first opinion offered states that the greatest costs are the result of institutional factors.
2. The second opinion argues that these costs are the result of internal technological factors such as wasteful or overconservative designs and failure to adopt techniques or methods currently used in Europe or Japan.

1.2.1 External (Institutional) Factors

Proponents of the first point of view argue that what is badly needed is a reduction of adversary relationships among owners, engineers, and contractors. These relationships have become defensive; they are characterized by excessive concern for liability exposure, censure and contract obligations. Contractors argue that bidders should be given full disclosure of all geotechnical data and ample time to review them before bidding. Designers argue that they should participate in the planning phase and that they should be able to advise the owner in prequalifying and selecting construction contractors. Consolidation of services (planning, design, and construction), reduction in layers of authority, pre-qualification of contractors, improved control of disuputes, and reduced "interference" by regulators are all measures recommended for the control of costs.

In short, the underlying concept is that institutional factors create an extra burden of risk on designers and contractors, over which they have no control.

1.2.2 Internal (Technical) Factors

The second viewpoint is that the planning, the design, and the construction methods are the crucial factors affecting the cost of tunnels. It is argued that U.S. subways employ too large tunnel diameters and station sizes as compared to European systems. This oversizing is compounded in its effect on costs by engineers being over-conservative in their methodology of designing the structural support system. Moreover, it is argued that U.S. engineering firms have been slow or reluctant to introduce new, cost-saving technologies; that design control seems to be the most promising solution to the problems of owners and contractors.

Over-conservatism in design will be the focus of this report. Its relation to the external (institutional) factors will be explored in depth in the following chapters. It would be appropriate here to list some of the reasons given by engineers to justify "over-design". They argue that:

a) Overdesign from a structural standpoint is a reaction to improper placement of responsibilities;

b) Overdesign is a symptom of the U.S. judicial system and the trend toward very high liability suit settlements;

c) It is difficult for them to establish low cost designs and contract specification requirements for difficult things to build (such as tunnels, complicated train control systems, and vehicle systems), if they have no idea who is going to be the contractor to carry out the designs.

Engineers suggest that owners purchase insurance to be provided to them on major underground projects, since insurance rates for professional liability (errors and omissions) have become extremely expensive, prompting designers to rely principally on tested, conventional designs such as the use of heavy steel supports, and designing for long lifespans (over 100 years). Owner-provided insurance will give them new liberty to seek out methods of effective cost reduction.

Designers argue that if they were reasonbly sure who the contractor was going to be, or at least that construction was going to be awarded to somebody who had demonstrated experience and competence, then they would certainly call for less costly designs than if they have to cover any eventuality that might occur to an inexperienced or incompetent, low bidder. If the designer does not know how his/her design concepts are going to be interpreted or what the quality of the work will be, he/she will tend to choose a more conservative alternate. For example, if he/she feels that requirements for controlling ground movements may not be achieved by the contractor, he/she may specify additional underpinning as an absolute requirement.

1.2.3 Recapitulation

In this section, the authors have shown that to accomplish the task of cutting costs, it becomes necessary, as a first step, to identify and isolate all the possible causes contributing to the cost escalation problem. This problem is attributed to non-technical factors both internal and external to the project organization as well as to technical factors that are influenced by the uncertainty of the environment.

Given the different opinions expressed, this study has attempted to link or show the dependence between non-technical and technical factors, i.e. the relationship of design conservatism and institutional factors, given the prevailing or uncertainties in the environment, and the corresponding impact of such design conservatism on cost.

1.3 THE DEFINITION OF CONSERVATISM

Conservatism is defined as "the maintaining of something against sudden change" (Oxford Advanced Learners Dictionary). If the authors are to proceed from this definition, and specify elements in the process of designing, constructing and operating new mass transit systems that are being maintained by that process against sudden changes, perhaps he can evolve definitions of conservatism in technical contexts that are more relevant to this study.

For example, conservatism in the design of mass transit systems can be defined as the behavioral inducement of rational and irrational desires to maintain certain controllable and uncontrollable elements against sudden change. Such elements are:

1. The conventional technology of design including all the traditional practices, techniques and codes thereof;
2. The conventional methods of construction;
3. The finished system as a serviceable, structurally sound facility;

4. The cost of operating and maintaining the finished system.

The first two elements indirectly describe conservatism in the context of innovation, i.e., it characterizes conservatism as being the opposite of innovation. Buhl (1960:134-135) states that,

> "the fundamental reason for our not coming up with unusual solutions and unusual methods when we are designing is habit--we think in familiar terms; we try to solve new problems on the basis of our experience and methods used in the past. Our habits transfer from one situation to another and we try to use them when they do not even apply. <u>These habits are reinforced by our perception, by our culture, and by our emotions. They represent blocks to our thinking</u>."

This study looks at how innovation is hindered through a set of factors or variables over which the designer has no control. One of these factors is discussed by Matthias (1979:135) who states that,

> "Increasing successful litigation against engineering firms, like against doctors, has multiplied insurance rates on professional practice insurance, commonly known as "Errors and Omission" insurance. Reluctance of engineering firms to promote innovative design apparently is increasing at something like an equivalent rate. The primary risk exposure to the engineer is a claim or lawsuit by the owner, although they may be generated through public liability concepts by individuals or organized groups. Mitigation of the primary risk would be for the engineer to evaluate thoroughly the risks of failure of the innovation as compared to life cycle benefits to the project and obtain the owner's unqualified approval of the innovation. Informing the public of innovations and their advantages and risks could mitigate the public liability risk exposure."

To clarify, it should be mentioned that the authors will be looking at innovation as it applies to two parties:

1. The designer and his reluctance to use new concepts in his designs such as shotcreting and rock bolts, elimination of redundant tunnel supports. These techniques are already used in Europe.

2. The owner and his reluctance to use innovative methods in his setting up of the contract and the project organization.

The last two elements, and specifically the third element, the finished system as a serviceable, structurally sound facility, are more related to the emphasis of this study.

This study is focused on the issue of excessive conservatism by tunnel designers in the process of designing the structure of mass transit tunnels. Excessive conservatism is sometimes referred to as "over-design" and is defined by Pedrelli (1979:105) as,

> "the 'gap' between the support system or quantities an engineer or contractor would specify if his only criterion was the construction of a safe tunnel at lowest cost, and the support systems and quantities actually being specified today. 'Safe' here implies an acceptably low risk of failure, equivalent to risks normally encountered in driving, airplane travel, etc."

However, certain important implications should be considered before a specific definition can be derived. Such implications are:

a) Conservatism, so defined, can be practiced, whether new or traditional methods are being used in the design. For instance, a steel beam could be very conservatively designed using Plastic Theory or Elastic Theory, depending on the safety factor used. The safety factor can be related to the probability of failure of the beam. This shifts the emphasis from absolute conservatism to excessive conservatism. The latter being an increased overdesigning of the structure practiced by the designer in excess of the normal degree of conservatism that is built in the methods, codes of practices, design criteria, standards and specifications that the designer uses in his design. In the case of tunnel design, the design codes and other such standards, if they exist, are not as specific and comprehensive as they are for other areas of Structural Engineering such as building design or highway engineering. Figure I-1 shows how the designer has the option of selecting a design load. This flexibility in selecting a design load is not allowed in many types of strucures where codes dictate design live loads, and dead loads are determined by the structure's weight. Codes will even dictate appropriate factors of safety for loads or allowable stresses or both. The premise of this study is that the designer tends to choose extreme levels of loading conditions to achieve a very low probability of failure (approaching zero) given the imbalance of risk allocation between owner and designer which is dictated by contract and organization setting. The point is that this flexibility leaves more discretion to the engineer, more room for conservatism or liberalism and a large role to be played by the project organization to affect the degree of conservatism.

b) The sources of costs in the design of structures are not all structural. For instance, the thickness of tunnel lining may be designed for waterproofing rather than for rock loads.

c) There is no standard reference--"bench mark"--against which

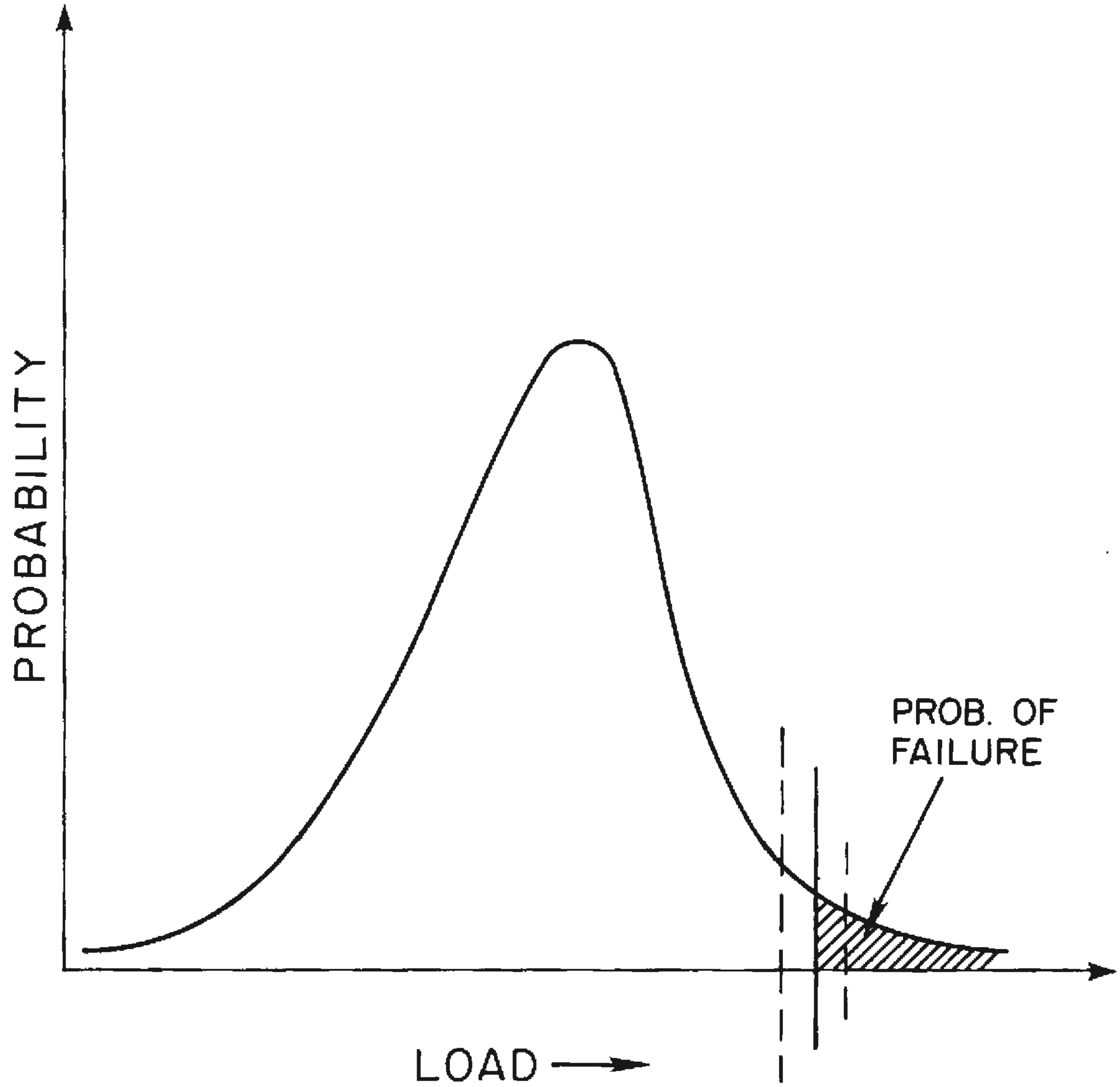


FIGURE 1-1

The Absence of a Benchmark in Design

the costs of facilities resulting from certain designs can be measured. The designs and total costs of tunnels are highly determined by underground conditions and other project conditions that vary greatly between two tunnels. No two tunnels are comparable; therefore, the comparison of costs between different tunnels is very difficult. In addition to preventing the detection of conservatism in designs, this unavailability of reference increases the level of uncertainty of the designer and hence his conservatism in designing.

The three implications discussed above lead to one important conclusion, which is that design conservatism cannot be defined by directly relating it to the methods and standard of design (first implication), sources of construction costs (second implication) or other tunnelin experiences (third implication). However, the research team felt that this problem could be solved by resorting to expert judgement; that is, having experts make informed judgements on changes that they would make in design levels for different combinations of institutional or external factors given a fixed geology. These design changes can then be translated into costs.

Conceptually the research team suggested that one common variable to which various degrees of design conservatism in a specific design could be proportionately related, or by which different designs could be compared, was the "Cost per Life Saved".

A good illustration of this concept is given by Figures I-2, and I-3. These figures show the relationship between the "expected loss of life due to structural failure" in a tunnel and the construction

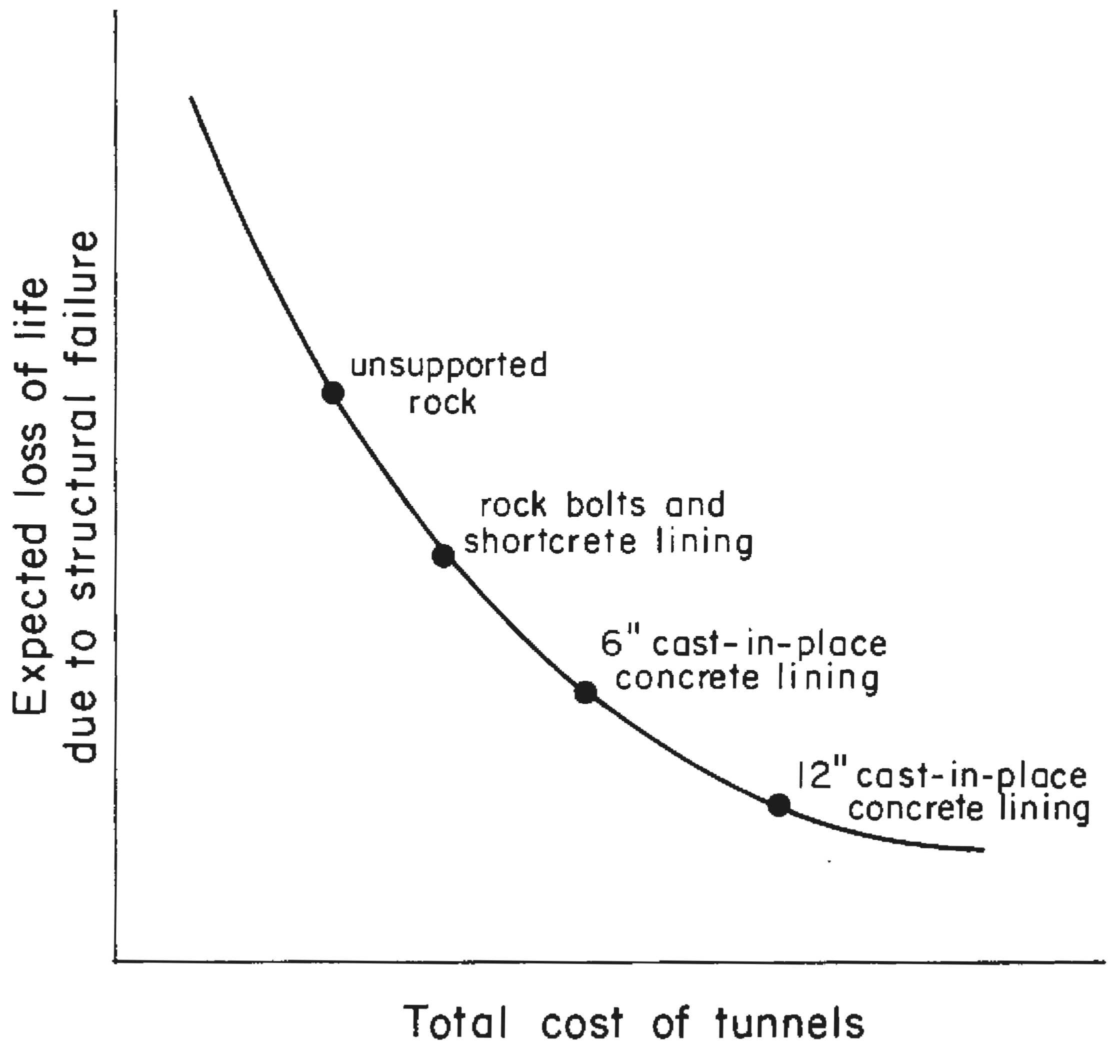


FIGURE 1-2

The Relationship Between the Cost of Tunnels and the Expected Loss of Life Due to Structural Failure

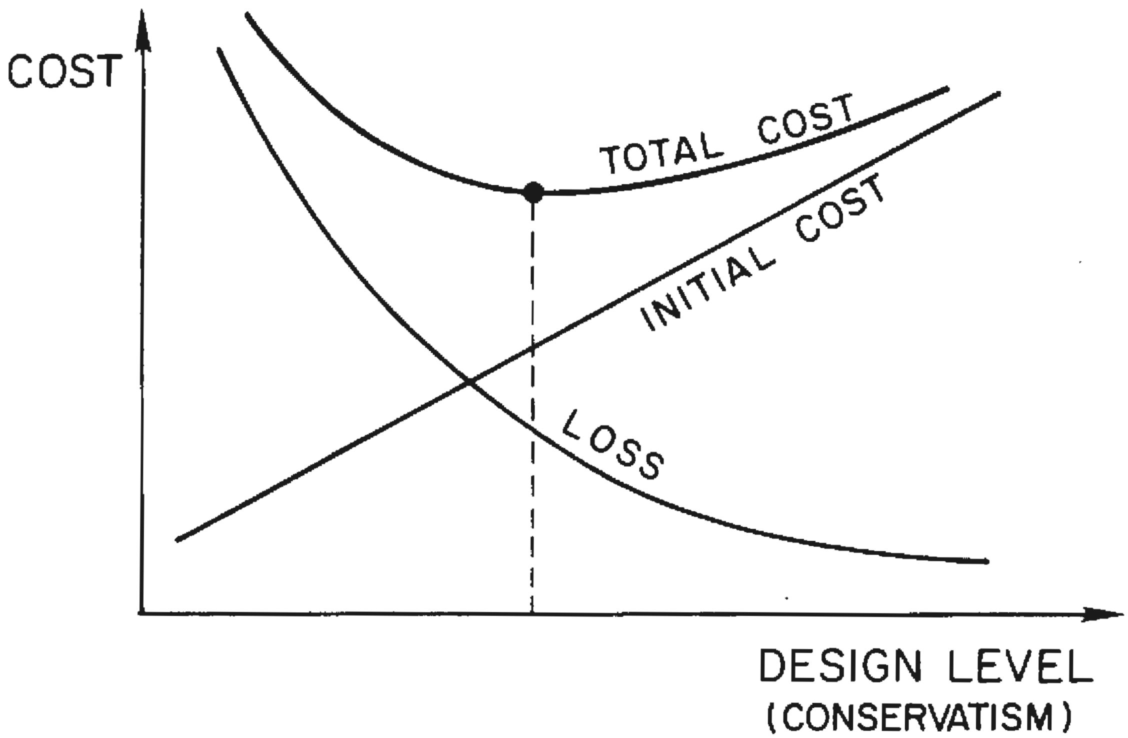


FIGURE 1-3

The Relationship Between the Design Level (Conservatism) and the Elements of Tunneling Costs cost of the tunnel. As shown, different tunnel designs, such as unsupported rock tunnels, rock bolts and shotcrete lining only, cast-in-place concrete lining, etc., correspond to different expected losses of life due to structural failures, but as the total cost of tunnels increases, the expected loss of life decreases. It is important to note that the exact shape of the plotted curves would have to be determined by subjective assessment of failure probabilities rather than based on statistics of failures; too few subway tunnels have ever failed to permit any statistical analysis. The values in the figures, specifically, the expected loss of life due to structural failure could be determined by subjective estimations made by experienced designers and measured by subjective encoding techniques known in the area of Decision Analysis and quantitative modeling.

The issue that must be addressed in this approach is how much more should the public spend on subway tunnels in order to save a human life, in a marginal sense, and how does this amount compare to the implicit or explicit cost per life saved under already accepted design practice in other forms of transportation. Since no evidence was found of a fatal, structural failure of a transit tunnel during 100 years of operation in the U.S., the probability of a transit tunnel failure in the U.S. would appear to be much smaller than the probability of dam failure—about 1/1,000 per year [VanMarcke (1978:4)]—or the likelihood of a highway or an airline accident. The scope of this research does not include questions involving public policy such as the value of life, or the acceptable level of safety in public facilities. These questions are treated in detail by Pate

(1978:Chapter 2). It should be noted, however, that the concept of evaluating the designs of public facilities in terms of the costs per life saved is being used explicitly in some European countries to equalize that cost and hence to achieve uniform levels of "conservatism" in different facilities.

In this study, the levels of conservatism or over-design in the design of rapid transit tunnels will be operationalized as a range of technical decisions made by the designer such as the choice of a support system and ground water control methods. Deviations from these decisions for changes in the institutional factors given a fixed geology will be translated into differential costs and defined as being impacted by conservatism.

1.4 RESEARCH ON CONTRACTING PRACTICE

Several research projects addressing the causes of escalating costs for underground construction have been conducted. They can be categorized into two groups: qualitative and quantitative. Most relevant among the qualitative group are the following:

a) "Better Contracting For Underground Construction", 1974, prepared by the U.S. National Committee on Tunneling Technology of the National Academy of Sciences and co-sponsored by the U.S. Department of Transportation.

b) "Tunneling--The State of the Industry", 1976, prepared by the Cresheim Company and sponsored by the U.S. Department of Transportation.

c) "Development of Research In The Construction of

Transportation Facilities: A Study of Needs, Objectives, Resources, and Mechanisms For Implementation", 1977, prepared by Stanford University, Department of Civil Engineering and sponsored by the U.S. Department of Transportation.

d) "Exploratory Study on Responsibility, Liability, and Accountability for Risks in Construction", 1978, prepared by the Building Research Advisory Board of The National Research Council and co-sponsored by the U.S. Department of Transportation.

e) "Proceedings--Conference on Construction of Urban Rail Transit Systems--The Challenge of More Cost Effective Construction", 1978, prepared by Pacific Consultants and sponsored by the U.S. Department of Transportation.

f) "Toward Improved Transportation Construction Through Research", 1980, prepared by Stanford University and sponsored by the U.S. Department of Transportation.

These reports provide recommendations for improved contracting methods. By these methods, it is claimed that the owner would receive the completed construction at lower cost and the contractor would receive a just profit. These benefits would foster a cooperative atmosphere in which there is incentive for both the owner and the contractor to stimulate the use of advanced technologies and innovative construction techniques. The new methods would also include provisions for equitable sharing of the risks, particularly those not identifiable at the bidding stage, which are inherent in underground work. Examples of these would be risks arising from changed geotechnical conditions, or escalation of materials and labor prices. Other recommendations include:

- expedited handling of claims;
- award to qualified contractors;
- improved organizational structures and techniques to assure better management of projects;
- timeliness of decisions;
- better coordination between the project parties;
- design effectiveness (e.g.: designing for economical construction, and constructibility).

These reports are unanimous in their call for equitable sharing of construction and financial risks between the different parties. The reports' results were arrived at through questionnaires, and interaction between owners, contractors, designers, insurers and laywers.

Most notable among the quantitative reports is "A Quantitative Method for Analyzing The Allocation Of Risks In Underground Construction", 1979. This report was prepared by the Department of Civil Engineering, Massachusetts Institute of Technology (MIT), and was sponsored by the U.S. Department of Transportation. The report focused on the issue of risk sharing between the owner and contractor. It concluded that if the owner is willing to accept a "proper share of the risk," then the contractor's contingencies are reduced, thus resulting in significant cost savings. An example of this would be contractors removing contingency charges to cover uncontrollable construction risks (e.g. those due to increased material prices and unforeseen underground conditions) if owners shared these risks.

1.5 OBJECTIVES OF STUDY

The previous reports acknowledged the presence of conservative designs and justified this presence as a result of the liability structure existing between owner and designer. However, previous research has not looked at the owner-engineer relationship and tried to model, analyze, and measure its impact on the costs of the system. This work looks at the engineer or designer as a relevant third party in the construction process and not merely an extention or an agent of the owner. Hypotheses concerning the relationship of design conservatism to external and institutional variables will be confirmed. These relationships will be measured in terms of costs which will give practical relevance to the findings.

This study was funded as a research project which constitutes the second phase of an ongoing investigation at Massachusetts Institute of Technology, sponsored by the U.S. Department of Transportation/Urban Mass Transportation Administration (UMTA). The first phase culminated in the 1979 MIT report discussed previously. This phase looks at risk allocation issues between owner and engineer, (e.g., the impact of professional liability insurance, and uncertainty about the qualifications of the low-bid contractor on engineering technical decisions). Moreover, the study attempts to diagnose and investigate the problem of engineering design conservatism. It looks at those variables affecting it and examines the end results.

The report combines previous research, conducted by Qaddumi, Bjarnason, Ioannou, and Al-Momen, (published as dissertations in MIT's Civil Engineering Department), by developing a detailed model which treats conservatism not as a one dimensional variable but as a series of technical decisions. This report includes testing of the interaction of these technical decisions with external variables resulting from the environment in which rapid transit projects are implemented. Finally the outcomes (costs) of different sets of technical decisions, which in turn are a function of different sets of these external variables are compared and evaluated. The following chapters look at those technical decisions and offer a comprehensive model of the interaction of environment and engineering decisions.

1.6 LIMITATIONS OF THE STUDY

1. This study will focus, as mentioned before, on engineering decisions made during the design stage and on variables that impact these decisions. It is recognized that the impact of decisions made during feasibility and planning stages is considerable, but these decisions will not be investigated here. They raise a different set of issues: Federal vs. Local funding; Transportation Planning policy; and Urban and Regional Politics.
2. The report will focus on tunneling in rock rather than in soft ground, since potential inefficiencies in rock tunneling are larger due to the frequent use of two stage support systems.
3. The study presents a combination of a qualitative and a quantitative model for explaining the interaction of engineering decisions with the external environment. The impact of the

interaction on final cost will be quantified; however, the authors found that it was unneccessary—and infeasible—to try to quantify the interaction of some intermediate variables, such as reputation and utility of the engineer. Rather, the authors found it more useful to identify the direction of correlation of intermediate variables and only to quantify the design outcomes, and their cost impact on the local owner, and the funding agency who in this case is sponsoring the research.

1.7 OVERVIEW OF REPORT

This chapter exposes the problem being dealt with and is considered an essential reading for those interested in this subject.

Chapter 2 is a background chapter on the environment of tunnel design in rapid transit systems. Discussion of the planning, design and construction processes is introduced. Organization theory concepts are discussed in the context of their application to the project organization. For those familiar with the implementation of transit systems in the U.S., the chapter should be considered as optional reading.

Chapter 3 outlines the methodology used in tackling the problem of conservatism. For those familiar with decision analysis, or not concerned with questions of methodology, the chapter could be skipped.

Chapter 4 is a discussion of the engineering technical decisions in rock tunnels and their interdependence. Review of contracting practices in European countries is presented. For those with sufficient design experience in rock tunnels the chapter could be bypassed.

Chapter 5 is a discussion of the non-technical variables influencing engineering technical decisions. This chapter is central to the report.

Chapter 6 is another important chapter which concerns the development of causal relationships as well as the development and verification of hypotheses in the authors' model.

Chapter 7 looks at the cost impacts of conservatism and is considered essential reading for those who are interested in the findings of the research.

Chapter 8 presents the authors' conclusions, recommendations and ideas for further research.

1.7.1 Summary

1. The chapter looks at the problem of escalating rapid transit costs and refers the causes to institutional as well as technical factors (Figure I-4).
2. Level of conservatism will be treated as a deviation from engineering technical decisions caused by changes in the institutional factors or external environment given a fixed geology. These deviations will be converted into costs.
3. Previous research on cost overruns has mainly focused on the owner-contractor relationship. This research could be divided into qualitative and quantitative studies. Recommendations for improvement of contracting practices are included in past research.
4. Objectives of the study include the modeling of the owner-engineer relationship in rapid transit systems. Engineering decisions will be looked at, as well as external variables influencing these decisions. Those external variables are geotechnical organizational as well as contractual in nature. They implicitly include the structure of risk allocation which, the authors hypothize impacts on the engineering

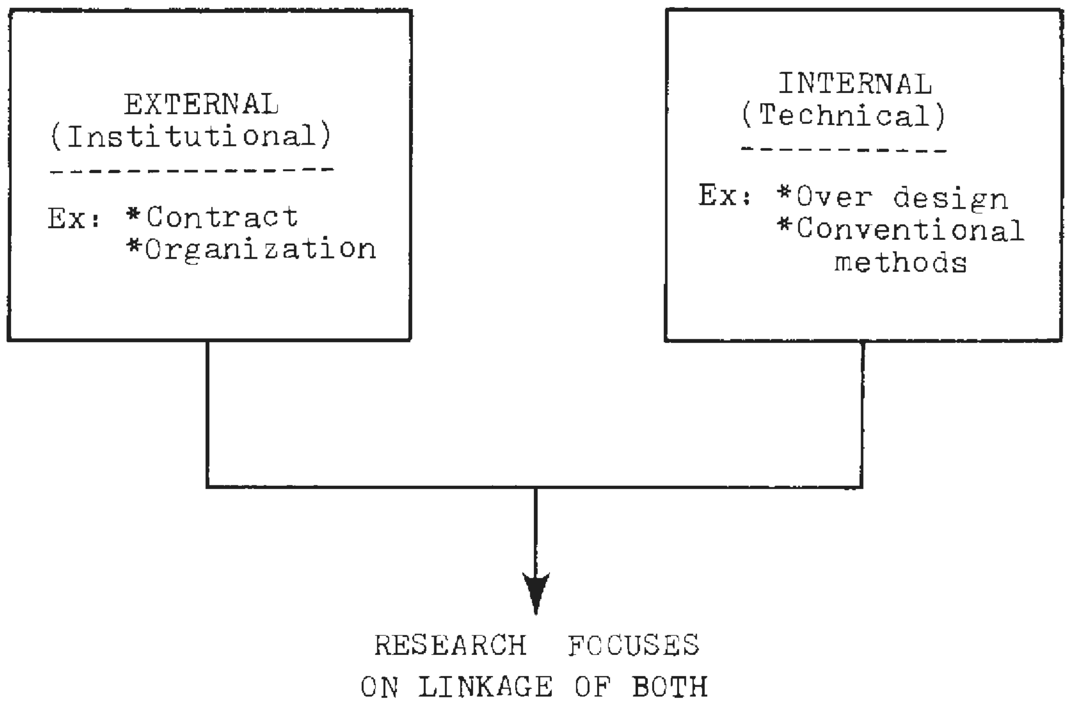


FIGURE I-4

Causes for Escalating Rapid Transit Costs decisions. The outcome to the owner of these engineering decisions given particular sets of external variables will be evaluated.

5. Limitations of research include the focus on decisions made during the design stage, and data on overdesign in rock tunnels only.

CHAPTER 2

THE ENVIRONMENT OF TUNNEL DESIGN IN RAPID TRANSIT SYSTEMS

The previous chapter laid out the objectives of the risk-sharing research, and how emphasis has been placed in this study on owner and engineer risk sharing on rapid transit projects. Furthermore, excessive conservatism in tunneling design was defined. The authors indicated that conservatism is a by-product of the environment in which the designer makes his decisions. This environment will constitute the focus of this Chapter.

2.1 INTRODUCTION - OBJECTIVES OF CHAPTER

This chapter sketches the environment in which engineering decisions are made and impacted. The implementation of a rapid transit project consists of three phases--planning, design, and construction. Figure II-1 shows those three phases. The planning phase consists of the study of alternatives in terms of their costs as well as their benefits to society and the individual. Although the authors will show that many planning decisions are political as well as technical in nature, they remain very crucial in their effect on the overall cost of the system. Examples of such decisions are those on vertical and horizontal alignments, station spacing, and operational requirements. Figure II-2 shows the contribution of the three phases to costs. Federal and State variables influence planning variables as well as costs. For example, the amount of funding influences decisions on system size, while Federal regulations on

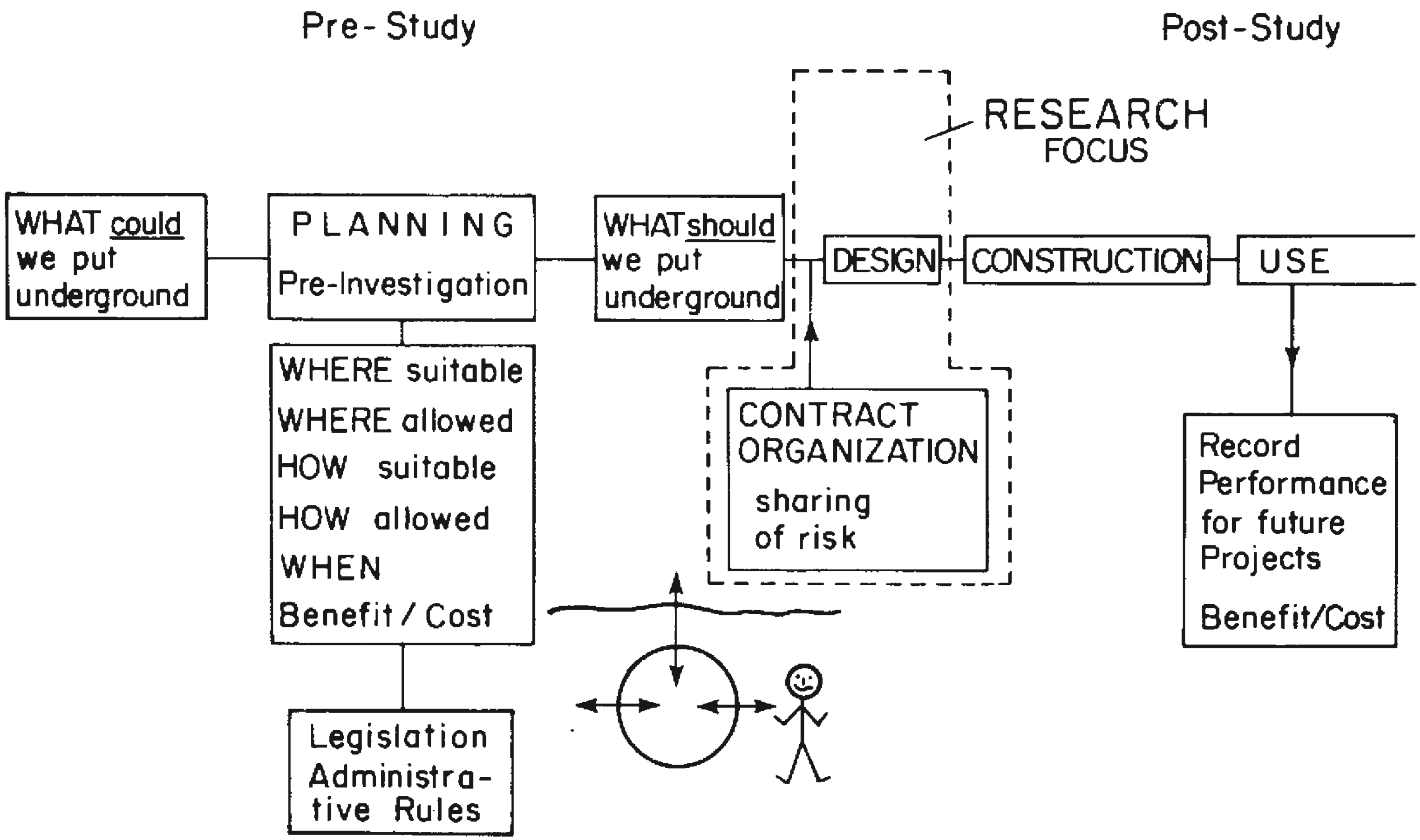


FIGURE II-1

Phases of Implementing an Underground Rapid Transit Project

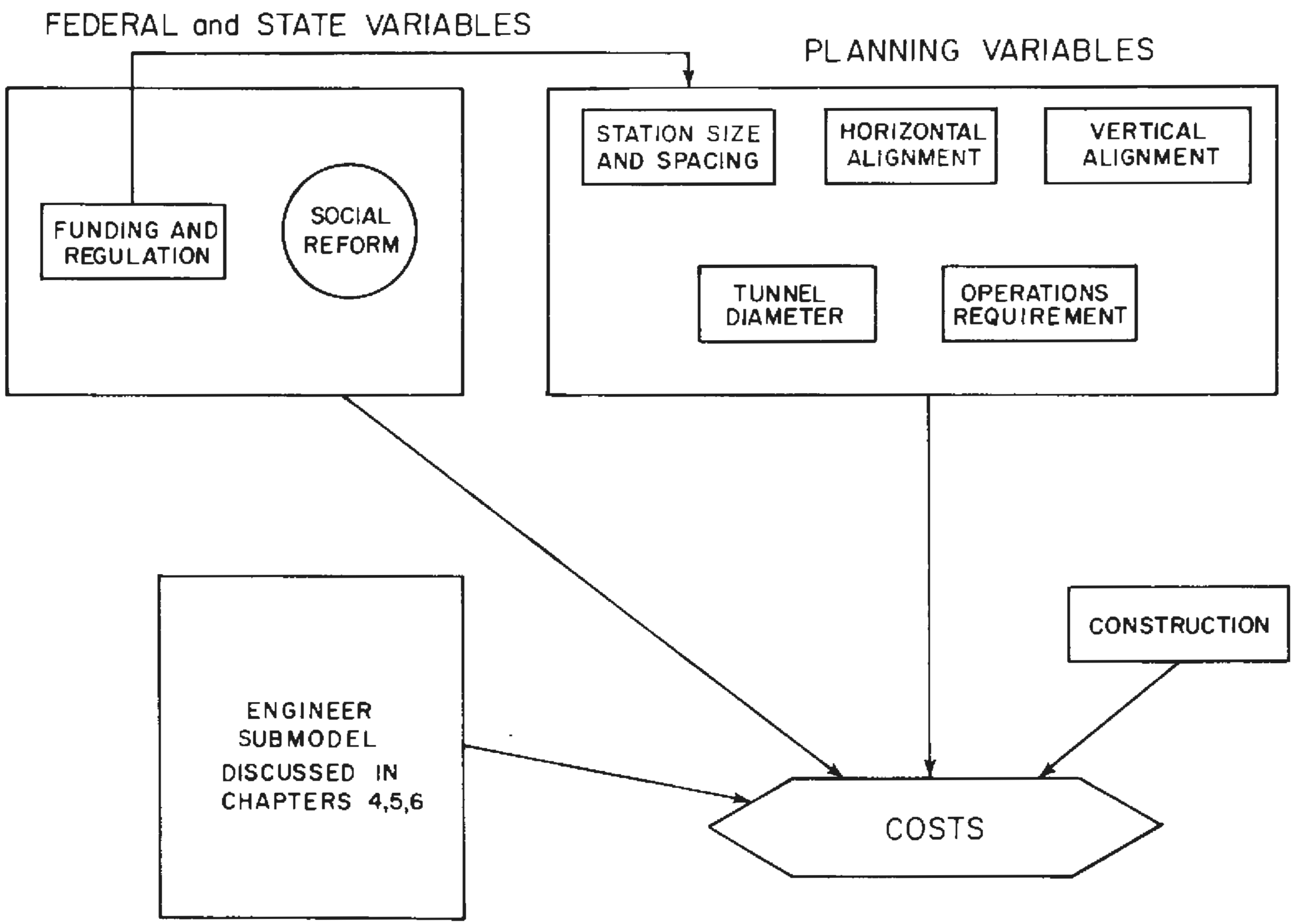


FIGURE II-2

Contribution of Implementation Phases to Costs minority business, "buy American" and other regulations influence final project costs. Engineering decisions on support systems contribute to cost. Finally construction operations conclude the influence and impact on cost.

The project organization and the contract between the owner and engineer are determined before technical design commences. Both (i.e., project organization and contract) contribute to the allocation of risks between those two parties. This chapter concerns itself with the influence of the project organization on the structure of assessment and reward systems for the designer. Furthermore, the influence of these systems on his design conservatism is discussed. Coordination in the project organization is discussed in the context of its impact on design conservatism. In addition to these topics the chapter looks at the significance of the planning phase including funding and community participation. Roles of the geotechnical and structural engineer are described.

Many of the opinions and analysis included in this chapter are based on extensive interviewing of planners, designers, the preparation of a case study and an engineering design workshop. These opinions and analysis are documented in more detail in the theses of Al-Momen (1980) and Ioannou (1980) who were members of the research team. The case study serves as a tool for providing actual examples throughout the chapter.

2.2 SIGNIFICANCE OF THE PLANNING PHASE

Since the focus of this study is on the design phase of transit projects, the planning phase will be discussed only briefly. This does not diminish its importance on engineering decisions as will be discussed in the following sections. The importance of the planning process to the analysis of the design phase is three-fold: setting project objectives, establishing relations with components of the task environment (such as the owner, engineering firms, contractors, community groups, federal and local agencies) and developing the bases for the design and construction processes. The influences on rapid transit planning can be grouped into: financial factors; community participation. The planning phase for a major transit project is a very crucial process, involving important decision making that has a great impact on the project's cost. As long as the project is undergoing its conceptual formulation, the decision makers have the greatest amount of flexibility to explore alternatives concerning all facets of the project. The planning phase is one where alternatives are studied in terms of their contribution to the benefit of the society. Subsequently decisions on optimal ways to achieve these benefits are considered. An example of a planning stage decision is the one on whether to have underground vs. surface transit systems.

The planning phase culminates with an environmental impact statement (EIS) which is discussed in detail in the following sections. Crucial decisions are made and written into the EIS. For example decisions on alignment of tunnel, both vertical and horizontal. There is little that subsequent parties can do to change these decisions towards more optimal solutions, without drastically increasing the project's cost or delaying the project's schedule.

In the course of the team's interviews some engineers argued that, in the planning phase, decisions are made by persons who are not experts on tunnel design or construction; and furthermore that planning decisions are based on very limited geotechnical information.

Mr. Dom D'Eramo of Sverdrup and Parcel (Planners for the Boston Red Line Extention) identified some of the planning decisions as highly political in nature, rather than being based on results of a transportation needs analysis, when referring to the horizontal alignment of the Boston Red Line extension. The initial alignment from Harvard to Alewife (bored tunnel) changed to Harvard-Porter (bored tunnel) and Porter-Alewife (cut and cover). At the same time, all of these alternatives were compared without a proper soil exploration program. Such a program was, in fact, infeasible, since by the time the program would have been finished, the alignment might have changed for some other reason. A few borings that the MBTA took in the 1950's did exist. However, they were very shallow and their results were not dependable.

This lack of information, along with the City of Cambridge's demand that a cut and cover approach should not be used because it would disrupt traffic flow, led to the subsequently questioned decision on a shallow bore. This alignment ran under a maze of utilities and in the section from Porter to Davis it ran diagonally under a block of houses, eliminating thereby the cut and cover approach completely.

When Bechtel, a leading U.S. design and construction firm, was called in as the design consultant their designers were reluctant to proceed with the proposed vertical alignment because in their opinion it was not a feasible solution. Mr. Harry Sutcliffe, Bechtel's Project Manager, argued that they could not dig a tunnel ten feet below houses' basements without damaging structures, utilities and disturbing people with construction and operation noise. Instead, Bechtel performed a thorough geotechnical exploration program on the proposed horizontal alignment and came up with a deep bore alternative. This alternative minimized excavation in mixed face, whereas the shallow bore was almost completely in mixed face, a factor affecting both direct tunneling costs and the advance rate. The deep bore was almost entirely in rock with only a small part in soft soil, thus taking advantage of the rock's strength and at the same time minimizing the potential damage from settlements in adjacent utilities and buildings.

Mr. Dom D'Eramo also mentioned that when planning a transit system for a city that already has one (e.g. Boston) many of the "design" decisions are already predetermined by the operations division of the existing transit authority. For example, decisions on walkways, tunnel diameter, size of cars, minimum horizontal curvature, maximum grade, are dominated by the characteristics of the existing trains in the system. Clearances for this project have been determined assuming a pantograph, even though cars on the Red Line currently do not use overhead power lines. This requires increasing the tunnel diameter by two feet. Mr. Sutcliffe proposed that, if pantographs were to be used for a street level, further extension of the line, there was no reason why a live third rail, at ground level, could not be used once the cars entered the tunnel. Reducing the tunnel diameter by two feet would result in significant savings in excavation, temporary support and final lining.

In Mr. Sutcliffe's opinion and that of designers interviewed during the course of the research (Appendix A), the planning phase as adopted in current practice and expressed in the environmental impact statement does not reflect an optimal procedure for sound decision making. It is their belief that the EIS is not serving the purpose for which it was originally intended, that is, looking at all of the alternatives in an acceptable fashion from an engineer's point of view; but rather it has become a quasi-legal document constraining the engineering decisions. Mr. Sutcliffe said that this belief is reinforced by recent UMTA attempts to limit the EIS to 40 pages.

All of the engineers interviewed agreed that the planning phase, in order to better fulfill its function, has to incorporate the views of the designer and the contractor. The latter parties are the most experienced in undertaking the task of implementing a subway project and thus they can pinpoint issues, in the form of expected difficulties or cost suboptimization, to the planners.

Experts could also be used to assess the value of geotechnical information as a means of reducing the uncertainty of the project. There exists a certain amount of information on the ground characteristics that is of significant value in choosing both the horizontal and the vertical alignment of the tunnel. The lack of such information is highly restrictive to making an optimal choice and the cost of obtaining it is usually less than the cost and time savings that it could help attain.

Having the designer participate in the planning of the project sets a much better design environment from both the owner's and the designer's point of view. The designer can thus present his arguments to the owner before any of the major decisions are made and he can thus steer non-experts towards the engineering issues that have to be considered. The same argument could be made for the input of a construction expert on issues like feasibility, construction methods, anticipated costs, etc. Neglecting the contribution of the participants who must turn the project from an idea into reality places very narrow margins on what these parties can subsequently do to decrease the cost of the system.

2.2.1 Financial Factors: Evolution of a Rapid Transit System

To understand the factors influencing the decision to build or not to build a project of the monumental proportions normally associated with a rapid transit system, one must have some understanding of the motivation of the agency charged with implementing the project.

Usually, the beginning of the project will have originated with a regional planning commission, a council of governments' transportation plan, or a comprehensive transportation planning process. Recommendations for rapid transit construction as part of a long-range transportation plan for the area and for the formation of an agency to begin work on it will have been made. Often the date that the plan is to be completed, type of vehicles (rail or bus) will be involved, and location details are included only in schematic form. The legislature acts on this general recommendation to enact legislation for the formation of an authority to plan, design, build, and operate a rapid transit system. The newly formed transit authority quickly perceives that its success will be judged by how quickly it can get a system planned, financed, designed and constructed. Most of the interviewees the research team members talked to indicated that getting anything built will require a successful bond referendum which, in turn, is most easily achieved with a system that is big, glamorous, fast, extensive, and above all, appears to serve as much of the affected area as possible from the day the system first opens. At this point, the authority must simultaneously satisfy two parties, each with conflicting objectives. The local one requires an extensive system with a minimal operating cost. The other party, the federal government, which provides up to 80% of the anticipated cost of the project, requires a truncated less costly project. The federal government knows that it cannot get enough money to fund all of the systems being planned around the country and believes that good transportation planning, economic analysis, and common sense would dictate a plan that begins small and develops over time. These two masters spend much time during the planning period demanding changes to the plan to better conform to their individual objectives. However, these rail rapid transit systems are still built with a planning horizon of a hundred years and are, by their very nature, massive projects which require huge initial capital investments. The cost of building a sizable system is presently around five to six billion dollars or more [Kang (1979:22)]. The scope of many systems has thus been reduced due to the scarcity of funds.

The "staged construction" method is reverted to as a solution to this problem, and construction is carried out in stages over a long period of time. In addition to the advantage of spreading out the initial capital requirement over a period of time, this method has added advantages of allowing periodic cost/benefit evaluations of the system and of producing feedbacks which can improve the quality and effectiveness of future phases. The decision to stage construction or to delay construction of a planned system to some future time, may prove to be a very costly decision to make. The reason is due to the effect of inflation, which plays a major role in controlling project cost. As general price levels and construction costs increase, financial plans for transit systems become disrupted. It can be argued that the project is paid for with inflated dollars, so that inflation is not a "real" cost. However, construction costs have been rising faster than the CPI or GNP deflator in recent years, so that delay does have a "real" impact on cost.

Therefore, the definition of project objectives and the securing of resources for their implementation is inherently a political process involving the owner, local state and federal governments, and local interest groups. As a result, both the objectives and resources of the project are highly uncertain and unstable.

2.2.2 Influence of Funding System on Design

It can be deduced from the above discussion that the owner of the project has little, if any, incentive to try to minimize cost since the funding system creates a cash flow from the federal government to the state or region. It was a belief, expressed in the project team's interviews with designers, that from a local, political point of view, the more conservative the design, the better. The philosophy behind the argument was that a conservative design (a) reduces the probabilities of any kind of failures or damages to public or private property, (b) creates a system that is more durable and thus requires less maintenance and operating expenditures (which are primarily supported from local tax revenues) and (c) increases the project's cost and thus the public's perceived value of what has been achieved by their political leaders in securing federal funds.

Moreover, the total cost should be kept close to the original, federally approved estimate, even if significant savings could be made by changing the design as the construction process develops and more geological information is acquired. This attitude is promoted by the lack of perfect information on ground characteristics on the part of the designer who thus, usually, adopts the philosophy "design for the worst case", and by the fact that major changes in the design, which might arise, sometimes have to be approved at a federal level, a procedure which could delay the project's construction.

2.2.3 Community Participation

A primary goal of a transit system is to provide the most effective service to users and to the neighborhoods in which it is located with a minimum of disruption to commerce, and inconvenience to the public during its construction. Community participation and support thus becomes vital to system development. Community participation during the final stages of design, however, can result in a significant delay in the design process, major and costly changes in the scope and quality of the original design, and a round of disputes, lawsuits, and compromises which further delay the system development process. This fact inhibits the designer from departing from what has been planned and trying innovative designs.

2.3 OUTCOME OF THE PLANNING PHASE

The final outcome of the planning phase is the Environmental Impact Statement (EIS). The topics discussed in the EIS are described by [Johanning and Talvitie (1976:25)] as follows:

1. Description of the proposed project,
2. The relationship of the action to land use plans,
3. The probable impact of the proposed action on the environment,
4. Alternatives to the proposed action,
5. Probable adverse environmntal effects that can not be avoided if the project is implemented,
6. Local and short-term impacts on the environment versus maintenance and enhancement of long-term productivity,
7. Irreversible and irretrievable commitments of resources if the proposed action is implemented, and
8. Comments by other agencies and the public.

Tables II-1, II-2, II-3 describe the process leading to the final EIS and the engineering data and decisions involved at each step of the process.

Moreover, the EIS contains the final decisions on the tunnel diameter within a few inches, the stations' locations and sizes, as well as the horizontal and vertical alignment of the tunnels. These decisions are based upon the distribution of potential service demand and urban conditions surrounding transit tunnels and stations and are made when only minimal geotechnical information is available. Urban conditions include traffic conditions, intensity of surface development, intensity of sub-surface development such as utilities, street patterns, and right-of-way configuration. As the design becomes more refined and station and route locations become more specific, additional geotechnical information is available and tunnel and station locations are adjusted accordingly. However, pressures

TABLE II-1

DECISION GATE: DRAFT E.I.S.

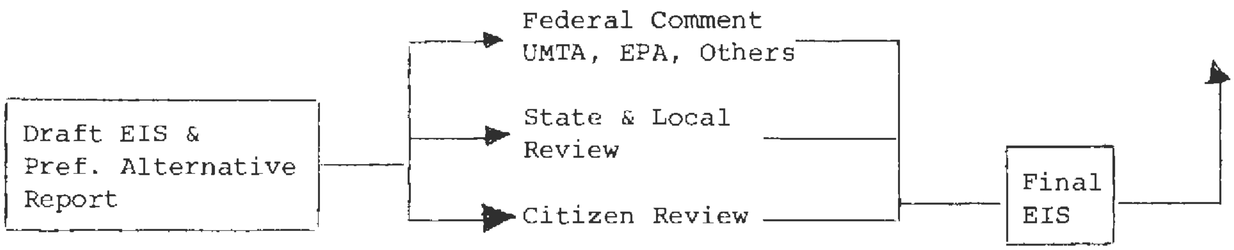
Alternatives Analysis Phase I & II	→	Report on Preferred Alternative	Draft Environmental Impact Statement
		- Assess cost-effectiveness and impact of initial set of alternatives - Choice of preferred alternative	- Assess alternative systems/technologies for similar level of performance and lower level of impacts as the preferred alternative

<u>Engineering Data on Each Alternative</u>

- System Segments
- Physical:
  - Horizontal Alignment
  - R.O.W. Map
  - Vertical Alignment (Elevation & Grades)
  - Typical Sections
  - Vehicle Technology
  - Station Location and Preliminary Design
- Construction:
  - Methods (tunneling, structural)
  - Resource Demands (material & labor)
  - Sequence of Operations
  - Schedule
  - For Impact Assessment
    - Equipment
    - Waste/Excavation Disposal
    - Protection of Existing Structures
    - Maintenance of Traffic
- Costs:
  - Construction: labor & materials by major category (structural, mechanical, etc.)
  - Contingency Amount for Design & Management Fees.

TABLE II-2

DECISION GATE: FINAL E.I.S.



<u>Final E.I.S.</u>: <u>Contents</u>

- Description of preferred alternative
- Comments from interested parties
- Modifications in response to comments
- Measures to mitigate adverse impacts
- Alternatives Analysis as Appendix

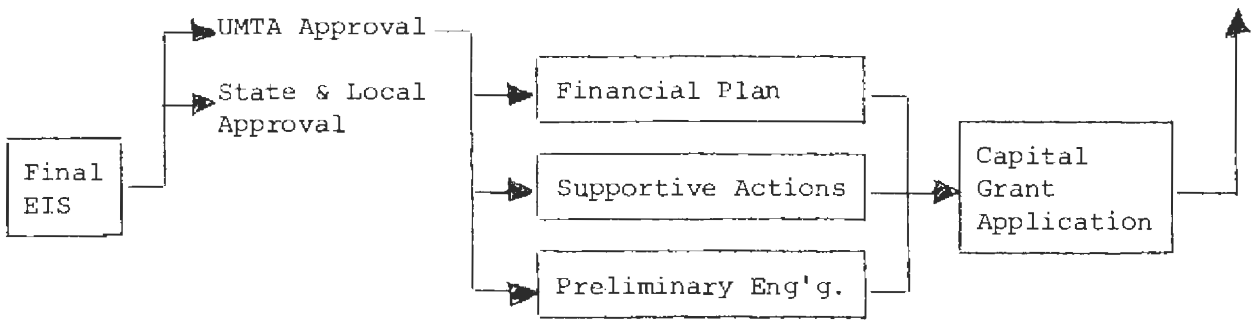
<u>Engineering Data & Decisions</u>

- Modifications to data presented in draft E.I.S.:
  - Segment Sequencing
  - R.O.W.
  - Alignment
  - Stations
  - Level of Service
  - Supportive Actions (feeder service, parking, etc.)
- Mitigating Measures to short-term impacts (construction):
  - Protection of existing structures, especially Historic and Public
  - Schedule of Operations, equipment to be used, allowable noise levels.
  - Source and Disposal Methods for fill and excavation material

<u>Changes</u> to the final E.I.S. require a verision, official approval from federal, state and local agencies and a public hearing.

TABLE II-3

DECISION GATE: CAPITAL GRANT APPLICATION



<u>Preliminary Engineering</u>

<u>Design</u>: Horizontal Alignment

Vertical Alignment
    Grades & Elevations
    Subsurface Geology from Test Bores

Typical Sections: structure of tunnel supports (options)

Vehicles: design speed, dimensions

Station Location, Length, Plan, Section, Ground Access (preliminary)

Preliminary Design of Control & Fare Systems

Project Breakdown for Subconsultants

Design Specifications

<u>Construction</u>:

Sequencing of Operations

Schedule

Tunneling Methods

Flow of Materials, Equipment & Manpower

Project Breakdown by Major Contracts

<u>Costs</u>: Design - Task Breakdown & Fees

Management, Supervision & Reporting (CM)

Construction
- ROW Acquisition
- Task Costs by Contract

At this point the contract schedule and costs are fixed for the Federal decision on funding:
- Total Federal Share
- Amount of Annual Grants (follows contract schedule)

are usually great to maintain the locations selected initially, on the basis of service to users. The EIS thus would be serving short-term goals rather than long ones.

According to the designers interviewed the EIS is the main vehicle for public participation. They believe that the EIS has been misused. Its commendable purpose is to provide a survey of the impacts of the various courses of action available to achieve a certain goal, including the choice of doing nothing. The comparative studies dealing with traffic flows, energy savings, historical sites and others mentioned previously are well documented in the EIS. It is when construction, and particularly underground construction, is considered that the process falls apart and even works against its intended purpose.

Since the EIS is not funded to go beyond the planning stage, the alternatives cannot be developed farther than the conceptual design stage—certainly not in such extensive areas as geotechnical exploration, which is critical to cost in underground work. Thus owners are committed to alignments and grades which may turn out to be both costly to construct and disruptive to the community. It is not practicable to analyze the construction impact of subway alternatives on the community in the detail which the public has been led to believe is attainable. The EIS is required to document the projects' impacts on the affected property owners along the route and the detailed construction methods, long before these can be forecast with confidence. The problem is that the public is being led to believe that the EIS is a legal document which binds the owner, in detail, to a detailed, rather than a conceptual design, and to construction methods and procedures which the planner, with very limited information, thought would be used to construct the project.

The cost impact of this misuse of the EIS comes when a project is challenged in court on the basis that the contractor's construction methods do not conform to those contemplated in the EIS. These lawsuits, successful or not, increase cost because they impact the most cost sensitive item of all--delay. Any individual, for broad, political aims or narrow, personal interest, can file suit and delay the project. Mr. Sutcliffe's opinion is that there is a time for public participation and a time for construction. Once the EIS is adopted, the project should go forward when the design and construction stages are underway.

The increase in the level of federal involvement and assistance presented the owner of the system with a host of regulations embodied in the EIS, such as environmental protection, citizen participation, historical preservation, affirmative action, prevailing wages, etc. Among these, as previously mentioned, citizen participation and the resulting disputes represented a significant problem to the owner. These disputes have frequently resulted in slowing the design process, delaying the letting of contracts, and causing a significant increase in both project scope and cost.

In conclusion, the project team found out through our discussions with designers, that they considered the EIS to be not serving the purpose for which it was originally intended, i.e., looking at the long range impacts associated with all alternatives, but rather to be a quasi-legal document focusing on short term, construction impacts of a single atlernative, and constraining engineering decisions and flexibility. Decisions on horizontal and vertical alignment and others found in the EIS, are made under a great amount of uncertainty as to the geological conditions along the proposed subway alignment, and with a large risk as to the feasibility and the cost optimality of the proposed solution. The designer seldom participates in the planning so that he usually has the project's physical location and size as given.

2.4 THE ROLE OF THE GEOTECHNICAL ENGINEER

It has already been shown that the greatest amount of uncertainty in implementing a rapid transit system lies with the geotechnical information available (Paulson, 1977). The whole structure is not only founded in soil, as buildings are, but at the same time it is being loaded and supported by the surrounding soil mass. A subway tunnel is also subjected to the hydrostatic load of ground water; it has to be somewhat impermeable, and its construction might create settlements that can damage its own integrity, that of adjacent structures, as well as utilities, like roads, sewers and water pipes.

All of the above factors are associated with a high degree of uncertainty due to the limited sampling that can be done given time and money constraints and the imprecision of the geotechnical science itself. Information concerning the soil characteristics can be obtained from existing data on adjacent structures and from soil exploration programs. These programs usually involve drilling of bore holes, surface geophysical exploration, or excavation of a pilot tunnel. In all cases, testing of the soil is performed in situ or on laboratory samples. The results are then conveyed from the geotechnical engineer to the party contracting his services.

The geotechnical engineer is usually contracted either to the owner or to the General Design Consultant. According to Mr. Thomas Kuesel of Parsons, Brinckerhoff, Quade and Douglas, Inc. (PBQ & D), it has become increasingly common that the geotechnical consultants are a separate organization hired by the owner for the whole system. The geotechnical consultants thus have little information on the designer and obviously no information about the contractor. They have no authority in their recommendations and at the same time they are faced with large responsibilities. The owner provides them with no financial reward as an incentive to promote design economy and their fee is too small to avoid their being inherently conservative.

It was of particular interest to this research to examine whether structural conservatism is due to the designer or whether it is partly embodied in the reports which the geotechnical engineer provides as an input to the structural design. These reports contain descriptions of the physical characteristics of the ground as measured from standard in-situ and laboratory techniques. Some of the characteristics and tests usually reported are:

(i) Description of the location of the borings and unified soil classification of the strata encountered;

(ii) In situ soil and rock permeability tests;

(iii) Piezometer and observation wells' results;

(iv) Soil laboratory tests: Natural water content, total unit weight, Atterberg limits, grain size analysis, consolidation tests, unconsolidated undrained tests, permeability tests;

(v) Rock laboratory tests: Megascopic Identification, petrographic analyses, unit weight determinations, hardness, unconfined compressive strength, elastic moduli, durability tests;

(vi) Geophysical survey results.

Geotechnical engineers sometimes provide their interpretation of ground loads to structural engineers as an input for the final lining design. They may also provide criteria for the underpinning of adjacent structures as well as dewatering requirements and advice on the design of temporary support systems for the tunnel's construction.

It was also mentioned during the research team's interviews with Sverdrup and Parcel that the geotechnical consultants are faced with the greatest risks. Hence, conservatism has to come from them. This suggestion is also supported by the fact that in the late 1960's, geotechnical consultants in the U.S., could not get professional liability insurance coverage at any reasonable price and, thus, they had to create their own insurance company.*

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* Consulting engineering firms engaged in soils and foundations engineering, were virtually uninsurable ten years ago. In 1969 they created the Association of Soil and Foundation Engineers (ASFE) which developed a loss prevention program for its members, and recommended liability limitation to them as a standard operating procedure. The ASFE established its own insurance program, leading to the foundation of Terra Insurance Ltd., an insurance company formed entirely by members of ASFE, and providing professional liability insurance solely for soil and foundation engineers participating in the professional liability loss prevention program conducted by ASFE. This insurance program has experienced an enviable success [Bjarnason (1980:134)].

The research team interviewed Mr. David Thompson, of Haley and Aldrich, in order to understand the role of the geotechnical engineer and to clear up some previous points about conservatism. Mr. Thompson indicated that their role as an intimate member of the Red Line Extension is not typical. Usually, the geotechnical consultants carry out the soil exploration program and they leave the interpretation of the resulting data to the designers. In this way, they remove some of the risk from themselves by allocating it to the structural engineers.

Mr. Thompson pointed out that geotechnical engineers do not vary their "factors of safety" concerning loads, strengths, elastic moduli, consolidation coefficients, etc., according to the uncertainty of the project. Moreover, manipulating the degree of liability imposed on the geotechnical engineers, that is, having the owner assume a greater portion of the risk of failure, would not make them change their factors of safety. The same factors of safety would be used on both private and public projects, even though in the latter case they carry a larger share of the liability. He indicated that the decisive factor in inflating cost is the design philosophy implemented in the project and that this was actually largely determined by the owner. A geotechnical engineer will always provide the best information he can, however, it is up to the owner to decide how reliable this information will be and how much time and money he is willing to spend to acquire more.

Mr. Tom Kuesel, of PBQ & D, Inc., also stressed the above point; he further stated that, fortunately, owners are beginning to realize that better planning and the acquisition of better information results in significant savings in time and money. He concluded that "Better

Contracting for Undergound Construction" (1974)* has started making an impact on owners.

2.5 THE ROLE OF THE STRUCTURAL ENGINEER

The structural engineer is the most important decision maker in the process of transforming the conceptual image of the subway project, as reflected in the results of the planning phase, into a set of drawings and specifications. It has already been pointed out that, in this process, some of the major decisions are already made by other parties. The engineer's decision making is constrained by the amount of geotechnical information with which he is provided, and also by design criteria imposed on him by higher levels in the organization.

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* The objective of this study was to develop improved contracting methods. By these methods the owner would receive the completed construction at lower cost and the contractor would receive a just profit. These benefits would foster a cooperative atmosphere in which there is incentive for both the owner and the contractor to stimulate the use of advanced technologies and innovative construction techniques. The new methods would also include provisions for equitable sharing of the risks, particularly those not identifiable at the bidding stage, which are inherent in underground work.

The amount of geotechnical information, along with the owner's policy in breaking down both the design and construction contracts, often dictate the level of design variations permissable for the project. Each section of the tunnel is subject to different geology, loads and external structural forces. Theoretically, the most cost efficient design would be one that continuously changes, depending on the above factors, so that uniform and acceptable safety exists in every cross section. This, however, would require an extremely complex construction process and the savings resulting from optimal use of materials would be overtaken by the increase in labor cost, equipment cost, decrease in productivity, loss of quality and time delays. On the other hand, the other extreme would be one uniform design for the whole project, based on the worst possible conditions. It is obvious that the optimal solution lies somewhere in between these two extremes. The designer has to break this section down into a finite number of segments and design for the worst conditions within each segment. The issue, however, is that the designer has few, if any, incentives to try to minimize the project's cost and, at the same time, virtually any kind of failure might ruin his firm's reputation and his own career. As the design becomes more complex the engineer becomes more vulnerable to law suits.

Mr. Sutcliffe believed that technical decisions are made in a climate that does not foster innovation. The contract with the owner is the first influencing variable. The owner says, "You are the engineer, you are being paid to design the tunnel, so take the risk." The second influencing variable is the power that the public has. The engineer can now be sued, and is sued, by anyone and everyone; the legal concept of "privity of contract"* does not exist anymore. Hence the reluctance to innovate is due to the unwillingness of most designers to assume the full risk that is inevitably associated with new technology. When an engineer introduces an innovation which is a departure from tried design or construction practices he has little to gain and everything to lose.

Mr. Kuesel agreed on the above comment and he offered, as an example, the case of the final lining in the Baltimore Metro. In this case, there were several mined sections so it was feasible to use precast concrete segments as a final lining. The engineers, however, were not willing to undertake this option as an alternative to steel plate liners, because they were not familiar with this kind of lining. UMTA was, at the time, interested in promoting this kind of concrete liners so it decided to take all the risk. The result was that the concrete liners, which appear to be performing in a satisfactory manner, cost as much as would the steel liners which are superior. This was mainly due to the designer's and contractor's lack of

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* At one time, the absence of privity of contract, that is, the absence of any connection (privity) with the underlying contract, between the design professional and any of the parties, other than the owner, made it impossible for third parties to sue the design professional. Although it can still be an obstacle, it is no longer an absolute barrier. (Bjarnason, 1980; Dunham et. al., 1979; Sweet, 1970.)

experience in employing precast concrete liners. The idea behind UMTA's decision was that, after some experience in the new system has accumulated, significant savings could be made using precast liners in subsequent projects. Mr. Kuesel pointed out that this approach required a good fabricator and a good contractor. Slurry walls got a bad name when they were introduced in the U.S. because the contractors were inexperienced. Another example where innovation did not work was the shotcrete option in Washington Metropolitan Area Transit Authority (WMATA). The contractors were not experienced in using shotcrete as a tunnel lining so the bids were high. Mr. Kuesel pointed out that the owners ended up paying "400% of what they should have".

Another factor that plays a big role in the engineer's decisions is his lack of knowledge of the potential contractor for the project and his experience. Mr. Kuesel commented that a designer cannot specify cost saving procedures and technologies because potential incompetence of the low bidder might end up causig a suit against the designer. Instead, he proposed design alternatives featuring both cost saving techniques and standard procedures. The competition in the bidding process would be based on either of the design alternatives. the bid prices will subsequently show whether the state of the industry can cope with the innovations proposed. This procedure will inevitably lead to the most efficient methods as contractors realize which methods make their bids more competitive.

Another comment that Mr. Kuesel made was that cost savings depend on the owner's policy for risk allocation. It is much more cost effective to have the owner assume some of the risk of damages, if they occur, instead of having the contractor increase his bid because of damage prevention work that has to be done. This also creates a reputation for the owner concerning his attitude in penalizing engineers. For example, in Baltimore the owner created a fund for paying damages and restoration instead of underpinning all the buildings along the tunnel's route. It worked. This kind of policy, however, depends on the quality of the work done by the contractor (e.g. using slurry walls instead of soldier piles, efficient compressed air use, grouting every ring individually, etc.).

2.6 VARIABLES IN THE PROJECT ORGANIZATION

2.6.1 The Allocation of Project Risks and Liabilities

There are several sources of risk in a mass transit project, either from the project itself or from its environment. The sum of these various risks comprises the total project risk. This total project risk includes, for example, the risk that:

- Completion of construction becomes impossible.
- The finished system becomes inoperable at any time in the future.

or - Damages due to any distrupting or non-disrupting event during construction or operation exceed a certain number of human lives or amount of dollars.

The liabilities entailed by the total project risk are in turn divided among the various entities that make, or participate in making, any decision on the project, according to a certain liability structure which is closely related to the structure of the Project Organization. It is easily conceivable that the allocation of liabilities among project participants might not correspond directly to the sources of risk or to the degree of control that a certain participant has over a source. In fact, it is possible that in the process of allocating liabilities, the total project risk might be broken down into elements that are totally different from the original sources of risk. For example, uncertainties about underground conditions and about contractor's skill are two original sources of risk to the owner and the designer in tunnel construction; but their consequent liabilities might be allocated to the designer alone as liabilities arising from the inadequacy of temporary and permanent support systems.

Levitt, Ashley, and Logcher (1980:299) defined two types of risks: controllable risks and uncontrollable risks. Controllable risks result from variations in human performance, e.g. worker's productivity, design omissions and material wastage. Uncontrollable risks are random variables such as price escalations, weather and unpredictable changes in underground conditions.

The essential factor in relating risk to conservatism, or in other words, inducing conservatism through liability, is the structure of liability allocation. For example, a designer, who bears no liability at all on his part of work in a certain project will have no incentive external to his own self or own organization to be more conservative; and, furthermore, he might find a motivation to be innovative. Thus, engineers use excessive conservatism to hedge against outside risks.

Consider three cases of allocating risk in the design of a mass transit project. These cases are not an exhaustive set of scenarios but are interesting extremes:

- The system's owner assumes almost all of the project risk allowing no reason to the designers and constructors for conservatism due to project risks.
- Risk is centered on the General Consultant who hedges against liabilities through the design criteria that he specifies to detail designers and through the process of evaluating, coordinating and approving the work of these detail designers.
- Risk is passed down, through heavy contractual liabilities and insurance requirements, entirely to the section designers, specialty designers and geotechnical engineers and then, depending on the internal structure of each of these organizations, to the individual(s) involved in the various design tasks.

As seen from these cases, different rationales would lead to the choice of one case or the other, or the more common use of combinations between these three extremes. To give examples of these different rationales, the first of the three cases above could be the result of an educated trade-off between the cost of possible liabilities and the cost of excessive conservatism; the second case might be the result of centralizing risk on the most technically capable party; and the third case might be rationalized by the belief that the responsibility for certain risks motivates designers and contractors to perform more efficiently.

All these rationales are valid and reasonable. However, a direct causal relationship to conservatism is not obvious in any of these cases which emphasizes the need for identifying a certain variable, or set of variables in the risk allocation structures to which design conservatism is directly sensitive. One such variable known to researchers in this area is the amount of risk that a certain risk allocation structure assigns to designers. Thus, a basic premise of this study is that a direct causal relationship exists between the risk allocated to designers through institutional variables and the degree of conservatism in the resulting designs.

The sensitivity of design conservatism to the amount of risk allocated to designers has two elements:

- The first element, as mentioned before, is that the responsibility for a certain amount of risk provides an incentive for designers to be efficient, provided that the risk is controllable by the designer.
- The second element is that the responsibility for controllable and uncontrollable risks over a certain amount is usually alleviated by designers through a combination of insurance and design conservatism.

A risk allocation structure assigns risks to all the various parties of the Project Organization, including the owner, financer, project manager, designer, constructor and others, and does not concern itself, in the process of allocating risks, with one isolated variable, such as the conservatism in design, but rather with the effect of different allocation structures on the main performance measures of the project; namely cost, time and quality. To this extent, design conservatism is one factor among several others that have impacts on project contingencies. As an example, consider the total cost of the project as one contingency. Increases in the total cost can be caused by design conservatism, limitation on construction methods, inflated costs by the bidding contractors, excessive contingency charges, time lost in approving change orders, and several other causes that are affected by the risk-allocation structure. Therefore, studies on the allocation or risks in mass transit projects have mostly focused to date on its effect on the total cost of a project rather than on the degree of conservatism in design. One such study is the research conducted for U.S. Department of Transportation by a team of professors and graduate students in the Department of Civil Engineering at the Massachusetts Institute of Technology (MIT) between September, 1977 and August, 1978 (Levitt, et al, 1979).

This study was based on seeking a balance between the risks allocated to owners and constructors so as to utilize the incentive value of bearing risk and minimize the costs charged for accepting the risk. The study recognized that owners will accept risks only to the extent that the project's value to them is not jeopardized by uncertainties on the total cost, time of completion and quality of the system. On the other hand, the shifting of risks to contractors would result in increased bid prices by contractors. However, as tradeoffs between these two factors are carried out in an iterative process, a certain risk allocation structure that optimizes the total cost of the system to the owner will be reached. A conceptual model for conducting the cost-risk tradeoff was developed and field tested with owners and contractors.

One approach to defining the exact relationship between risk allocation structures and the degree of conservatism in design is to conduct a study similar to the study described above but tradeoffs would be investigated between the allocation of risks among owners and designers, and the resulting degree of conservatism in project designs.

2.7 THE SYSTEM OF ASSESSMENT AND REWARD

The concept of integrating several parties with diverse and sometimes contradictory objectives for the purpose of achieving a common desired objective is well-known in organization design. A more familiar situation is the designing of an individual organization's structure (including the system of assessment and reward) so that the plans of the organization are compatible with the plans and objectives of its employees.

J.D. Thompson (1967) differentiates between the goals <u>of</u> an organization (or organizational goals), and the goals <u>for</u> an organization. Thompson views the former as a meaningless abstraction, while the latter is the intended future domain (markets, products, clients, etc.) for the organization as perceived by various organizational participants. The establishment of organizational goals may involve important outsiders and individuals that have no affiliation with the organization, either exclusively or in addition to individuals from within the organization. Thompson also contends that the individuals that set organizational goals are interdependent individuals who collectively have sufficient control of organizational resources to commit them in certain directions and to withhold them from others; an opinion shared also by Cyert and March (1963). This group is referred to as the "dominant coalition" within the organization.

From these definitions, one can recognize the existence of two sets of goals: the goals stated by individuals for the organization, and the personal goals of individual members of the organization. One can also conceive the possibility of conflicts between goals of the same set or between goals from both sets. The design of an assessment and reward system, as an essential part of the organizational structure, is aimed at eliminating or minimizing these conflicts.

This section is focused on a very similar but less familiar situation which is the design of a mass transit Project Organization so that the objectives of individual organizations that compose the Project Organization are compatible with the objectives of the mass transit project.

2.7.1 The System of Assessment

The criteria and methods of assessing the performance of the various parties are very important for the following reasons:

- Incentives and rewards will be provided according to the results of these assessments.
- The various participant organizations will conduct

their performance so as to optimize the value of
their assessment criteria (or control variables).

It should be noted that these factors become more effective if extra rewards based on performance were provided in addition to contractual incentives, and if the project control system has the sophistication to record and measure performance of various organizations that are participating in the project along the lines of designed criteria. While these techniques are not used in most current Project Organizations they are certainly powerful methods for structure integration that are worth consideration in future projects.

2.7.2 The System of Reward

The incentives of different parties for participation in a project vary not only between parties but also between different projects for the same party. For example, designers sometimes participate in projects that they know are not profitable to them in order to establish their reputation in a new area and "get a foot in the door".

In general, three important elements enter into designing the incentive of an organization participating in a mass transit project:

- The type of organization, e.g., a consulting firm, an engineering firm, a contractor, etc.
- The type of contract that the organization has with the mass transit agency, e.g., lump sum, cost-plus-free, turnkey contract, etc.
- The specific role of the organization in the project, which in turn, is indicated by the

structure of the project organization. Different organizational structures may assign different roles to the same type of organization. For example, general consultants may be assigned a management role in some cases while in other cases, they might be responsible for the actual performing of design through their own staff and/or through sub-contracting.

Rewards vary from pure monetary profits to reputation and professional status incentives.

Before discussing these two types of rewards and showing the effect of the three elements discussed above, it will be appropriate to review the definitions of three important types of "motives" or, as called in our discussion, "incentives". These three types are: primary motives, general motives and secondary motives. Luthans (1977:315-332) defines them as summarized below:

Primary motivies: are unlearned physiologically based motives. The first level of Maslow's hierarchy of needs (Maslow, 1943) fall under this classification of primary motives.

General motives: are unlearned nonphysiologically based motives. The motives of competence, curiosity, manipulation, activity and affection are examples of general motives.

Secondary motives: are all the motives that are learned through reinforced experience. Examples of secondary motives are power, achievement, affiliation, security and status.

In the following sections, two types of rewards will be discussed: monetary rewards and status rewards.

2.7.3 Monetary Rewards

Three common practices have been predominant in present mass transit Project Organizations.

- The mass transit agency (owner) has usually been a government or quasi-public agency that does not have profit-making as its main objective, although it is not officially chartered as a non-profit organization. Mass transit agencies have usually been funded and subsidized by federal and local governments to overcome the difference between their expenses and earnings. Therefore, monetary rewards have not practically been the main incentive for mass transit owner organizations.

As far as the effect of system owners' incentives on design conservatism, it can be seen that the incentive to eliminate increases in cost caused by design conservatism can be diluted because of the availability of sudsidies and funds that do not have to be raised or earned through technical and managerial efficiency. In other words, system owners might be motivated to spend efforts more in obtaining government funds than in improving design efficiency. This, of course, is all dependent on the ease or difficulty of obtaining funds and on the conditions attached to these funds.

In addition, the 80% federal funding for capital costs, and the primarily local funding of operating costs gives owners an incentive to overinvest capital funds to reduce operating costs, from a life cycle cost viewpoint.

- The consulting and design firms who are established as profit-oriented private organizations. These organizations are not prequalified or hired on the basis of price competition but on the basis of a combination of criteria including price, particular project proposals, professional reputation and degree of specialization in certain applications. Therefore, the primary incentive for these organizations is profit. However, due to the common system of assessment (prequalification and award of proposals) they learn other secondary "status" incentives that dominate their short term planning. This point will be elaborated on in the next section that discusses status incentives.

Principles of Organizational Behavior (Luthans, 1977) state that secondary motives have the greatest impact on organizational behavior.

Nevertheless, to the extent that primary incentives might govern in some situations, it would be appropriate to discuss certain points relevant to the effect of the reward system on profit-maximization in designers' organizations.

As mentioned before, design contracts are usually cost-plus-fee contracts which means that profit-maximization is accomplished by maximizing the fees. These fees are determined as percentages of other costs. First, attention should be given to the fact that cost-plus-fee design contracts where fees are determined as a percentage of the construction cost have been made illegal for public works. This suggests that fee-maximization by designers is a phenomenon that is perceived to have led to increased costs, and was consequently made illegal. It also indicates that profit-making is a primary incentive for designers and provides an example of the legal restrictions and regulated procedures that have created secondary incentives and "conditioned" designers' behavior.

The second type of design contract is the cost-plus-fee contract where fees are determined as a percentage of design costs. This type has two possible effects if fee-maximizing was the governing criterion. First, it could motivate designers to increase the amount of design work, which in turn, could increase the efficiency of design, thus reducing the total cost of the system. On the other hand, if the same designers were to perform planning as well as final design of the system, the possibility exists that these designers may plan excessive systems that cost more to design. A hypothetical example of this situation is the planner of a residential complex who volunteers the planning of impressive plazas between every two buildings to keep his landscape designers busy later.

The third type of design contract is the cost-plus-fixed fee contract. This type does not motivate conservatism or over-design through its incentives in the way that the second type of contract (cost-plus-percentage of design cost) may do, but neither does it discourage conservatism through incentives. The cost-plus-fixed fee type is the predominant type of contract for designers at the present time.

- The construction contractors are hired on the basis of price competition according to the federal and state laws. Construction contracts are, in effect, almost lump-sum contracts, and contractors have to "work out" their profits from the difference between bid price and actual price. A contractor's incentive is largely monetary because of the contracting procedure and the method of extracting rewards. The most important effect of this arrangement is that contractors' incentives would most likely be contradictory with the project objectives. Prequalification and award procedures do not create other incentives than monetary ones for contractors and because of the lump-sum nature of contracts, contractors can maximize their profits by minimizing their level of performance. Also, price competition motivates contractors to underbid, thus jeopardizing the possibility of satisfying all of their contracts' requirements and increasing the chance for change orders and litigations during construction.

The effect of the contractor's reward system on design conservatism lies in the possiblity that designers may over-design to prepare for the chance that the contractor might "cut corners" during construction to maximize their profit or dangerously underbid in order to win the contract. This effect is more aggravated if designers have unlimited responsibility for any failures in the system without means to check the causes of failures.

2.7.4 Status Rewards

This type of reward is applicable to consulting and design organizations more than to any other organizations participating in a mass transit project.

In many situations, designer organizations have been shown to have high priorities on their reputation and professional status which becomes higher than their priority on monetary profits. A field investigation based on interviews with mass transit system designers was performed within this research project, and showed that designers are driven by a combination of personal and firm reputation incentives, constrained by the need for short-term profits. Figure VI-1 shows the engineer's decision framework suggested by this research project as part of an overall influence diagram for the utility of the engineer. The figure shows the various motives and forces that enter into an engineer's decision.

However, the authors believe that there is a danger in not recognizing that status rewards for engineers are secondary incentives that engineers have learned through the common procedure for prequalifying design proposals and awarding design contracts. As mentioned in our discussion of the designer's monetary rewards in the previous section, these procedures are based on the professional status and track record of the designers and, in some cases, on their price proposal also. Our hypothesis is that through the continuous reinforcement of these procedures, designers who have naturally sought monetary profits as their primary motive have associated the satisfaction of this primary motive with the fulfillment of status and reputational requirements. The danger in failing to recognize the actual primary rewards and secondary rewards for engineers is that the effect of different designs of assessment and reward systems will be confused, thus limiting the ability of organizers to monitor conservatism through these systems.

Clearly, impacts on personal and firm reputation have the most influence over designers' decisions, according to principles of organizational behavior and findings of field research that we mentioned previously. Hence, they should be given the highest importance in monitoring the effect of designer's incentives on conservatism.

So far variables in the assessment and reward system that may become causes for design conservatism have been discussed. The authors have not discussed the possibility of incorporating features in that system that would positively provide incentives for economization to designers. In the following, the authors will discuss some possibilities that are interesting in that regard:

- First, project organizers must be particularly sensitive to incentive arrangements, such as some types of cost-plus-fee contracts, where designers rewards are positively proportional to project costs.
- If underground and other conditions are reasonably predictable, which is not the most common situation, guarantees for ceiling costs can be required from planners and designers with possible sharing of savings that offers the designer sufficient benefits from reducing the cost of the system.

- An interesting arrangement that was used in some of the existing mass transit systems, including Massachusetts Bay Transportation Authority, is to require contractors to submit Value Engineering proposals with their bids for the system. These proposals may be based on the existing design with variations in construction techniques, or on a new suggested design. The possibility that contractors may submit such proposals is believed by some designers to be a strong incentive to economize or, at least, avoid over-designing in order to avoid the possible challange. Although the effectiveness of such proposals is dependent on the availability of a third party designer evaluation of the proposals, and on the type of guarantees that contractors are willing to attach to them, the option as an incentive measure is worth further investigation.
- A central data base on designers should be established and maintained at some federal or other transportation agency for all transit system owners. This data base should keep record of all designers and consultants who have previously participated in designing mass transit systems in terms of their cost performance and their ability to design within specified budgets excluding unusual circumstances. System owners should necessarily refer to this record in prequalifying new design proposals and awarding

design contracts. This system might be impeded by the fact that accurate budgeting is not always possible for mass transit projects prior to actual construction due to unknown underground conditions. However, the system should be established and used whenever it is possible. It will be more usable when a sophisticated cost estimation model for tunnel construction is developed. Work is currently being funded by the U.S. Department of Transportation/ UMTA to develop better tunnel and underground station cost-estimating techniques.

2.8 COORDINATION IN THE PROJECT ORGANIZATION

Before discussing the next two areas of coordination, i.e., coordination between the owners, planners and designers, it is appropriate to review some aspects of coordination discussed by Mintzberg (1979:Chapter 1). Mintzberg defined three methods of coordination.

- Mutual adjustment.
- Direct supervision.
- Standardization of work processes, input skills and/or output products.

The coordination of owners', planners' and designers' works in mass transit projects has usually been a combination of three variations:

- Mutual adjustment, face-to-face meetings.

- Standardization of work processes.
- Standardization of output products.

Mutual adjustment is predominant in the coordination of owners and planners. In fact, in some projects, the planning group is composed of individuals from the owner's staff and the staff of his General Consultants. In such case, coordination is required actually between the Owner and the Consultants and mutual adjustment, again, is the predominant method at that aggregate level.

For coordinating the works of planners and designers, as well as the different levels of designers, certain "tools" are typically used, besides mutual adjustment; namely the design criteria, technical specifications and technical drawings. These documents are simply the means used for standardizing the work processes of designers and/or standardizing the output product, i.e., the contemplated system. They standardize the designers' work processes by specifying the methods of design, the minimum requirements for geological, structural and hydrostatic loadings and the rest of the criteria that the designer is required to consider in the design. They standardize the output product by either specifying the physical dimensions and properties of the system and its components, or by specifying the minimum acceptable performance levels that are expected of the designed system.

These various methods of coordination used at the planning and design stages are important structure integration techniques that sometimes have direct or indirect effects on the degree of conservatism in the design and on reducing or increasing the total cost of the transit system. For example, coordination by mutual adjustment in many situations helps to avoid wasting time and money on compiling technical specification documents and formal communications. On the other hand, the design criteria and technical specifications are powerful means of delegating design decisions and responsibilities without the loss of control. They can be highly specific so as to convert designers' work into a mechanical exercise, or highly delegating such that the designer is left room for conservatism or innovation according to other conditions. In many cases, design criteria that specify the output product are favored over those that specify the design methods and procedures if full benefit from the designers expertise is desired. In any case, the methods of coordination are indicative of the degree of integration of the Project Organization's structure and can certainly be used to hedge against the possibility of excessive conservatism in design.

This chapter has discussed the environment within which tunnel design is carried out for rail transit project in the U.S., and has summarized some relevent organization theory concepts. The following chapter lays out the research methodology employed in this study.

CHAPTER 3

RESEARCH METHODOLOGY

In the previous chapter the authors looked at the environment of tunnel design. The planning, design and construction phases were discussed in the context of their influence on design conservatism.

This chapter describes the authors' methodology in attempting to understand the relationships between geotechnical, institutional (both organizational and contractual) variables and engineering technical decisions, and their corresponding outcomes.

3.1 INTRODUCTION

In their attempt to tackle the problem of structural design conservatism, the research team employed the following approach:

1) Extensive interviewing of prominent design professionals, rapid transit systems owners, contractors, insurers, and lawyers.
2) Preparation of a case study covering design of a section of a rapid transit subway.
3) Model building incorporating features of the decision analysis methodology.
4) Model verification through a workshop.
5) Analysis of the workshop's results.
6) Further model development and modeling sensitivity.
7) Cost impact assessment.

These steps will be elaborated below.

3.2 INTERVIEWS

Extensive interviews were conducted at different stages of the research project in order to fully understand the project delivery process of a subway system. The research team interviewed structural geotechnical engineers, as well as transit owners, contractors and lawyers. The interviewing was necessary to capture in a qualitative manner those factors which influenced designers to produce more or less conservative designs. The next step was to formalize this qualitative information in a model that combined those factors. More interviewing was needed to verify and refine the designer's model. The names of the persons interviewed are presented in Appendix A.

3.3 CASE STUDY

The first tangible outcome of the research team was the preparation of a case study, based on interviewing and literature, to illustrate some of the reasons for increasing costs of U.S. subways. The aspect which was of primary concern to the research team was conservative structural tunnel design.

The case study selected for investigation was the Red Line Northwest extension project for the Massachusetts Bay Transportation Authority which is currently under construction. The project is an extension of the existing Red Line beyond Harvard and up to Alewife Brook with two intermediate stations in Porter Square and Davis Square. The case study served the following functions:

a) to familiarize all members of the research team with underground construction in general and with the Red Line extension in specific;

b) to focus on the flow of engineering technical decisions (see Chapter 4), identifying points of discretion;

c) to explore the type of risks designers take into consideration when making these decisions in an uncertain environment (see Chapter 2);

d) to look at how technical decisions evolve during the planning stage and to determine how much discretion is left to the designers in the engineering stage (see Chapter 2);

e) to search for conservative technical decisions and pinpoint causes (see Chapters 5,6).

f) to highlight important variables and their interdependency (see Chapters 4,5) and use them to structure an influence diagram which will be discussed in the following section.

3.4 MODEL BUILDING

Chestnut (1965:108) defines a model as,

> "a qualitative or quantitative representation of a process or endeavor that shows the effects of those factors which are significant for the purposes being considered."

The model describes the essential inputs (such as geotechnical, organizational and contractual conditions), outputs (such as costs of the system, utility or degree of "happiness" of the engineer), and internal characteristics (such as engineering decision making on type of tunnel support).

Because of the complexity and uncertainty involved in the problem, the research team decided on using certain features of the decision analysis methodology. Decision analysis is defined by Howard (1973:51) as,

> "the balancing of the factors that influence a decision and, if we wanted to add another word, a logical balancing of the factors that influence a decision. Typically these factors might be technical, economic, environmental, or competitive, but they could also be legal or medical or any other kind of factor that affects whether the decision is a good one."

In addition, Howard (1968:12) states that,

> "the decision analysis formalism serves both as a language for describing decision problems and as a philosophical guide to their solution. The existence of the language permits precision in specifying the many factors that influence a decision."

In this case the decision is one made by the tunnel designer and concerns the choice of a structural support, excavation method and ground water control method. These decisions will be discussed in detail in the next chapter. The factors influencing the decision, the authors hypothizes, are combinations of geotechnical, organizational and contractual factors.

One of the features of decision analysis that the authors have adopted is the influence diagram tool. An influence diagram is a graphical representation of variables showing their relationships. In decision analysis variables are considered either as "decision variables" or as "state variables". Decision variables are represented as rectangles and they are the variables which are totally under the decision-maker's control. State variables are represented as circles and they are the variables over which the decision-maker has no control. In other words, the decision variables represent the choices facing the decision-maker whereas the state variables represent the environment; state variables may be decision variables controlled by other decision-makers. Accordingly, state variables are associated with probability density functions (pdf) whereas decision variables are represented by a number of possible choices open to the decision-maker. An influence diagram is a set of decisions and state variables which are connected with arrows. Figure III-1 explains the arrow notation in an influence diagram. The influence diagram utilizes this scheme of representations in order to demonstrate the interaction between the decision-maker and his environment. It should also be noted that variables represented by hexagons represent calculated intermediate outcomes and are not associated with a pdf. This explanation can also be given to the variable named utility. The decision-maker's utility function is the means of capturing his attitude to, or preference for, risk. According to deNeufville (1971), one of the basic axioms of decision theory is that the decision-maker should choose those alternatives that maximize his expected utility. Figure III-2 is an example of an influence diagram which will be discussed in detail in Chapter 6.

To clarify the preceding paragraph, the authors will relate it to the problem at hand. For example, geotechnical, organizational and contractual conditions are state variables from the tunnel designer's point of view because he exercises no control over them. His decisions on type of structural support and, ground water control method are decision variables because they are under his span of control. Similarly those same state variables are considered decision variables from the owner's point of view because they are under the

The p.d.f.'s associated with state variable B depend on the outcome of state variable A.

Ex: Ground water infiltration depends on quality of rock.

The p.d.f. of state variable D depends on decision C.

Ex: Uncertainty about ground conditions depends on decision on subsurface investigation.

The decision-maker knows the outcome of state variable E when decision F is made.

Ex: The type of contract, organization is known when the designer selects a support system for the tunnel.

The decision-maker knows decision G when decision H is made.

Ex: The tunnel designer in Europe knows type of temporary or initial support when he makes a decision on permanent or final support.

FIGURE III-1

Explanation of Arrow Notation in an Influence Diagram

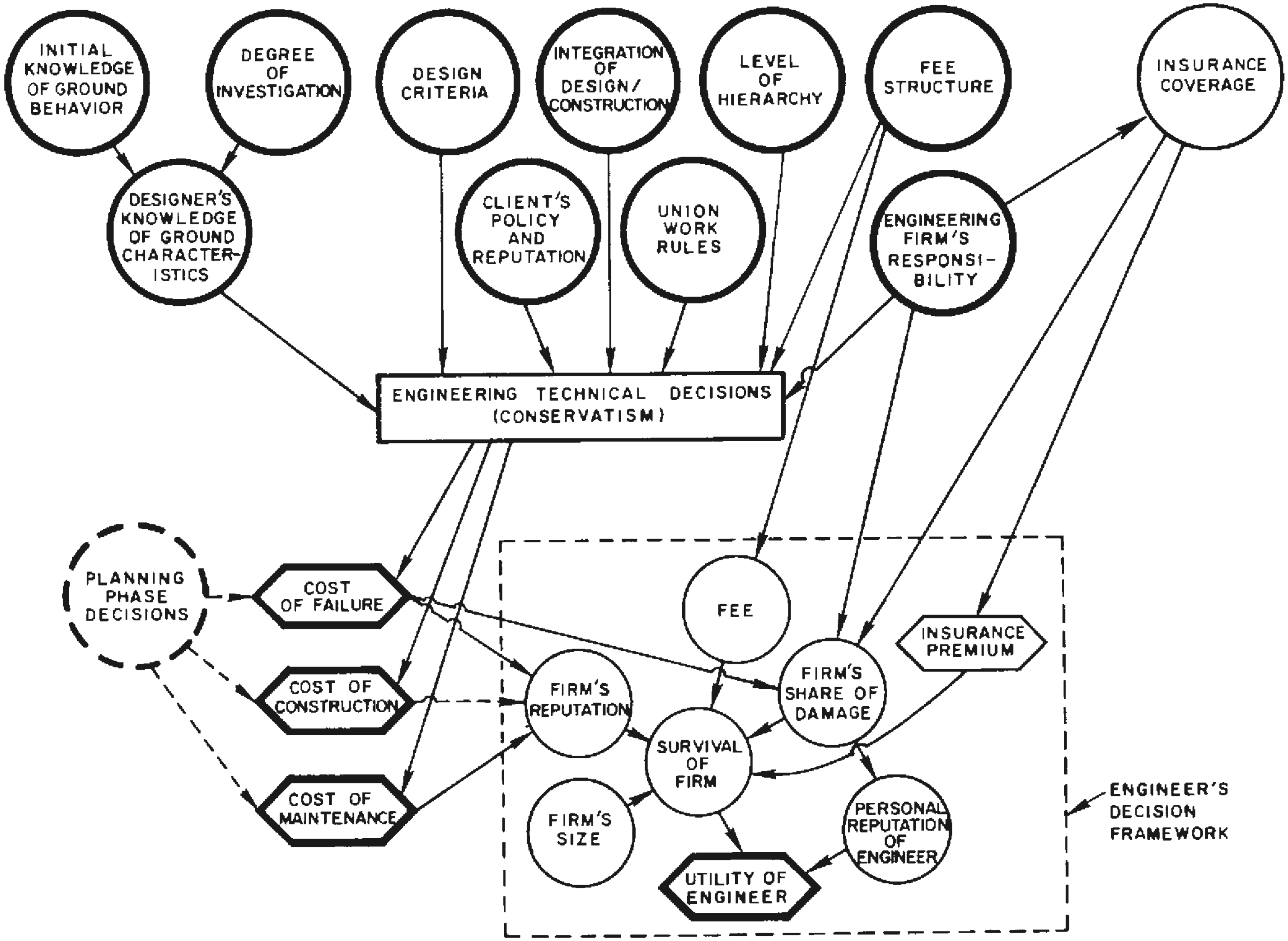

FIGURE III-2

Influence Diagram Representing Designer's Model owner's control. Furthermore, the designer's decision variables are considered state variables form the owner's point of view. This idea is conceptually represented (see Figure III-3) in a decision tree format which represents the structure of possible sequence, of decision variables, state variable and outcomes. The outcome to the engineer is the maximization of his utility, including his aversion toward risk.

For the authors'purposes it was unnecessary to quantify the engineer's utility. The authors' objective is to predict his design decisions, assuming only that he acts to maximise utility. Therefore, they only need to know whether a variable correlates positively or negatively with the engineer's utility, in order to predict how it will effect which design decision he will make.

For the owner, the authors assume that his utility is maximised for this set of decisions by minimising the costs associated with design decisions. These include initial capital cost, and the expected costs of future maintenance, and structural failures. These will, therefore, be quantified in the analysis (see Chapter 7).

It should be mentioned here that the problem of conservatism in the design process is not always a result of a single individual's decision. Usually structural design decisions are made by a group of engineers who work on the project as a design team. The "formal" approach would then be to use the utility function of a group of individuals rather than the utility function of a single engineer.

The same argument could be made also for the owner. In this respect the transit authority represents the "owner", because they select designers and control their work, whereas UMTA serves more as a

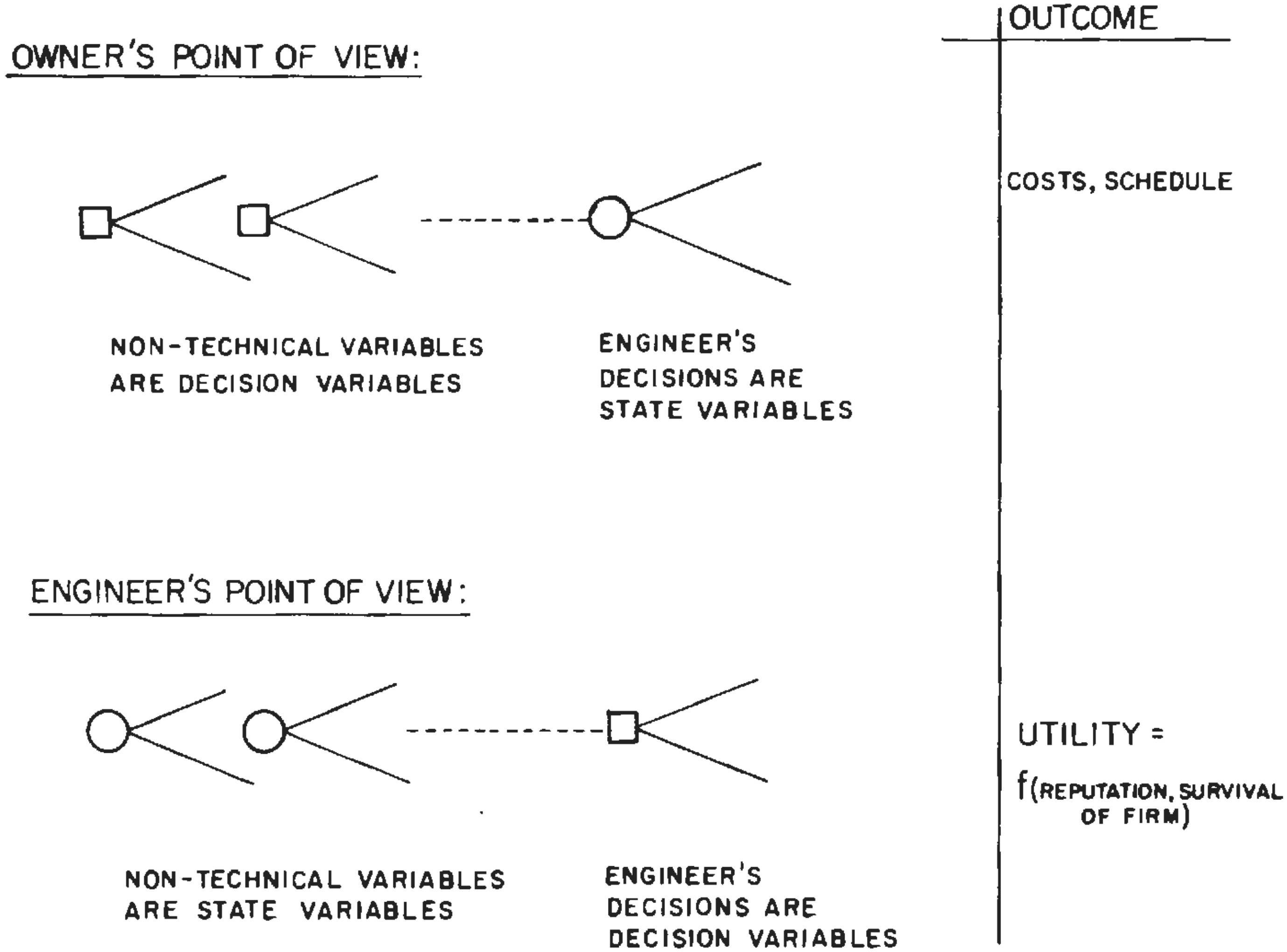

FIGURE III-3

Sequence of Decision Variables, State Variables and Outcomes "mortgage bank", providing 80% of capital funds. In both cases there are some key individuals whose opinion determines more or less the final outcome of the decision process. Each group (i.e., owners' and designers') are attempting to optimize their utility within constraints. The constraints to the owner group could be political, budgetary, or legal in nature (see Chapter 2). The constraints to the designer group could be contractual, organizatioal, and geotechnical in nature. The main question--and this is what the research group is concerned with--is whether those constraints imposed on the designer are set in such a way that the result is optimum for the public (see Chapter 7). This idea is conceptually represented in graphical form in Figure III-4 which provides a macroscopic view of the research problem. The figure shows how the owner makes decisions within constraints (dashed boxes 1 and 2). These decisions (box 3) are impacted by the owner's risk attitude or his utility function (box 4). Owner's decisions could relate to schedule, type of project organization, contract with designer and contractor, design criteria provided to designers and others. The owner's decisions constitute constraints on the designer's decisions (box 5). The designer's decisions are also constrained by geotechnical conditions which are represented in information provided by the owner. Similarly, designer's decisions are impacted by his risk attitude (box 6). The outcomes of the owner's as well as the designer's decisions can be measured in terms of costs (box 7). These costs are perceived differently by owners and designers. The authors assume that the owner's primary objective is to minimize construction as well as maintenance costs and this enters into the determination of his

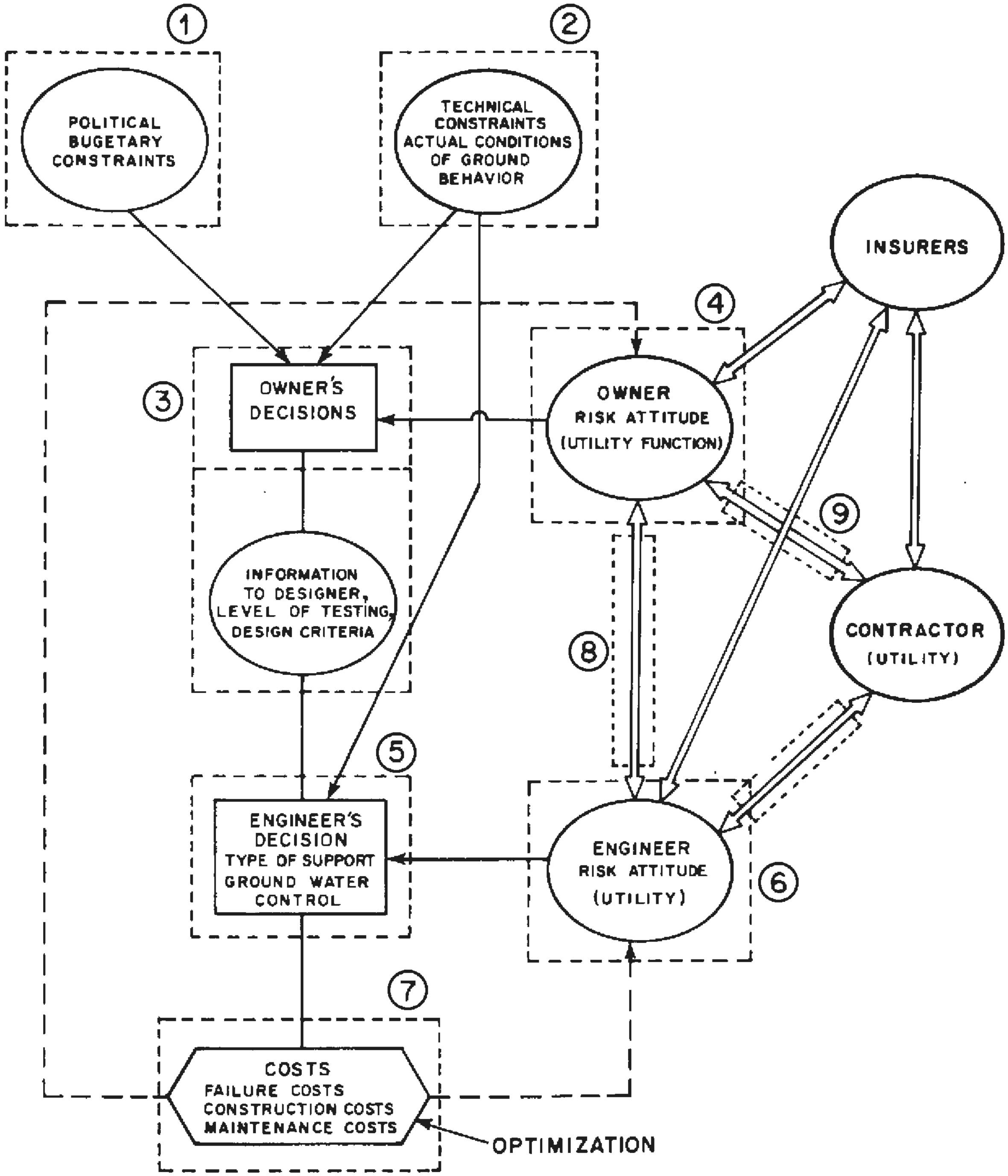

FIGURE III-4

Macroscopic View of Research Areas Relating to an Underground Rapid Transit Project utility function. The designer's primary objective is to minimize failure costs. This could be achieved through conservative designs. The situation is one of two different organizations each trying to suboptimize different objectives. The interface between the two organizations is represented by the 2-way arrow (box 8). This interface which is defined through contractual and organizational variables determines the structure of liability allocation between the two groups. This interface happens between owner and contractor (box 9) as well as designer and contractor and with external groups such as insurers. These numbered boxes represent part of what will be covered in this report. Box 1 is discussed in Chapter 2, boxes 2 and 5 in Chapter 4, boxes 3 and 8 in Chapter 5, box 6 (engineer submodel) in Chapter 6, box 7 in Chapter 7, and finally box 9 has been discussed in an MIT study comprising the first phase of this research project (see Chapter 1).

It should be noted that the research team considered modeling the process as a problem of multiple decision-makers, however, it was considered best to proceed with the approximation that the problem involves decisions by single individuals. The utility of a group of decision-makers is a function of each member's individual utility and of the weight associated with each member's preferences in the collective decision making process. Individual utility functions are relatively easy to encode; however, capturing, the way these functions interrelate in a group's decision making process is practically difficult and theoretically questionable. The difficulty lies in understanding interpersonal relationships and social exchange processes between the group's members. Furthermore, these relationships are time dependent; a fact conflicting with the utility theory axiom of time independence. These complications along with the observation that the behavior of multiple decision-makers, from a macroscopic point of view, could be represented by a hypothetical single decision-maker's utility curve, led the research team to approximate the problem by using the "engineer's utility" submodel discussed in Chapter 6. The first assumption is that whatever decision the engineer makes for a given set of state variables, his utility is being maximized. The authors' concern, therefore, is to understand how these state variables influence his decisions. Since the allocation of risk between owner and engineer is implicitly expressed in those state variables, the designer's decisions can be controlled through a manipulation by the owner of these state variables. The second assumption is that when determining the outcome for the owner (which in our case is a public agency) the focus of the research team would be on costs rather than "utility". The reason for this is that utility of a public agency which is "an extension of the public" is very vague to determine. Costs are tangible and easy to understand when making a justification for change.

3.5 WORKSHOP

In order to validate and refine the model which consisted of a descriptive influence diagram, the research team conducted a workshop at MIT on May 1, 1980. Three experienced tunnel designers participated in this workshop; their names are presented in Appendix B. In this workshop the participants were asked:

a) to criticize the model and make recommendations for the model's improvement;

b) to put ranges on the model's variables for a given subway profile, and geotechnical report;

c) to produce a brief definition of what they thought the tunnel design would be under the best and worst conditions of the designer's state variables for a given set of geotechnical information which the research team provided;

d) to rank the model's variables according to their significance on the engineer's choice of a structural support system for a subway tunnel.

3.6 ANALYSIS OF WORKSHOP RESULTS

Once the influence diagram was confirmed and the results of the workshop known, the research team proceeded with the following analysis:

a) ranges on the state variables in the influence diagram were established for the best and worst cases;

b) the variables were ranked in their order of significance for both the best and the worst case in a manner representing the mean of all the participants' rankings;

c) the project team derived ranges for the cost of excavation, temporary support and final lining for both the worst and best cases. This was done by utilizing existing tunnel cost data (Mayo, 1968; Spittel, 1971), and checked against preliminary figures supplied by Multisystems Inc., who are performing the task of structuring a contractor's estimating model, under a contract with DOT. This step was considered to be essential in order to check the magnitude of the cost difference between the two cases. If this difference came out to be relatively small, the continuation of the research project might be questionable on its existing foundations. As it turned out, assuming a current total system cost of about $50 million per mile, it could be stated that shifting from the worst case to the best case could result in a 20% savings for twin tunnels! (Findings of the workshop are included in Appendix C.) This provided ample justification to proceed with the line of research.

3.7 FURTHER MODEL DEVELOPMENT AND MODELING SENSITIVITY

The influence diagram represented a crude descriptive model of the owner-engineer environment. After the completion of the workshop, the need for further development was felt by the research team. The development took place on several fronts:

1) Relating structural conservatism (which at the time was considered as a one dimensional variable) to engineering technical decisions. This segregation of technical decisions is discussed in Chapter 4.
2) Looking in more detail at the designer's state variables and attempting to understand the causual relationships between these variables (which are organizational and contractual in nature) to design decisions. The causual relationships explain how by changing or setting those state variables to

different levels, the engineer's risks are altered, and consequently his decision is influenced. These developments in our model are discussed in Chapters 5 and 6. Figure III-5 is a simplified way of showing the areas of development. The state variables or non-technical variables which are under the owner's control are discussed in detail. The uncertainties associated with these non-technical variables are causally related to the engineering decisions discussed in the next chapter.

3) The workshop participants ranked the non-technical variables according to the importance of their effects on their decisions. However, the authors decided to double-check by using a sensitivity analysis procedure.

Sensitivity analysis is used to explore the effects of changing the designer's state variables. The effects are reflected in his designs. Moreover, sensitivity analysis is used to explore the effects of changes in the engineer's designs. The effects of changes would be reflected in costs of the system. The authors' aim was to isolate those state variables that influenced the designer's technical decisions. The authors' modeling sensitivity took the form of a deterministic sensitivity analysis which is one of the features of the decision analysis methodology and part of its cycle. Carl-Axel S. Stael von Holstein (1973:125) discusses deterministic sensitivity as,

> "The analysis in the deterministic phase takes the form of measuring sensitivities to changes in state variables. The state variables are assigned nominal values (which migh be, for instance, estimates of their mean values) and are then swept one by one through their ranges of possible values. We observe which alternative would be best and how much value is associated with

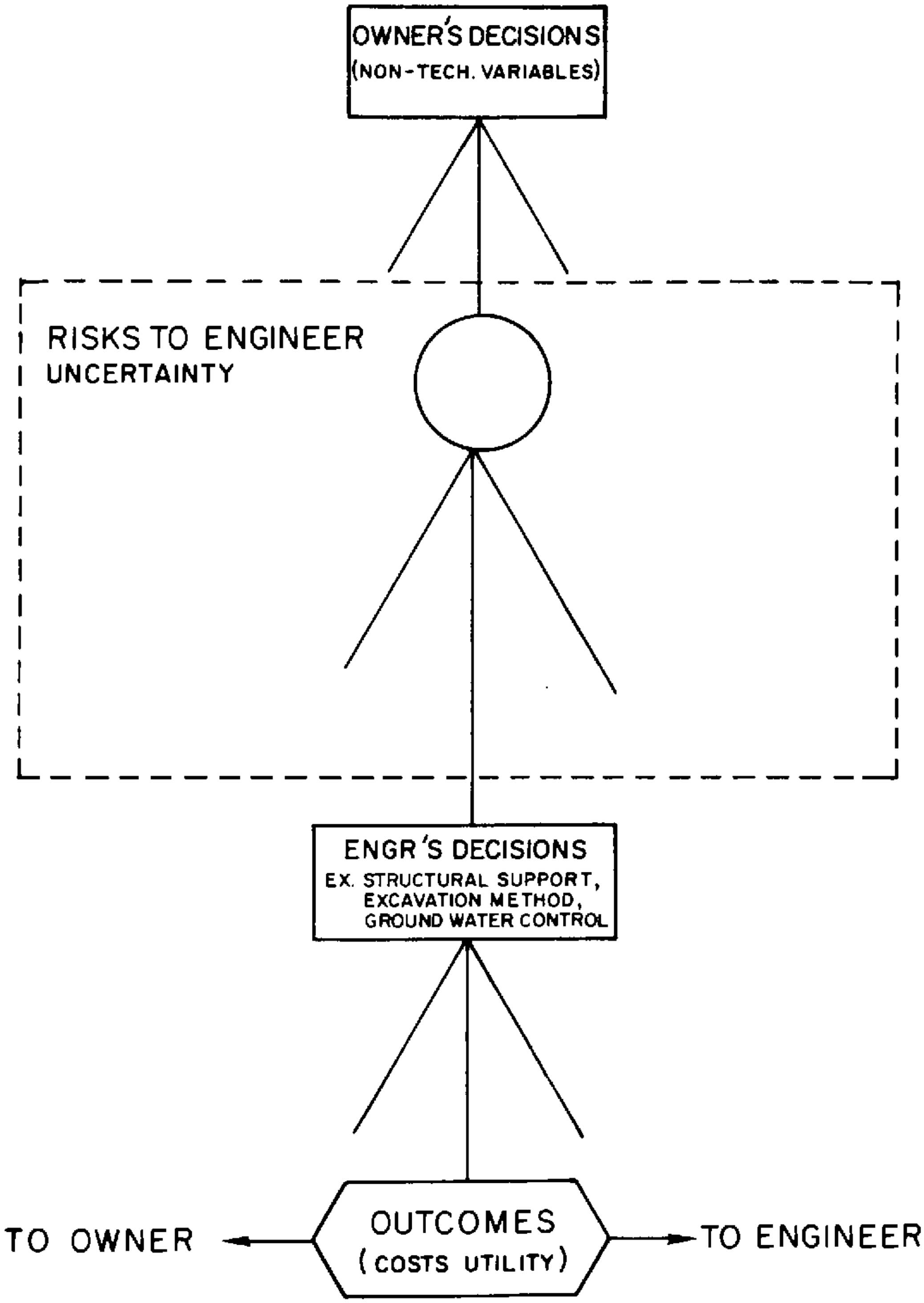

FIGURE III-5

Development of Designer's Model

this alternative. Sometimes we may observe that an atlernative is dominated, which means that there is a better alternative for all values of the state variables. Dominance can often lead to a substantial reduction in the number of alternatives (in terms of the present equivalent). The analysis indicates the variables for which uncertainty is important."

The preceding is similar to the procedure used in the authors' analysis. State variables were discretized into levels, then set at their nominal values, and then one variable at a time was swept through its range. Changes in technical decisions for a given scenario were observed. The sensitivity analysis confirmed workshop results as to which variables are important. Moreover, the authors noticed the dominance of certain state variables for given geotechnical scenarios. For example, it was noticed that for bad ground conditions the designer's decisions did not change for changes in the levels of the non-technical variables. The authors also noticed that changes in designer's decisions did not occur until joint sensitivities were tested.

These sensitivities were obtained by interrogating an expert (Harry Sutcliffe). Although the authors' model does predict changes in designers' decisions for changes in state variables, it was necessary to verify by using expert judgement. The authors are not concerned with whether the expert's decisions are right or wrong under the given conditions, but rather concerned that the expert perceives the causality between his decisions and changes in those state variables. This approach underlies the whole research. The sensitivity analysis is discussed in Chapter 6.

3.8 COST IMPACT ASSESSMENT

Chapter 7 concludes the research by determining the impact on the costs of the system due to changes in design resulting from changes in the state variables. Figure III-6 shows the two stages of analysis. Stage 1 is the testing of how sensitive design decisions are to the non-technical variables. Stage 2 is the evaluation of the cost of the system for changes in design decisions brought about by changes in the levels of the non-technical variables. These costs are evaluated under fixed geotechnical scenarios which are discussed in Chapter 6. The sensitivity analysis is conducted for each geotechnical scenario, one at a time.

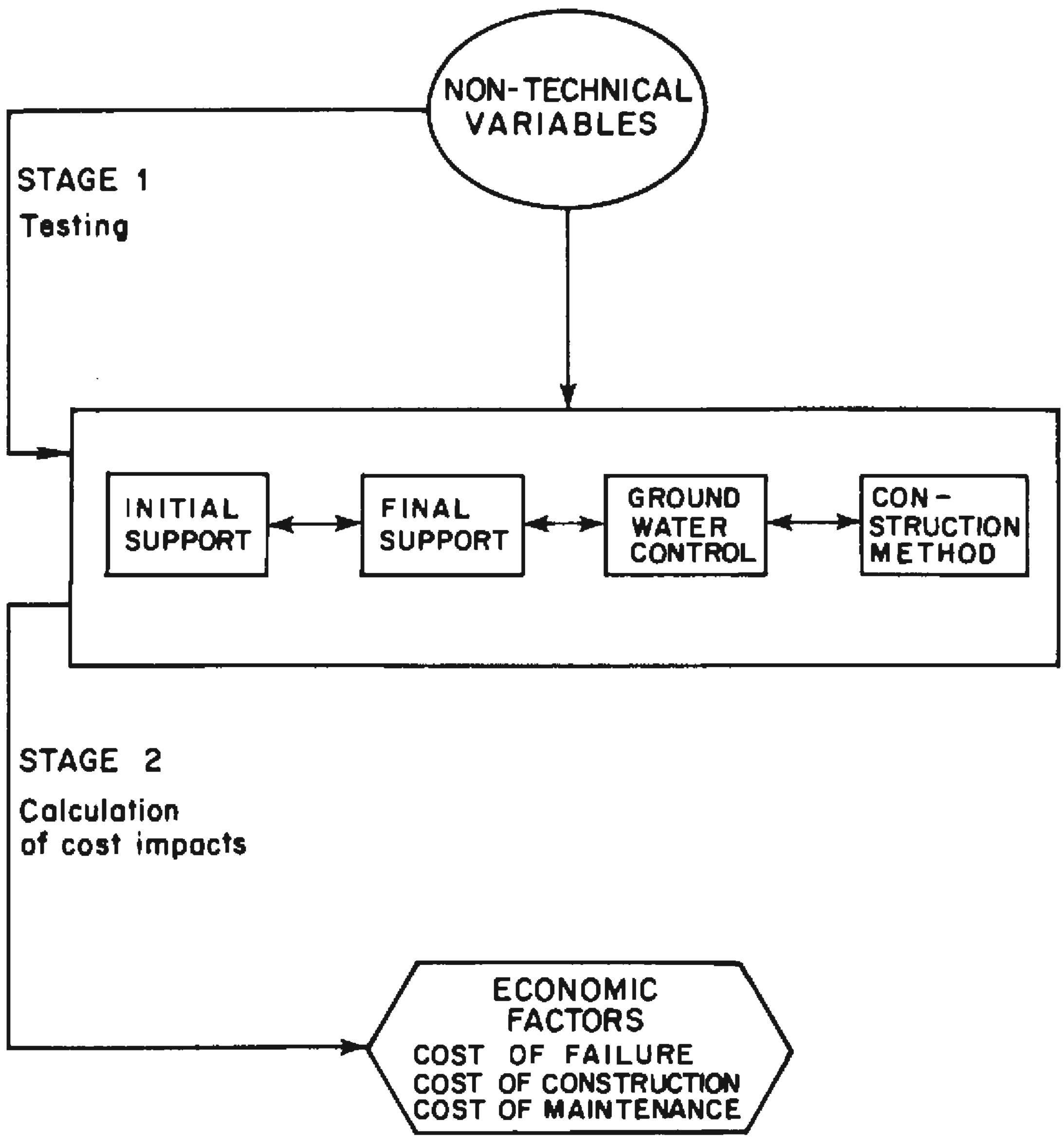

FIGURE III-6

Stages Of Designer's Model Implementation

CHAPTER 4

AN UNDERSTANDING OF THE TUNNEL DESIGNER'S TECHNICAL DECISIONS

In the previous chapter the methodology to be used in modeling the problem of design conservatism was discussed.

Design conservatism was viewed as a one dimensional variable and a by-product of the environment of tunnel design. This chapter associates design conservatism more directly with a set of technical decisions made by the designer, such as the choice of temporary and final support systems. The segregation of these technical decisions is helpful in gaining further insights into the designer's thinking process.

4.1 INTRODUCTION

The engineering decisions on type of temporary and final ground supports, excavation method and ground water control, are the key determinants of the cost of underground construction. This chapter will, therefore, focus in depth on the content and interdependence of these decisions. The impact of non-technical factors on these decisions will be discussed in the following chapters. In this chapter the authors will be discussing:

1.) Performance criteria for the behavior of structural linings in rock tunnels.
2.) Technical factors influencing the choice of a lining system.

3.) Evaluation of various lining types.

4.) The decision on ground water control.

5.) The decision on the choice of an excavation method.

6.) Technical decisions in soft ground tunneling.

7.) European construction and contracting practices.

8.) Designer's model--geotechnical variables.

4.2 GENERAL PRINCIPLES GOVERNING THE BEHAVIOR OF TUNNEL LININGS

The behavior of a rock mass around a tunnel opening is governed by a wide variety of parameters, the effects of which are not all equally well understood, and which can be expected to vary widely within short distances in any tunnel. Hence, the "textbook" design methods for a support system for a tunnel in rock can be considered only as guides to the experience and engineering judgement of the designer.

When constructing a tunnel in rock it has been common practice to provide two stages of linings: a primary lining placed directly against the tunnel walls to support the rock temporarily; and a secondary lining constructed at some later stage and designed to ensure the long-term stability of the tunnel opening as well as to provide a low maintenance, and aesthetically acceptable finish. Under usual practice, both linings are assumed to support the entire rock load. This design approach dates back to the early days of rock tunneling where the early support needed behind the face was provided by timber sets. Since these sets would deteriorate with time, a permanent lining, made of concrete, was necessary and both linings were designed to carry the full rock load at some stage. However, with the introduction of more durable materials such as steel and concrete for use in primary linings, such linings can be made permanent.

Secondary linings are, therefore, only required for structural support in exceptional cases, to waterproof or fireproof the first lining, or to improve the appearance, acoustics or dynamic flow properties (air or water) of the inside of the tunnel. If the rock around the tunnel is capable of swelling over extended periods of time after the excavation, the secondary lining will have to carry a part of the swelling pressures. If the tunnel is to be waterproofed, the secondary lining will be subjected to hydrostatic pressures.

Typically, the engineer has the task of designing the secondary or final lining; the contractor has the responsibility of choosing and placing the primary or temporary support. However, the choice of a final lining influences to a great extent the types of temporary lining which will be technically and economically feasible to use. Moreover, the engineer does not stop at the determination of the type of final lining, but he often specifies spacing and performance requirements for temporary support. This, therefore, constrains the contractor's options for the choice of a temporary support.

It is widely recognized that many tunnel linings utilize redundant support. It is not the purpose of this chapter to analyze the causes of that problem, but rather the authors are interested in focusing upon the behavior of linings in rock and their evaluation. The behavior of tunnel supports and lining is mainly influenced by the following factors:

1. The geometric characteristics of the discontinuities in the rock mass. These characteristics determine the applicability of various support systems, as suggested by Peck et al (1969). They have a direct bearing on the magnitude and variability of the loads applied to the support system. Interestingly, Thomas Kuesel (1979:3-57) of Parsons, Brinckerhoff, Quade and Douglas, Inc., a leading U.S. tunnel designer whose opinion is supported by other designers interviewed (Appendix A), believes that, in a majority of cases, the material and dimensions of a tunnel lining are determined by functional and construction considerations. According to him, the influence of permanent ground loads on lining performance is usually of secondary importance. Linings that have been selected on the basis of other criteria may be analyzed for their behavior under certain assumed ground loads; they are rarely designed for such loads. Mr. Kuesel adds that the most important loads on a lining are construction loads. Proper consideration of these loads requires a realistic appraisal of ground and lining behavior during construction. Variations in construction techniques and equipment may have profound effects on lining behavior. The point is that the designer at this stage has no control over the choice of those techniques and equipment.

2. One of the most important variables in tunnel lining behavior is time. Variation in the time that elapses between excavation and installation of initial support frequently has a great influence on the loading and deformation of the lining. In establishing his rock load theory, Terzaghi (1946) recognized the influence of "stand-up" time or "bridge action period", defined as the period of time following exposure that the roof will remain stable. During this

period there is a progressive loosening or disintegration of the structure of the rock around the opening. If allowed to continue, the rock will loosen and fall out until the cavity is filled or a stable ground arch is formed.

3. Excavation method and associated amount of rock disturbance, greatly influence lining behavior. The process of construction disturbs pre-existing ground and ground water conditions before the lining is installed. A harsh construction method will cause loosening and fracturing of the rock around the tunnel in a zone which will tend to expand until a stable natural opening is reached. This loosened zone will exert increased loads on the support system. The loosened zone is typical of a drill and blast excavation technique. In a machine driven tunnel, little or no disturbance of the rock is caused during the excavation process so that the loads on the support system can be expected to be significantly lower than in blasted tunnels. The question to be asked by the designer is related to the type of the excavation method. Should he design for a machine driven or a blasted tunnel? The answer to this question can not be determined at the design stage, because the contractor has not been selected yet, and consequently the choice of the excavation procedure is a contractor's decision. This situation is one of the paradoxes involved in the set-up of project organizations dealing with rapid transit systems and other public works projects in the U.S.

4. The flexibility of the support system is another important variable that governs the behavior of linings in rock. Any discontinuous rock mass has a certain strength because of interlocking and arching. The support should, therefore, supply only that

load-carrying capacity which the rock itself cannot provide. The tunnel support should be both flexible enough to allow sufficient movement of the rock walls so that arching develops, and strong enough to carry the load the rock cannot carry or to stop and continue to hold any deformations that would tend to impair the use of the final tunnel. According to Thomas Kuesel (1979:35-57) controlled deformation of the lining ring is not only acceptable but desirable, in that it transfers load and more particularly inequality of load to the surrounding ground. It is, therefore, desireable to design linings with sufficient flexibility, which, in addition to reducing the overall magnitude of rock loads, also ensures a more uniform distribution of such loads and consequently, a more economic design.

5. According to Thomas Kuesel (1979:35-57) "unsatisfactory" tunnel lining performance is usually related to water leakage, rarely to structural failure; design for water tightness is more important and generally more difficult than design for load capacity.

4.3 TECHNICAL FACTORS INFLUENCING THE CHOICE OF A LINING SYSTEM:

In the previous section the authors discussed those factors influencing the behavior of linings in rock. In this section technical factors that the designer takes into consideration when selecting a lining system will be looked at. It should be noted that there are other non-technical factors involved in the selection process but these will be discussed in the following chapter.

There are three technical criteria for the selection of a tunnel lining system. These are outlined and discussed in detail by Kuesel (1979:35-57), and mentioned by the experts interviewed (Appendix A) during the course of the research. They are:

1. Functional criterion
2. Site conditions criterion
3. Construction methods criterion

4.3.1 Functional Criterion:

This refers to the intended use of the tunnel. Water tunnels generally require a smooth lining for hydraulic flow characteristics. Pumping and suction pressures, and infiltration or exfiltration limits, may govern the design. Highway tunnels require reflective finishes for lighting considerations. Water leakage in highway tunnels is objectionable from operation and maintenance viewpoints, especially if the water can freeze. Rail and transit tunnels can accept rough finishes, even, unlined rock, and are somewhat more tolerant of minor leakage. Pedestrian tunnels, and public areas in rail and transit stations, require durable, maintainable finishes. Functional requirements can be satisfied by the use of two stage lining systems - a rough structural lining with a furred-out architectural finish. But in many cases, a single lining that can be given an acceptable finish is preferable and economical. Prefabricated metallic or concrete segmental linings can provide construction support, permanent structure, and interior finish for rail tunnels in a single stage. In Atlanta's Peachtree Center Station, the natural rock will serve as both structural and architectural finish material.

When considering functional use, maintainability and maintenance cost require as much attention as initial construction cost. The cost of retrofitting an unsatisfactory installation to eliminate a maintenance problem may be much greater than the extra cost of a design carefully thought out so as to minimize maintenance problems.

4.3.2 Site Conditions Criterion:

This criterion refers to expected ground conditions of the tunnel. Some rocks are permanently self-supporting, many have an appreciable "stand-up" time. Some are so unstable as to require pretreatment before any excavation is possible. The degree to which the gound requires early temporary support may be the controlling factor in lining selection.

Moreover, the presence of ground water and its pressure and flow-rate play a role in determining the type of lining and its method of construction. As mentioned previously, unsatisfactory lining performance is most often associated with leakage. The possibility of earthquake loads requires ductile tunnel linings. This can be achieved through bolted segments, or in monolithic linings through appropriate jointing at changes in structural section or ground condition.

4.3.3 Construction Methods Criterion:

Construction methods are mainly determined by ground and ground water conditions. Lining types are linked with construction methods. For example, drill and blast rock excavation is usually associated with a temporary support system, followed by a permanent second stage lining. Tunnel boring machines lessen the requirement for temporary support. They make single-stage segmental linings attractive. The choice, therefore, of a lining type by the designer influences the selection of construction method to be chosen by the contractor later on. The designer's choice of the lining system is influenced by uncertainties in the technical criteria such as anticipated ground and ground water conditions, and uncertainties in the non-technical criteria such as the designers lack of knowledge about the contractor's skills. The choice, therefore, might not be the optimal one as far as cost is concerned, and, the choice might not result in the selection of the optimal construction method by the contractor.

4.4 EVALUATION OF VARIOUS LINING TYPES

In the previous section the authors showed that the tunnel designer must evaluate functional requirements, ground and ground water conditions, and possible construction methods to make a selection of the most suitable type of lining.

In this section the authors will look at the different lining options available to the designer. These options are: (1) unlined rock, (2) rock reinforcement systems, (3) shotcrete systems, (4) ribbed systems, (5) segmental linings and (6) adaptable techniques. These are discussed in more detail by Kuesel (1979:35-57) and Tunneling Technology (1976).

4.4.1 Unlined Rock:

This option is suitable only for rock of exceptional quality. Even in unfractured, stable rock, long-term drying and slaking may be a problem, but surface sealers may be helpful.

4.4.2 Rock Reinforcement Systems:

The principle of such systems is to encourage rock to support itself by providing tensile reinforcement, rather than to provide independent structural support. Rock bolts provide tunnel support by reinforcing the rock mass to partially overcome its deficiencies. They are used to provide direct support to rock blocks or slabs which would fall out of the tunnel roof or walls if left unsupported. Rock bolts usually consist of a steel rod, 0.5 to 1.5 inches in diameter, 6 to 10 feet long, installed in holes drilled into the tunnel roof and walls, and tightened in place by means of an appropriate anchoring device at the end of the hole (e.g., mechanical anchors, cement and grout), and a plate and nut at the rock surface in the tunnel. To provide the necessary rock reinforcement, the rock bolts are installed on a regular pattern to form a continuous reinforced rock arch. In order for the arch to be formed, the spacing of the bolts must be selected appropriately. This spacing is a function of the rock quality and the size of the tunnel. Considered first as a replacement of steel ribs, but still as a temporary support, rock bolts are now being used on several European tunnel projects for the permanent support of tunnels. As rock quality deteriorates, there is increasing requirement to supplement the rock reinforcement with a lining. This may range from a moisture barrier sealer, through single and multiple layers of shotcrete, to a poured concrete shell. The justification for that is to contain the loose surface rock layer and prevent spalling of the rock arch.

The main advantage for using rock bolts is that they are relatively easy to install. This is due to the fact that their installation does not interfere with the excavation process, especially in the case of tunnels driven by drilling and blasting or by partial-face tunneling machines. Another advantage is that rock bolts do not require a materials-handling system as the one required for a steel ribbed support system, since the volume and weight of materials to be handled is limited. Moreover, from a geotechnical point of view rock bolts have an edge over steel rib systems, since the inherent strength of the rock mass is used to help support the rock load. Due to their minimum projection into the tunnel opening, rock bolts do not require any significant enlargement of the tunnel diameter, as is the case with steel ribs. However, the support provided by rock bolts is still discontinuous. Isolated falls of rock masses are possible. To eliminate this risk in transportation tunnels it would be necessary to provide a continuous coverage of the tunnel roof by wire mesh or concrete, therefore, providing a final lining. Rock bolts cannot be used in badly broken rock where the development of necessary anchorage is difficult and where the spacing between bolts would have to be kept so small as to render the system infeasible economically. It should be added that the design of rock bolt systems is largely empirical and is coupled with a higher degree of uncertainty than that for steel ribs.

4.4.3 Shotcrete Systems:

Shotcrete is used for temporary construction support of rock of widely ranging quality, usually in conjunction with rock bolts. Shotcrete is adaptable to drill and blast, multiple heading excavation. The thickness of a single layer of shotcrete is controlled by practical application limitations. To have a thick shotcrete lining it would have to be done by the build up of multiple layers. For temporary support, shotcrete is usually unreinforced.

However, when used as a final lining a steel mesh is generally added to eliminate crazing and fallout under long-term drying conditions. Shotcrete's main advantage is that the lining is relatively thin, and the reductions in volume of both excavation and lining material can be important. Shotcrete is well adapted to use with road header type mechanical rock excavations, which permit ready access to the face but are limited to rocks of medium hardness. Full faced rotating tunnel boring machines are usually incompatible for use with shotcrete, both because the machine occupies the full heading space and because shotcrete rebound clogs the machine. If the ground has sufficient stand-up time with the assistance of rock bolts, shotcrete can be added from the tail of TBM. For a detailed study on shotcrete, refer to "State-of-the-Art Review on Shotcrete," (1976).

4.4.4 Ribbed Systems:

Steel ribs, combined with timber lagging, are the oldest method of rock support still commonly used in tunnels. While they still find their application in poor rock conditions, their use today, especially in Europe, tends to be reduced in favor of other support systems such as rock bolts and shotcrete. In the U.S. steel ribs are used in a wide range of conditions. According to Tom Kuesel (1979:35-57), this system can be effective and economical, when provisions are made to adjust the size and spacing of ribs on the basis of field observations in contrast to rigid designs based on conservative interpretatoin of geological studies, which can be wasteful.

The ribbed system has two main advantages:

1. Due to the continued use of this system, wide experience has been gained. Possible sources of failure of the system have

been identified. Labor as well as contractors are familiar with this system.

2. As mentioned before, this system is adaptable to any rock condition and is suitable for any of the rock loads which can be encountered in tunnels. The ribs supply all the necessary support without any direct contribution from the rock so that they can be installed even in the poorest rock.

This system has its disadvantages also, mainly:

1. The installation of wood blocking is usually done by hand, and requires extreme care, which makes the process a very slow one. Moreover, timber blocking and lagging decays and, therefore, the support cannot be considered permanent and must be complemented by a secondary permanent lining.
2. Steel ribs project 6 to 12 inches into the excavated tunnel sections. Hence, to obtain a given finished tunnel size, the excavated section must be increased to allow for the space necessary for the ribs and future secondary lining. This implies, increased cost of the entire tunneling operation.

4.4.5 Segmental Linings:

These are usually associated with soft ground. However, segmental linings have occasionally been used in rock tunnels, especially in conjunction with TBMs, mainly to speed construction. Segmental linings serve as both immediate and permanent support and are installed immediately after excavation. The main requirements for tunnel lining segments are to provide resistance to high axial stresses produced during the advancement of the shield by the propulsion jacks; immediate bearing capacity against external ground and water pressures without detrimental deformation or leakage; resistance to impact stresses due to rough handling, transport or erection operations; resistance to corrosion, moisture; economy in construction and maintenance (water-tightness). Segmental linings could be made of precast concrete or cast-iron segments.

4.4.6 Adaptable Techniques:

In adaptable methods, according to Ashley, et al (1979:990-991),

> "The support type and dimensions as well as the construction procedure are (optimally) adapted to the encountered conditions; moderate average production rates will be achieved but the variability of the production rates will be relatively small even under extreme conditions (the construction equipment will usually consist of several smaller and redundant units). Support dimensions and quantities will be close to the minimum necessary for stability of the opening. In short, moderate average production rates and minimal material resources characterize adaptable methods. The adaptation of tunnel design and construction to encountered conditions requires observation of these conditions, monitoring of performance and incorporation of the thus gained information into design and construction; in other words, an observational procedure is used. The main features of observational methods are: the complete development of a number of design-construction alternatives, the full integration of observation (type of observation, critical values of observed parameters are a part of the design) and the feedback of information into design-construction selection. The feedback not only involves switching from one alternative to another if specific observations are made, it also involves a continuous updating of the design-construction procedures (i.e., the previously defined alternatives are modified) as knowledge about a particular project increases. This kind of adaptation requires—in addition to integral observation—very flexible designs, operational procedures and contractual conditions. Such a design provides for small incremental changes of support dimensions and materials, the operational procedures permit these design changes as well as similar changes in excavation procedures, and finally contractual flexibility involves the details of the bidding documents, payment procedures and the decision making in the tunnel. The New Austrian Tunneling Method (NATM) is one of many observational methods; it is well developed and has had several successful applications. Full integration of observation, design flexibility through use of

shotcrete-bolt-wire mesh combinations and operations flexibility by using several pieces of equipment which allows easy switching of excavation procedures are the basic characteristics of this observational approach. The NATM has also successfully surmounted many institutional barriers by development of a refined contractural arrangement including mediation-abritration clauses."

The authors refer the reader to Steiner et al (1980), who present a detailed study on adaptable techniques or observational methods.

In general in U.S. practice where a primary (temporary) lining is installed, a secondary (permanent) lining of mass concrete will be constructed at a later stage to provide long-term structural support to the ground.

A lining of unreinforced concrete with a thickness between 1 and 1-1/2 inches/foot of finished tunnel diameter with a minimum thickness of about 8 inches is built. Mass concrete is used to reduce the need for reinforcing steel which can increase the cost of the tunnel construction by adding another material handling factor to the process. However, the mass concrete is a relatively rigid lining system which is not compatible with the flexibility and deformations of the temporary support. The rigid system is designed to withstand bending moments as well as ring compression. Because of the difference in flexibilities of the temporary and permanent lining systems, the permanent system is often designed as if the temporary support did not exist under the long-term loading. A rigid system may be necessary for some forms of sewer and water tunnel construction where leakage is an important factor, but this is not necessarily a criterion applicable to transportation tunnels. However, the authors will show in the next chapter how water-tightness becomes a criterion in the design of transportation tunnels due to the influence of external non-technical factors. It is upon this problem of redundant and unnecessary support that this study will focus.

This section has attempted to introduce the most commonly used support systems in rock tunnels. Combinations of these systems are being used. The section was not intended to analyze the details of each system, but rather to expose the reader to an outline of the range of systems currently available to the designer.

4.5 DECISION ON GROUND WATER CONTROL

From a purely technical standpoint, and without giving any consideration to external factors such as the mechanism of funding in transportation tunnels (i.e., emphasis on capital expenditures rather than operating or maintenance expenditures), the question the designer asks is whether or not to attempt to limit leakage. Before answering this question the authors will describe the ground water control process. This process consists of two operations:

1. Preventing excess quantities of water from entering the tunnel.
2. Removing the water that does enter.

During construction this water comes from two sources. The first is water used to wash the cuttings from the drill holes during construction, and this inflow can be accurately estimated. The second is water flowing from the ground through which the tunnel is driven. This amount of inflow is subejct to great variation.

After construction the decision the engineer is faced with, is whether to allow drainage in varying degrees or to seal completely.

Pumping and/or grouting off heavy flows can be used to accomplish these objectives. If the designer believes that inflows are slight and temporary or permanent lowering of the ground water table is acceptable, the tunnel may be encouraged to leak and to act as a natural drain, with the leakage intercepted, piped, and if necessary pumped. Natural gravity drainage could be used if possible. The problems with this option of allowing some leakage could be:

1. Is long term pumping cost effective?
2. Quality of ground water should be investigated. Calcification may clog the drains and result in build-up of unanticipated hydrostatic pressures. Moreover, poorly sealed exploratory bore holes, and development of new drainage paths outside the tunnel may produce unexpected hydrostatic pressures.
3. Some urban tunnels could be driven beneath chemical, petroleum or, nuclear storage facilities, from which harmful and dangerous drainage may percolate into a free draining tunnel.
4. Changes in land use and water management policy may cause ground water level to rise resulting in enormous increases in the volume of water flowing in the tunnel.

The designer's second option is to design the tunnel for water-tightness. This could come about because of his uncertainty about water inflows as well as the influence of non-technical factors. According to Tom Kuesel whose opinion was supported by other designers during interviews, a criterion is needed for what constitutes a dry tunnel. He believes that this will vary according to functional use. He believes that achieving "a dusty invert" is usually impractical as well as unnecessary, and pursuit of this goal can become very expensive. Good practice, he says, usually limits the obligation of the tunnel construction contractor to reducing the amount of infiltration to not more than a certain number of gallons/minute/100 feet of tunnel.

4.6 CHOICE OF AN EXCAVATION METHOD

The choice of an excavation method for rock tunnels is a major decision which influences all aspects of the tunneling operation. The excavation method influences the rock support and lining system, amount of overbreak, extent of loosening of the surrounding rock, and stability of the unsupported tunnel. It also influences the rate of advance of the excavation and, hence, the duration of the project; the possible shape of the tunnel; the muck-handling system; and the local environmental impact (e.g., vibration and noise considerations). The choice of an excavation method may be influenced by specific conditions related to the above parameters. For example a drill and blast excavation method may imply the use of a double support system (i.e., primary and secondary linings). A horseshoe-shaped tunnel would eliminate the option of using a full-face TBM since a TBM can only produce circular openings in rock. If adjacent structures cannot withstand vibrations or if blasting is prohibited by local laws, methods other than the drill and blast method will have to be used.

Due to the importance of the excavation method, in particular on the design of the tunnel support and lining, it is logical to suggest that it becomes part of the tunnel design considerations. However, in U.S. practice, the contractor chooses the excavation method. This choice is made after the design is completed and after the award of the contract.

This practice can lead to certain potential problems. The main problem relates to the designer's decision on type of support. This decision might impose an unfavorable excavation method upon the contractor resulting in an uneconomic project. Another problem relates to owners decisions as implied in the contract with the contractor. Clauses on duration of project, labor relations, or length of tunnel sections might eliminate the possibility of using an excavation method which could have been superior from a technical or economic standpoint.

4.6.1 Comparison of Excavation Methods:

Two main excavation methods are used in tunneling in rock: (1) Drill and blast and (2) Boring machines. Drill and blast is the most used in the U.S. It is easily adaptable to widely variable rock conditions, and has been tested and proven successful for the past 100 years. The advantages of its use include: the experience gained by contractors and engineers from its very wide application in the past; adaptability to all rock conditions; availability of well trained labor because of its continuous use; low capital costs; and its ability to produce any shape of tunnel.

Its disadvantages include the fact that drill and blast causes an unavoidable loosening of the rock surrounding the tunnel opening, therefore, requiring more support to remain stable. Lack of control on size and shape of excavation is characteristic of drill and blast excavation. To eliminate rock projecting into the designed tunnel opening, drill patterns are chosen to produce overbreak which leads to significant increases in concrete quantities in case of concrete liners, and an increase in the quantities of muck to be hauled. Moreover drill and blast is a cyclical operation (i.e., drilling, blasting, mucking), where to achieve high advance rates, each sequence of the operation has to be carried out in the minimum amount of time. To do so, high capacity equipment is essential; this is particularly obvious for ventilation and muck-handling. Capital costs for such equipment are, therefore, greater than would be required for a continuous operation. Further, the equipment used in each sequence is left unproductive for the duration of other sequences, so that it is in operation only a fraction of the time.

A full-face Tunnel Boring Machine (TBM) consists of a wheel cutter head fitted with teeth or rollers to cut the rock. The wheel is slightly smaller than the bore of the tunnel and is equipped with gaff cutters to produce the designed bore. The wheel may consist of spokes or of a solid disc with slots to allow the muck to pass through. The wheel is rotated at speeds which vary between 4 and 10 rpm. The speed varies according to the diameter, and power is provided by means of electrical or hydraulic disc motors. The wheel is forced against the tunnel face by hydraulic jacks which apply a thrust varying between 200,000 and 5,000,000 pounds, according to the strength of the rock and the tunnel diameter. The strength of the rock is a basic parameter in the design of a TBM, the evaluation of its power requirements, type, number and location of cutters on its face. In fact, rock hardness and abrasiveness determines type of cutters.

Advantages of a full-face TBM include the reduction in loosening of rock in walls and roof implying less support requirements than a drill and blast method; the elimination of overbreak which implies less concrete usage and muck-handling; smooth bore and less damage to local environment.

The disadvantages include: TBMs' operation becomes more difficult when rock conditions vary over the length of a tunnel; TBMs cannot be used in rocks of poor quality since they are not suited for rapid installation of a rock support system close to the face; they can only produce circular sections, whereas when a flat invert is required to support track, a horseshoe shape is preferred; they have high capital costs, long delivery times, a one size bore; and tight curves cannot be negotiated by a TBM.

Part-face tunneling machines consist of a small rotating cutting head mounted at the end of a boom attached to a crawler frame. Their advantages are similar to full-face TBM's, moreover, they have low capital costs and more meneuverability. Their disadvantages lie in their slow rate of advance.

4.7 TECHNICAL DECISIONS IN SOFT GROUND

In soils, support must be provided to the surrounding ground or the tunnel will collapse. In some soils, the support must be supplied immediately, but in others the soil has a stand-up" time during which it can stand unsupported thus allowing some time for the erection of the lining. Past practice has been to erect a temporary lining to give immediate support to the soil, and a permanent lining at a later stage. With the large scale introduction of soft ground shields which are, in effect, TBM's, there is a growing tendency to use only one lining which is erected in the tail of the shield immediately after excavation and which serves as both immediate and permanent lining (e.g., precast segments). The scope of this study will focus on rock tunnels since potential inefficiencies are larger due to the frequent use of two stage support systems.

4.8 EUROPEAN CONSTRUCTION AND CONTRACTING PRACTICES

In this brief section the authors attempts to compare the techniques, equipment, and contracting practices used in Europe with those common in the United States.

Degall, (1973:619-623), discusses several features of European practice. Among these are the use of tunnel-boring machines, and pilot tunnels. According to him European manufacturers seem to concentrate more on a universal type of multiproject machines, in lieu of designing a mole for a certain project, as Americans typically do. The possibility of using a mini-mole in advance, followed by a TBM that is enlarging the pilot gives the contractor the opportunity to work faster and safer. A pilot tunnel can be used for inspections, water drainage, handling and transport of materials, ventilation and emergency access. In the United States, the municipalities divide up a project into segments which are too small to warrant boring machine operation. For short tunnels the small quantities of excavation make the operating costs minor compared with the depreciation of the excavation system. The contractor uses equipment he owns and which has been almost completely amortised on previous jobs.

In Europe most of the liners are based on flexible design, thus allowing relief of the stress concentrations which cause failures. In Sweden almost all tunnel support measures are based on the components cautious blasting, bolting, shotcreting and grouting in various combinations. Cast-in-situ concrete is almost exclusively used to guard against swelling clay and similar very dangerous rock inadequacies. Strengthening measures in the Swedish experience aim at helping the rock mass to form "natural arches" around the opening, which will guarantee stability. Strengthening measures, hence, do not try to hinder the "arching" movement but aim at obtaining and consolidating as even a rock surface as possible and to reinforce such faults, that might prevent stable "arch" compression forces from developing. Practical experience with shotcrete in Sweden is very successful. This is demonstrated by the fact that shotcrete linings are used more and more as permanent and finishing surface protection in underground transit tunnels and stations. Ryan, (1973:539-543), discusses three main advantages of shotcrete:

- the immediate ability to seal a freshly exposed tunnel face regardless of the quality of the ground;
- the ability to provide immediate support thus helping prevent relative movement and holding loose top rock;
- the ability to absorb small movements induced by the stress relief in the adjacent concentric layers of surrounding ground which takes place in the first few hours after excavation. This movement absorption takes place while the gunned lining is gaining in strength but is still relatively

plastic. This stress arrangement permits the "natural arch" to form around the tunnel.

Ryan (1973:539-543) disputes in detail criticism against shotcrete. This criticism relates to high wastage percentages, dust, quality control techniques, unproven record and thickness and steel reinforcement cover control techniques. Moreover, graphs by Sutcliffe & McClure show that shotcrete strength compares and is even better than that provided by traditional support systems such as steel ribs. The point is that American designers are becoming aware and knowledgeable of the potential of shotcrete but are reluctant to use it because of the influence of non-technical considerations discussed in the next chapter.

For the Vienna subway, over 300 types of lining were studied before selecting the ductile spheroidal graphite cast iron segments [Degall, (1973:621)]. Whereas, in the United States the trend is still toward massive rigid sections. Mr. Hayes, one of the experts interviewed at Bechtel, indicated that:

- reinforced concrete linings used for final support are very thick and that the amount of money spent on perceived safety is not justifiable;
- large portion (up to 95%) of temporary tunnel support is not required but installed for commercial reasons; bidding documents enable contractors to place higher prices for temporary support. And since the choice of temporary support is a contractor's decision, he/she has no incentive

to stop using it where it is not needed.

- union rules and attitudes do not promote cost savings. Mr. Hayes gave the example of a drilling crew in Britain where each man ran two drills, compared to two men per drill in the U.S. Sharing of footage bonus among the gang in Britain provided incentive for the individual workers.
- the legal approach towards the settlement of claims in the U.S. prevents innovative actions on the part of designers and contractors, whereas in Europe the emphasis is on arbitration.
- European, and in specific, British specifications are briefer than those in the U.S. Moreover, the engineer takes the role of the arbitrator there. A report titled "Tunnelling-improved contract practices," (1978), sponsored by the British Construction Industry Research and Information Association, considers the risks in tunnel design and construction, and also the methods by which the ICE Form (Conditions of Contract and Forms of Tender, Agreement and Bond for use in connection with works of civil engineering construction) and other contract documents allocate responsibility for risk. The importance of this report is that the engineer's or designer's role is emphasized, as is the need for his independence to be preserved during the execution of the contract.

The subject of European contracting practices is included in several publications. Most notable among these are:

- "Tunneling For Urban Transportation: A Review Of European Construction Practice," by O'Rourke, (1978).
- "Better Contracting For Undergound Construction," [NRC(1974)].
- "European vs. United States Construction Contracting Practices," a paper by Sol Ribakoff, (1981), included in the 1981 Rapid Excavation Tunneling Conference Proceedings, Volume 2.

A synthesis of this material includes:

- engineering design is performed by the transit authorities in most European countries with the exception of Britain. Consulting engineers are not extensively utilized by owners in the planning of projects and in the preparation of contracts, including drawings and specifications. Contractors, on the other hand, are allowed to submit alternate proposals and are given more flexibility during construction to use innovative techniques;
- prequalification of European contractors based on experience, management personnel, financial capacity, equipment availability, and the investigation of their past record of work performance and claims submissions. Bids are in general opened privately, and negotiations may then be conducted with the low apparent bidder and with other bidders, covering bid prices, alternatives, and qualifications on bids;
- an arbitration clause is generally included in the contract.

Contractors are reluctant to resort to arbitration and especially to count litigation because this usually results in their removal from the list of qualified contractors. Dispute over changed subsurface conditions is generally resolved in European practice by the owner assuming that risk. Moreover, owners furnish contractors with extensively investigated data on ground conditions including interpretations. This is in marked contrast to U.S. practice.

In this section the authors attempted to show that European practice is characterized by the efforts of the owners of the transit systems to provide incentives through contractual means and equitable sharing of the risks.

4.9 DESIGNER'S MODEL - GEOTECHNICAL VARIABLES

The designer's model discussed in Chapter 6, included two sets of variables which influenced the designer's technical decisions. The first set relates to geotechnical variables and is the focus of this section. The second set relates to non-technical variables and is the focus of Chapter 5.

The geotechnical variables are:

- Prior ground behavior: this is the soil and design engineers' initial perceptions of ground conditions which are based on existing data on the ground and structures' behavior in the vicinity of the planned project.

- Degree of investigation: this variable represents the extent to which a program of ground investigation is conducted and is controlled by the owner. The intensity of this program can be crudely measured by the number of test borings per unit length along the alignment of the tunnel, or the cost of exploration as a percentage of expected construction costs. A trade-off problem is always involved when making a decision on the extent of investigation. This problem is focused upon by Baecher (1972). He concludes that more exploration for tunneling should lead to a reduction of construction costs.
- Designer's knowledge of ground characteristics: based on the soil engineer's initial perception of ground conditions and the results of the investigation program, a report on expected ground behavior (e.g. soil type, RQD, earth pressures, soil strength, permeability, etc.) is submitted to the designer. The information contained in this report is the basis for the design of the support system. The research team submitted such a report to designers when conducting the workshop discussed in Chapter 3 and Appendix C. However, those desingers used certain features of the report relating to rock quality and water conditions. Lack of time as well as the experience of the experts make the use of Deere et al (1969) Rock Quality Designation System (RQD) and information on amount of water infiltration adequate for the purposes of the research.

During the authors' interviewing of designers and subsequently when conducting the structured sensitivity analysis with the "representative expert" (see Chapter 6), the geotechnical scenarios were fixed. Designers and the "representative expert" expressed their satisfaction with a general system describing ground conditions. Their responses as to the choice of structural support systems reflected the changes in non-technical variables given fixed geotechnical scenarios. This research is focusing on the causal relationships between those non-technical variables (discussed in Chapter 5) and engineering technical decisions under several fixed geotechnical scenarios. However, in no way does the research attempt to belittle the importance of those geotechnical variables in influencing design decisions. For those interested in learning about other geotechnical classification systems, the authors refers them to "Tunneling Technology" (1976:25-33), which discusses in detail several classification systems for rock.

4.10 RECAP

Table IV-1 summarizes the interdependencies between the various technical options available to the designer. The table covers most options used under U.S. practice and is based on the authors' interviews with designers and contractors. It should be noted that the table is set up in such a way where the sequence of technical decisions reflects the U.S. contracting practice. The designer makes a decision on the type of final support and specifies criteria for the use of temporary support which he believes would be used by the contractor. The table does not include: 1) information about degree

ROCK QUALITY	SUPPORT FINAL (Engineer's Decision)	 INITIAL (Contractor's Decision with Designer's Influence)	EXCAVATION METHOD	COMMENTS
Excellent RQD>90	1. Segmental 2. Mesh (occasional) 3. Shotcrete 4. Unlined	1. Segmental 2. Rockbolts 3. Shotcrete 4. Unlined or unreinf. rock	Boring Machine	Notice here that choice of segmental lining influenced choice of excavation method.
Excellent RQD>90	1. Mesh (occasional) 2. Reinforced concrete 3. Shotcrete 4. Rockbolts	1. Rockbolts 2. Light steel sets 3. Rockbolts 4. Rockbolts	Drill and Blast	-Reinf. conc. required if other criteria exists, e.g. water proofing, aesthetics, swelling rock, etc. -Steel sets associated with concrete liners.
Good 75<RQD<90	1. a) Mesh required and/or b) Shotcrete & spacing requirements 2. Segmental	1. Rockbolts 2. Segmental	Boring Machine	
Good 75<RQD<90	1. a) Mesh required and/or b) Shotcrete & spacing req. 2. Concrete & spacing req. on steel sets	1. Rockbolts 2. Light steel sets	Drill and Blast	Steel sets associated with a drill & blast method.
Medium 50<RQD<75	1. Rockbolts/Shotcrete & spacing requirements 2. Segmental	1. Rockbolts/Shotcrete & spacing requirements 2. Segmental	Boring Machine	Problems arise when placing shotcrete while using a full-faced boring machine.
Medium 50<RQD<75	1. Rockbolts/Shotcrete & spacing req. & reinf. conc. 2. Reinf. conc. & spacing req. on steel sets	1. Rockbolts/Shotcrete & spacing requirements 2. Steel sets	Drill and Blast	
Poor 25<RQD<50	1. Reinforced concrete 2. Segmental	1. Rockbolts/Shotcrete (stricter requirements) 2. Segmental	Boring Machine	Problem here is stand-up time. Would the ground support itself before support can be placed?
Poor 25<RQD<50	1. Reinforced concrete 2. Reinforced concrete (stricter requirements on spacing of steel sets)	1. Rockbolts/Shotcrete 2. Heavy steel sets	Drill and Blast	Same problem here.

TABLE IV-1. INTERACTION OF VARIOUS TECHNICAL UNDERGROUND DESIGN DECISIONS IN THE UNITED STATES of subsurface investigation conducted, 2) it does not specify whether design criteria pertaining to ground water control and water tightness is included.

The table implicitly includes all the technical options that are feasible under varying conditions of subsurface investigation and water control. For example when rock is of excellent quality and requirements for controlling water infiltration are strict, the designer might choose segmental linings as a final lining system. This implies that segmental linings would be used as a temporary support system and that a boring machine excavation method would, therefore, be more suitable. On the other hand, the designer might choose a reinforced concrete liner as a final support which would probably imply that the contractor would use light steel sets as temporary support. The most suitable excavation method in this case would be a drill and blast method. A third option would be to specify shotcrete as a preventive measure. The table, therefore, is a compilation of options suggested by U.S. tunnel designers and contractors authors' interaction with them through interviews, workshops and media. The table is not intended to provide design procedures under certain conditions. It only represents the thinking process of tunnel designers which is influenced by technical as well as non-technical criteria to be discussed in the following chapter.

For example, designers might be using reinforced concrete as a final lining not for structural stability reasons but for reasons related to water proofing, fire protection, etc. The only structural design they have to perform in such a case is limited to the analysis of the stability of the lining under its own weight. Fear of liability and lack of knowledge about contractor's skills might have prompted the designer to use this type of lining. The next chapter will explore further the influence of these non-technical variables.

CHAPTER 5

NON-TECHNICAL FACTORS EFFECTING DESIGN DECISIONS IN TUNNELING

In the previous chapter, the authors showed that design conservatism could be segregated into a set of technical design decisions.

This chapter presents the non-technical or institutional variables. The authors hypothesize that these non-technical variables impact the technical design decisions.

5.1 INTRODUCTION

The authors separated the non-technical, institutional variables into two groups—organizational and contractual.

The organizational variables stem from the manner in which the project organization is set up. They include:

1. "Integration of Design and Construction" variable.
2. "Level of Hierarchy" variable.
3. "Design Criteria" variable.
4. "Client's Policy and Reputation" variable.
5. "Union Work Rules" variable.

The contractual variables include:

6. "Engineering Firm's Responsibility" including "Insurance Coverage" variable.

7. "Fee Structure" variable.

Workshop findings, interviews, and literature in the field were unanimous in emphasizing the importance of three major non-technical variables in influencing technical design decisions. These are: "Integration of Design and Construction," "Design Criteria," and "Engineering Firm's Responsibility." Nevertheless, the authors included a discussion of all the non-technical variables in this chapter. The three major non-technical variables mentioned previously will be used in the sensitivity and costing analysis to be discussed in Chapters 6 and 7.

5.2 NON-TECHNICAL VARIABLES: ORGANIZATIONAL

5.2.1 Integration of Design and Construction: The Uncertainty in Tunnel Design

Design decisions are based on a limited amount of geological information. This poses a great amount of uncertainty as to actual ground behavior and characteristics. The designer knows far less about the subsurface conditions than what the contractor finds out once the design is completed and construction commences. In order to avoid this kind of uncertainty and the inherent conservatism, European subway projects usually employ adaptable methods, such as the New Austrian Tunneling Method (NATM), where the design and construction go on in a parallel fashion and thus the geotechnical design information is continuously updated as construction goes on (Tse 1977). Even though this practice is not used in the U.S., the need for adaptability in tunnel construction is recognized implicitly by the fact that usually the designer is responsible for the final lining only, leaving the "temporary" support to the contractor's discretion. Sometimes the designer specifies minimum requirements for the type and amount of the temporary support required, but even then, the temporary support's strength may be totally disregarded in the consideration of the strength of the final lining. This double counting has a considerable cost impact to the public, whereas its incremental contribution to safety may be negligible (see Chapter 7). Hence, integration of design and construction effects the designer's knowledge as to who the contractor will be, and it effects the degree of control excercised by the designer over the construction process. In U.S. practice where the low bidder is selected, the designer has no information about the potential contractor's experience and skills. Moreover, his role as an interpreter and supervisor of his own design often stops at the completion of the award process. This might enter into the designer's decision on the support system and suggested excavation method as will be verified in the next chapter.

All of the designers interviewed thought that the traditionally low level (U.S. practice) of design-construction integration was a very important factor to be considered in their decision process. Interestingly enough, contractors and owners expressed similar opinions as to the undesirability of this practice. The following are opinions expressed by the different parties:

Hammond (1979:136), a leading tunnel designer, states that,

> "Obviously what the engineer would call for or permit to be done by a contractor whose qualifications he knew and trusted

would be quite different from what he would allow a contractor whom he knows only as the low bidder with bonding capability but of otherwise questionable or even unknown virtues."

Kuesel (1979:57), another leading tunnel designer, states that,

"Particularly for underground construction, it has become increasingly difficult to separate design from construction methods. The designer should have at least an idea of how the work may be constructed, and will frequently specify restrictions on construction methods, either to reflect design criteria for new construction or to protect existing facilities. But the designer cannot know who the low bidder will be, nor what special expertise, equipment, or ideas he may have that could significantly alter the way the work is constructed and even justify a redesign."

Nadel (1979:66), who expresses the contractor's point of view, states that,

"Clearly we could produce construction more efficiently if we could provide the designer with the incentive to produce designs which are cheaper to construct. Perhaps the best way to accomplish this is to utilize to a greater extent the turn key contract where-in a designer-contractor entity (initially possibly a joint venture of the designer and the contractor) contracts with an owner to provide a facility which will meet certain stipulated requirements for a fixed consideration. It would seem that under such a system, greater effort and creativity will be invested in the design process."

The turn-key approach Nadel refers to will be dealt with in the final chapter as a solution for implementation.

Strauss (1979:27), who represents the owner's view, states that,

"In considering the potential risks in this blind folded process of contractor selection, both the public owner and designer adopt defensive postures in a legitimate attempt to avoid risk to themselves and to their clients - the taxpayers."

The question is, however, whether the taxpayers are willing to pay for the defensive designs implemented.

O'Rourke (1980:43), who represents the academic view, states that,

> "Often, major metro projects amplify risk by separating responsibilities. For example, when design and construction management are done by different agencies, the design engineer must deal with uncertainties in site inspection and construction quality as a future event over which he has no control. His assumptions are likely to reflect these uncertainties as he attempts to cover contingencies and protect himself from future litigation. The complexity of large-scale urban construction points toward consolidation of services - not dispersion. As a minimum, the design contract should enforce continuity by providing for design support during construction.
>
> As practiced by most U.S. metro authorities, the award of contract solely on the basis of lowest bid tends to isolate the design from its logical conclusion in practice. Design of underground structures can't be divorced from construction. The use of specialty methods, such as diaphragm walls and soil grouting, places immense emphasis on contractor experience. Without controls on contract award, the risks of new construction methods may be prohibitive. Reducing risk and encouraging new construction techniques may require changes in procedures for letting contracts: e.g., prequalification of bidders, and contract award without being bound to the lowest tenderer."

Another level of integration occurs in the case of a joint venture, where a designer and a contractor in the capacity of a construction manager undertake the project. The construction manager injects construction know-how and experience into the design stage.

The third level would be a design-construct approach by a single firm or joint venture. This approach is sometimes used for carrying out private projects in the U.S. and is a common approach for carrying out subway projects in Europe. Although the authors were aware that this approach is not yet applicable to U.S. subway projects it was, nevertheless, included so that they could examine whether the decision on a support system might vary with such variations in the level of integration.

5.2.2 Level of Hierarchy: The Design Organization

After the completion of the planning phase, the owner usually hires the designer or performs the design in-house, if he has the capabilities. The design firm is either hired as a General Design Consultant (GDC), or as a Section Designer, having in both cases a direct contract with the owner, or as a Section Designer subcontracted under another architectural or civil engineering firm which in turn is contracted with the owner.

From interviews that the research team had with owners and designers, it also became apparent, that in the organization structure usually adopted, the design is fragmented both geographically and vertically. From the geographical point of view, Section Designers undertake the design of small sections of the project. As a result, the more fragmented the project's length is, the more need is created for coordination of the design at a higher level. The necessary coordination is provided either by the GDC or by the owner.

The design is also fragmented vertically in the sense that higher levels of the design organization structure impose constraints on the lower levels in the form of general design criteria or minimum requirements. Through discussions with designers and owners it became apparent that the design criteria for a subway system are more strict than the codes existing for other types of structures. As a result, designers may be left with less freedom of choice in their search for a cost effective solution. The topic of design criteria will be handled in the next section.

In short, the authors hypothesized that the technical decision such as the structural support decision may be influenced to some extent by whether the design firm acted as a General Design Consultant or only as a Section Designer. Assuming that the owner's organization does not specify the design criteria, the GDC has three options:

1. Specifying criteria for innovative and cost effective designs, thus accepting the risk of their failure.
2. Giving the section designers leeway in coming up with their own design at their risk.
3. Specifying rigid design criteria which would lead to conservative designs and hence protecting themselves and the section designers against risks of failure.

5.2.3 Design Criteria

Design criteria are the set of design rules and specifications to which the designer must conform. They are either set by the owner, especially if the owner has some experience in the task already, or by the General Design consultant, if the decision-maker is a section designer. The design criteria includes specifications on the underpinning and protection of adjacent structures as well as dewatering requirements.

Mr. David Thompson (Principal) of Haley and Aldrich, Inc., indicated that when it comes to considering loads on permanent structures, the Massachusetts Bay Transportation Authority (MBTA) has a design criteria booklet, documenting for example how stations are to be designed and giving criteria for the various loadings to be assumed. That is why when a situation of unsymmetrical loading exists it is specified that temporary and permanent support should be used. Unsymmetrical or unbalanced loading is a loading condition which assumes full active pressure on one side and at-rest pressure on the other side of an underground structure. This situation represents the case where after completion of the subway, an excavation takes place for the construction of an adjacent structure. As a result, considerable bending moments are created in the corners of the original structure, especially if it has a rectangular cross section. These moments require a great amount of well anchored reinforcement in the joints. This, however, cannot be achieved when using slurry walls because the construction methods make it very difficult to meet the reinforcement requirements. This philosophy or criterion of anticipating for conditions that do not exist now, but might be introduced in the future started in Washington's metro; it was then adopted in Baltimore and finally in Boston. It is interesting to note that the engineers designing the Davis Square Station in Cambridge, Mass., adopted the philosophy of unbalanced loading, whereas the designers of the Harvard Square station, a couple of miles away, rejected it.

In the first case, slurry walls are considered "temporary" structures and another wall is to be built inside them as a member of the box structure. In the second case, the engineers could not afford to spare the thickness of two redundant walls because of space requirements, so, they looked back and reconsidered the situation. Their argument was that it is highly improbable to have such excavation in the area and, even if there was any, it is the responsibility of the party creating the unbalanced loading to compensate for it. This problem is known under the legal name "doctrine of support".

The question addressed is whether the designer has the legal right to design in a manner that makes construction in adjacent properties infeasible or more costly. It is beyond the scope of this study to go further into this issue. The point of interest, however, is that when the latter practice is specified in design criteria then considerable impacts on construction as well as legal costs might result. O'Rourke (1980:42), states that,

> "both temporary and permanent support can be provided by the same structure. During construction of the Bay Area Rapid Transit (BART) System, for example, concrete diaphragm walls supported temporary excavations and permanent metro structure...
>
> A wall for both temporary and permanent support eliminates redundant construction and saves money."

The task of designing underpinning for the protection of adjacent structures has evolved from being the responsibility of the contractor to that of the engineer. The fear of third party claims due to damage of the adjacent structures has resulted in adopting very conservative general design criteria. This situation is thoroughly discussed by Kuesel (1979:55-56), who states that,

> "One of the most complex risk areas, because it involves all parties on the construction scene, is the protection of adjacent property. This is also a peculiarly prominent item for urban construction projects. In the past, the owner left all temporary and protective work to the contractor, and allocated all the risk to him (or so the owner thought if he didn't speculate about high bids and litigation). This produced so much controversy that owners generally recognized they had better make provisions for protection of at least the more prominent existing structures adjacent to the work. Engineers were, therefore, directed to design underpinning and other forms of protective construction. Unfortunately, about this time the doctrine of capability was taking hold in owners' contracting divisions, and a new risk was perceived - who would be held responsible for damage to adjacent structures and facilities? The owners initially attempted to allocate this risk to the designers (with respect to defective design, as contrasted to defective performance, which was still allocated to the contractors). This attempt backfired into what Vern Garret of WMATA aptly dubbed "defensive engineering" - the

designer's deliberate increase in the owner's cost for protective construction in order to reduce the designer's exposure to errors and omissions claims....

To hedge against the risk of damages to third party property, the owners actually encouraged their engineers to elaborate their underpinning and building protection schemes, thus increasing their defensive engineering problem.

Some owners succeeded in topping this achievement by placing all their design engineers under the direction of a general soils consultant, who was supposed to provide a uniform high professional judgement on geotechnical matters. Unfortunately, the general soils consultant usually (and with good reason) was preoccupied with concern for his risk of high judgements against professional soils engineers. The resulting general design criteria for underpinning were understandably conservative, and hardly calculated to optimize the owner's total expenses for construction and damage restoration."

Moreover, owners specified strict requirements for water-tightness. The local transit authorities felt that by doing so, their operating costs would be minimized. However, these requirements influenced the engineering technical decisions such as the choice of a final lining system (see Chapter 4).

It was the opinion of several owners that transit projects being very much in the public eye, should be designed for more stringent performance--therefore, more conservative design. However, what needs to be established is what constitutes rigid criteria and the cost impact of such criteria. For this purpose, the authors segregated design criteria into the following levels:

1. Rigid Criteria: implying adherence by the decision-maker to strict specifications regarding protection and underpinning of adjacent structures as well as maintaining water-tightness standards in the tunnel.

2. Nominal Criteria: meaning that some general guidelines exist as to the protection and water-tightness requirements.

3. Flexible Criteria: this level gives the decision-maker discretion as to what he feels best for the protection designs and water control methods.

These levels will be used in the analysis chapters (Chapter 6 and 7)

5.2.4 Client's Policy and Reputation

This variable expresses the owner's policy towards the engineer and the reputation the owner has acquired through past dealings with design firms. The owner's attitude regarding payment of fees, adjustment of fees, law suits, etc., has a potential impact on the engineer's design approach from a risk-benefit point of view. The authorshypothesized that an owner who has a tradition of allocating the risks of new technology (via law suits) to his designers, will subsequently lead them to adopting conservative designs.

5.2.5 Union Work Rules

This is a variable which indicates that different cities and states have different labor union agreements that have to be met in the construction of subway systems. These rules have to be taken into consideration when the designer makes his design decisions, and may have significant cost impacts.

Another aspect of this variable relates to the use of "factory" prepared structures or elements, which can be installed by relatively unskilled labor for a much wider variety of construction. This development is an integral part of the potential for improved efficiency and the use of new and innovative designs. However, Fead (1980:94), states that, "Many such developments, however, are prevented by a combination of labor unions and government politics relating to labor relations. Because of the politics, there seems to be a serious question as to whether a solution can be found to this--unless we first have a collapse of the construction industry comparable to or worse than the collapse of the auto industry."

5.3 NON-TECHNICAL VARIABLES: CONTRACTUAL

Contractual variables are those which determine the liability of the design firm based on the contract between that firm and the owner, and most significantly, based on the concepts, practice and precedence of American law. The following sections will highlight the different types of liabilities and judicial concepts. An in depth study of these was accomplished by Bjarnason (1980), one of the research team members. The following components of contractual variables will be discussed:

1. Distinction between contract and tort liability.
2. Distinction between professional and general liability.
3. Concept of strict liability.
4. Concept of limited liability.
5. Liability to the owner and liability to third parties.
6. "Engineering Firm's Responsibility" variable.
7. "Insurance Coverage" variable.
8. "Fee Structure" variable.

5.3.1 Distinction Between Contract and Tort Liability

A very important distinction should be made between contract liability and tort liability. Contract liability supposes the existence of a contract between the person liable and the other party. It relates to a duty created by this contract. Tort liability, on the contrary, does not need the existence of any contract. It relates to a duty created by law. A design professional, for instance, can be held liable by the owner or any third party because of a negligent act. The same negligent act can constitute a tort and a breach of contract. Whether the owner can elect contract doctrines or tort doctrines in making a liability claim against a design professional is not clear in American law. It is likely that tort will be used where there is bodily injury or property damage, and less likely where there is only economic loss. According to Bjarnason (1980:29),

> "American courts, however, are in practice more prone to solve owner-designer cases according to principles of tort law rather than contract law."

5.3.2 Distinction Between Professional and General Liability

Professional liability relates to the acts of the architect-engineer committed in the performance of his professional services. Non-professional or general liability relates to the operations of the architect-engineer's office, and non-professional activities on the job site. In this study the emphasis will be on professional liability. The distinction is made because of its importance for insurance purposes.

5.3.3 Concept of Strict Liability

Design professionals sell their services but do not guarantee that a totally satisfactory result will be achieved. They are expected to excercise reasonable care, skill and diligence in carrying out their work. Although this does not imply that perfect plans and specifications will always be produced, the level of performance is required to be consistent with ordinary professinal standards, that is, with what would normally be provided by other similarly qualified professionals at the same place and time, under similar circumstances. Today, a design professional can be held liable in any situation where he owes a duty of care or a professional duty to some other person, i.e., not to damage his property, or to cause him economic loss. This duty may arise out of contract, or may be owed to some person with whom the designer has no contract, but who can show a causal relation between his damages and the designer's act or failure to act. Therefore, infallibility should not be expected from design engineers. However, a few states apply a higher standard of "implied warranty of suitability". This "implied warranty" or "strict liability" doctrine has probably had its greatest impact in the field of mass produced products. In an article in Engineering Education, Jur et al (1981:271-272), state that,

> "In the early 1960's, changes in design criteria started coming from the non-technical public. In 1963, the California appellate court wrote a landmark decision in which the court stated that a manufacturer is strictly liable in tort when he places an article on the market - and knows that it is to be used without inspection for defects - which proves to have a defect that causes injury to a human being. This principle has been extended by the courts to most of the states in this country, and has been an important factor in the large number of products cases that are before the courts in which it is alleged that the design was defective and was responsible for an injury."

Strict liability refers to liability without fault; that is, liability for damages is not based on demonstration of negligence, but by simply showing that a loss was caused by a defective design. The basic rule is that a manufacturer is strictly liable when an article he places on the market proves to have a defect that causes injury or damages, even if the article was produced without negligence. Jur et al (1981:272), add that,

> "There is no question that litigation, too, has had a significant influence on design in the last 10 to 15 years. The concept of strict liability, which requires proving that a product is defective because it is unreasonably dangerous or has an unreasonable danger associated with it, has in many cases required the designer to reconsider product performance in the real environment of product use. Responsibility remains with the design engineer to consider modes of failure and potential hazards by recognizing the limitation of human capabilities."

5.3.4 Concept of Limited Liability

The inclusion in the design contract of a provision limiting the liability of the designer to a designated amount, is one contractual method to decrease the professional, contractual liability of the designer. Such a liability limitation will not effect third parties to the design contract, but since the bulk of the claims against the designer are made by owners (their clients), it can be a useful device to limit the liability of the designer, and reduce his professional liability insurance premiums. The designer can also ask the owner to pass the same liability limitation on to the contractor who performs the work, through the construction contract. This does not change the status of the contractor in any way, but it means that the amount of damages the contractor may be entitled to receive from the designer, because of his negligence, errors or omissions, will be limited. Such a clause is an additional factor of reduction of the designer's liability. Moreover, it curbs the practice of contractors, who price their bids extremely low in order to get the job, and then seek extras for alleged inadequacies in the plans and specifications. The designated amount for the liability limitation can be a lump sum, or can be related to the fee or cost of construction.

Limitation of liability becomes attractive because of the tendency by U.S. judges and juries to believe fault must exist if someone suffers a loss. Attorneys take advantage of this fact in developing their bargaining power. As a result, when a party is involved in litigation, it becomes common practice for the plaintiff's attorney to inflate the damages as much as possible for the purpose of creating a bargaining advantage. Under such conditions, limitation of liability becomes a device for desingers to create a more favorable environment for their practice. Limitation of liability is now recognized and used by claims-susceptible businesses such as hotels, international airlines, financial analysts, and others. Limiation of liability, as recognized by many porfessional organizations both in the U.S. and Europe, would establish a reasonable assumption of liability on the part of designers in proportion to their fees. It would have the effect of bringing some types of claims for damages back into a reasonable perspective so that the issues involved could be faced on a more realistic and less expensive basis and still be equitable to all parties concerned.

5.3.5 Liability to the Owner and Third Parties

The primary source for determining whether the design professional has performed properly is the design contract, which binds him to the owner. The owner, then, is the primary potential claimant against the design professional. When professional liability lawsuits began to mushroom after 1950, design contracts began to reflect increased liability, and to specify more precisely the designers' professional duties.

Examples of claims often successfully brought by owners against the designer include:

1. Drawing and specifications claims: When the designer prepares plans and specifications, he moves into an area of heavy exposure. This potential liability in design is far greater than in inspection. Allegations of deficient drawings and specifications represent the major source of claims, over 60% [Bjarnason (1980:35)]. Negligence in design can be based on negligently incomplete specifications, as well as upon complete but erroneous ones. It should be noted that one major source for the information used in the designer's specifications and drawings is provided by the owner. The owner can disclaim any responsibility for the information he provides.
2. Cost estimates claims: If the designer designs a project which greatly exceeds the owner's budget, the plans are unsuitable. In this case too, the owner may be excused from any obligation to pay the designer his compensation. An unreasonably low estimate, on the other hand, may also be considered as a breach of contract. Usually, the courts give the design professional a tolerance of about 10% in his cost prediction [Bjarnason (1980:35)]. In many contracts, provisions are included, which are supposed to insure that fees will not be lost when cost predictions are inaccurate, and that fees will be lost only when the cost predictions

are made negligently. However, courts frequently ignore these contract provisions. This type of claim explains, to some extent, the reluctance of designers in departing from conventional designs. This departure might lead to discrepancies between their estimate and the submitted bids.

Historically, the courts have usually held architect-engineers immune from negligence suits filed by third parties to the design contract existing between the owner and the artchitect-engineer. This came from the principle that the lack of privity of contract precluded recovery of damages by any stranger to the design contract, for damages occuring during the construction process. After the acceptance of the project, the owner normally assumed the liability under the "completed and accepted rule". Both these defenses have substantially weakened today, and the courts are increasingly holding architect-engineers responsible when they failed to perform their duties in keeping with the "usual and accepted standards of their profession". Architect-engineers now find themselves subject to claims by the general contractor, subcontractors, workers, lenders, sureties, suppliers, adjacent land owners and other members of the public. Moreover, when the owner is the Government, he is in many states shielded by the Government's sovereign immunity principle. The architect-engineer, then is naturally the first one to be sued by third parties.

5.3.6 Engineering Firm's Responsibility Variable

This variable refers to the degree of liability the architect-engineer may assume by his contract. As the authors have shown, the designer may assume a degree of liability which approaches strict liability. This variable is characterized by the following attributes:

(i) Degree of liability, which can vary betwen strict and limited liability.

(ii) Degree of indemnification of the owner, which can be narrow, intermediate, or broad.

(iii) Owner's responsibility in the information he provides.

Three levels of the variable will be used for analysis - high, nominal and low. The high unfavorable level corresponds to each of the attributes assuming its worst level. The low favorable level corresponds to each of the attributes assuming its best level. Finally, the nominal level corresponds to the attributes assuming different combinations of their levels.

5.3.7 Insurance Coverage Variable

A design professional's primary exposure with regard to liability claims is in the professional liability area, and it is in this area that architect-engineers pay the largest premium. Professional Liability insurance, also called malpractice or "Errors and Omissions" insurance, protects the designer for claims arising out of errors, omissions or negligent acts in the performance of his professional services. For many design firms, professional liability insurance coverage is now the largest single cost item after payroll. According to Bjarnason (1980:126), premium has increased from 1% on the fees of the design firm in the sixties, to 5% today. The premium can go up to 11% on some projects where the uncertainty is great such as tunnels.

Premium, however, is only a part of the total liability cost. As premiums have escalated, many design firms have raised their deductible limits, so that the deductible payouts now usually approach, equal or exceed the annual premiums. This means that a design firm which has several claims lodged against it in a single year can end up paying several times the amount of the premium, even if none of the claims are successful (because of the defense costs)!

According to O'Rourke (1978:142-143),

> "In the U.S., engineers increasingly have been subject to high cost-deductibles on insurance policies and named as either the defendant or third party in construction disputes. If insurance premiums are a rough measure of vulnerability, it's noteworthy that idemnity insurance for engineers is four to five times greater in the U.S. than in the U.K."

Even though insurance coverage does not directly influence the engineering technical decisions, it is influenced by the engineering firm's responsibility and in turn determines the insurance premium the firm has to pay. It is undoubtly a state variable representing the environment of the design since the amount of coverage an insurance company would be willing to provide, at a certain fee, is based not only on the engineering firm's past performance but also on the amount of risk inherent in the insured task. The breadth of insurance coverage that a firm of professionals can provide measures the extent of the project the firm can undertake and also the amount of litigation to be expected later on.

On the topic of liability and liability insurance, Sutcliffe (1979:40-41) gives an excellent description of the situation designers face,

> "There is a growing tendency on the part of owners to try and make the designer an insurer with unlimited liability for errors and omissions over and above a set insurance level. There are several reasons why this will not work and why it adds risk

to the project. A consulting engineer normally owns very little in the way of corporate assets - his assets are his skills and some office furniture. In a few cases, he is part of a much larger organization with substantial assets - assets developed from other than design work, but still vulnerable to litigation. The small organization is usually willing to offer unlimited liability over and above insurance amounts, but this is worthless to the owner-unless the owner is interested in collecting office furniture in lieu of cash. The larger organization is not about to expose its entire corporate assets on revenues from consulting ventures. Insurance and liability are usually for errors, but construction extras are potential litigation against the designer, since errors and extras can be read by some to mean the same thing.

The economics back this up. An engineer's design revenue under Federal regulations is normally limited to six percent of construction cost, or \$60 per thousand. The profit and risk fee portion of this is about \$5 per thousand dollars of construction cost, or 1/2 percent. How many projects, particularly underground projects, have been closed out with less than 1/2 percent of extras? Ten percent is the most common experience. For his \$5 per thousand, which is his fee and not an insurance allowance, the engineer is asked to take the risk of \$100 per thousand, or more, without limit. This is not enough to pay the premium, even if such additional insurance were available commercially, but the designer is expected to carry it. If an insurance company won't touch it, why should the designer be required to accept it? The knowledge of this liability breeds defensive designs and documents and adds to the risk. A designer should be required, and is willing to shoulder an equitable share of the risk commensurate with his potential for gain on the project. Liability over and above reasonable bounds is a hot potato which is being passed around between the parties and it should come to rest where it belongs, which is with the owner."

Hence, the level of coverage is an important element of consideration when technical decisions resulting in engineering designs are made.

5.3.8 Fee Structure Variable

The fee paid to a design firm typically covers the design cost plus a fixed fee with or without an upper limit, or it could be a lump sum figure. The fee is usually based on historical accounting records and on fees charged by other design firms on similar jobs. This fee, however, does not reflect the problems encountered in the implementation of the particular design on hand. The more restricted the engineer is, as far as the fee is concerned, the more reluctant he is to spend more time in searching for better alternatives. Given this situation the research team believed that the fee might influence the design technical decisions at least in a negative sense. According to Hammond (1979:134), thorough planning and complete engineering before the start of physical construction is seldom done adequately due to,

> "financial constraints either as funds available for planning and engineering or through misguided desires to hold planning and design costs to a formula minimum not always recognizing that this does not result in sufficiently thorough planning and engineering."

Biggs (1981:73), discusses the limitations of present fee structures and suggests new methods for determining engineering fees. He states that,

> "The problem with each method is the correlation between fees and construction costs. Lower construction costs mean lower fees, thus no financial incentive for engineers to create design solutions below estimated construction costs.
>
> A new more equitable method would encourage rather than discourage lower construction costs. The engineer's final fee should include three parts: (1) fixed fee, (2) percentage of the construction costs savings, and (3) percentage of the life-cycle (operational) cost savings."

Along the same lines, Fead (1980:93), adds that,

> "Another factor stifling innovation is the standard fee system for consultants. It will normally be faster (and thus cheaper) for a consultant to follow an establised, routine design procedure. Normally, standard fees do not provide sufficient funds to pay for the full evaluation of complex innovative alternatives. And under competitive bidding for design services, this situation will be even more likley to be aggravated. Politically, it would be all but impossible to rule a bidder incompetent because his work followed routine standard practice rather than innovative techniques. The lowest cost design will seldom lead to the lowest cost project. In fact, the total cost generally--within limits--will be an inverse function of the design cost."

CHAPTER 6

DEVELOPMENT OF HYPOTHESES, CAUSAL RELATIONSHIPS AND MODELING SENSITIVITY

In the previous chapter the non-technical variables affecting tunnel design and the levels they can assume were discussed. In this chapter the authors will develop hypotheses that relate those non-technical variables to engineering technical decisions.

6.1 INTRODUCTION

The authors' approach in this chapter includes:

a) discussion of the formulation of his descriptive model which relates the non-technical variables discussed in the previous chapter to engineering technical decisions discussed in Chapter 4;

b) development of hypotheses which includes the explanation of causal relationships between the significant non-technical variables and the engineering decisions;

c) discussion of how the model works;

d) verification of hypotheses which includes modeling sensitivity and discussion of results.

6.2 DESCRIPTIVE MODEL FORMULATION

Based on the case study and interviews described in Chapter 3, the authors hypothesized that engineering technical decisions are influenced by non-technical variables acting together with geotechnical variables. These non-technical variables, shown in Figure VI-1, are considered to be state variables from the point of view of the engineer. The owner, however, has the power to control some of them (such as design criteria, organizational setup, liability of the designer as represented in contract), and hence to him they represent decision variables. This is the justification for this research. These non-technical variables represent the state of the environment surrounding the engineer's decision on the selection of the structural support system, ground water control, and suggested excavation method. These non-technical variables have been identified and discussed in detail in Chapter 5. The influence of each non-technical variable on conservatism, or in detail, on the engineering technical decisions, are hypotheses that need to be proved in the context of risk allocation between owner and engineer. Formulation and testing of hypotheses will be presented in the following sections.

Formulation of hypotheses involves the discretization of the non-technical variables into levels, and the observation of the impact of changing the level of the non-technical variable on the technical decisions. The expected change when varying through these levels was hypothesized; these hypotheses were then confirmed or modified by the assessment of experts in the field.

The outcome of the designer's decisions needs to be evaluated in terms of costs to the owner. These decisions, under a given set of non-technical and geotechnical variables will subsequently influence the cost of construction, the cost of maintenance and the expected cost of failure resulting from the implementation of the design.

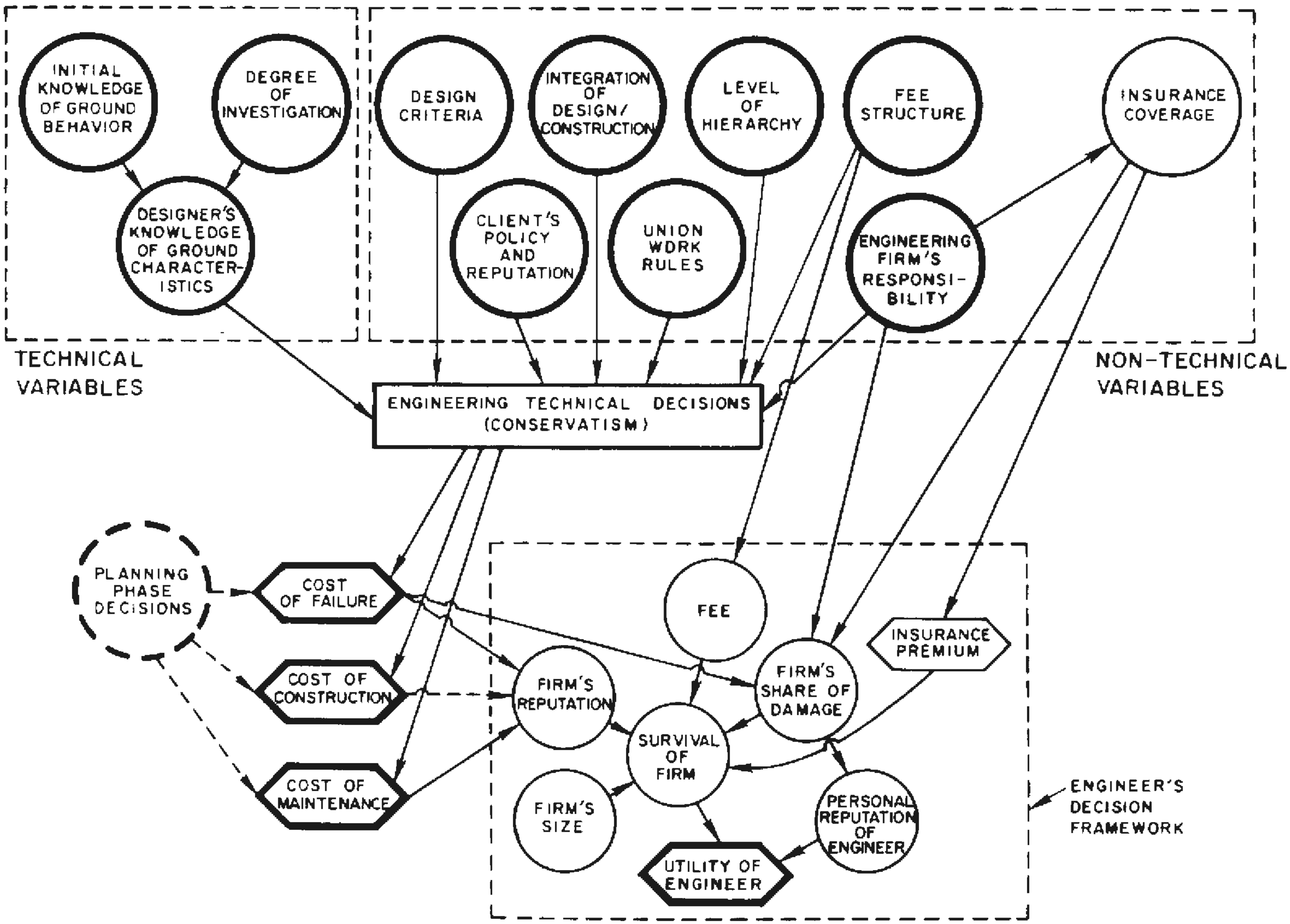

FIGURE VI-1

Designer's Model Showing Non-technical and Technical Variables, Engineering Technical Decisions, Elements of Cost and Engineer's Decision Framework

Chapter 7 presents these costs resulting from design decisions. These costs are also impacted by other variables which are decisions made in the planning phase (e.g., tunnel diameter, station size, horizontal and vertical alignment, etc.) or those set by government regulations. The examination of the effect of these variables, however, is not included in the scope of this study; they are taken as "givens".

The "owner's" objective is to maximize his utility which, in this case, is assumed to be proportional (inversely) to costs. To minimize costs the owner can manipulate these non-technical variables, which from his stand-point are decision variables. It should be noted that the owner being referred to is the federal government which finances up to 80% of many mass transit projects. It was indicated in Chapter 2, that the federal government's emphasis is on the control of construction costs whereas the concern of the local transit authority is probably to control maintenance costs. This difference in emphasis might lead, for example, to the incorporation of conservative designs (in terms of initial cost) due to the existance of water-tightness requirements specified by the local transit authority and consultants who are typically selected by the local authorities. These consultants, hence, may design for minimum maintenance costs, rather than minimum life cycle cost.

Whereas the owner's objective is the minimization of costs, the engineer, on the other hand, attempts to maximize his utility. This is represented in the "Engineer's Decision Framework" in Figure VI-1. The figure shows the three types of costs--construction, maintenance and failure. These influence the "design firm's reputation" in the industry which can be measured through different attributes such as the number of requests for proposals per year, the degree of alienation of old clients or percentage of repeat business. The "survival of a design firm" (a variable shown in the framework) is influenced by the firm's attainment of a certain level of reputation, which, unlike for contractors, is of paramount importance in its ability to generate new business. Moreover, the firm's continuity depends on whether it can handle "insurance premiums" which depend on the insurance coverage specified in the contract. The design "firm's share of potential damages" resulting from failures is compensated for in part by insurance coverage and by the responsibility terms specified in the contract. Any kind of failure will also reflect adversely on the reputation of the engineer decision-maker. His "personal reputation" is a function of the following, among other variables:

a) the level and rate of change in his salary, and his rate of promotion within his firm;
b) the positive and negative citations he receives from his supervisors, and his peers within and outside his firm;
c) whether he is being sued for deficiencies in his designs which might lead to disbarring him from professional practice.

For the purposes of this research it was unnecessary to quantify the "engineer's utility". Although the attributes which are the utility constituents can be quantified. The authors' objective is to predict the engineer's design decisions, assuming only that he acts to maximize utility. Therefore, what is only needed to know is whether a variable correlates positively or negatively with the engineer's utility, in order to predict how it will effect which design decision he will make.

For the owner, it is assumed that his utility is maximized for this set of decisions by minimizing the costs associated with design decisions. These include initial capital cost, and the expected costs of future maintenance, and structural failures. Since maximising owner's utility is the objective of this research, these costs will, therefore, be quantified in the next chapter.

6.3 DEVELOPING CAUSAL RELATIONSHIPS: DEVELOPMENT OF HYPOTHESES

The purpose of this section is to extend the work already done by the research team to date, by developing causal models of the influence between the significant non-technical variables and the engineering technical decisions. The model, as represented up to this point (Figure VI-1), is empirical and provides a framework for further analysis presented in the next sections.

It should be pointed out, that decision analysis is not used here as a prescriptive tool but rather as a descriptive tool. The aim is not to prescribe how designers should make their decisions, but rather to understand the decision making process, the relevant variables and their interrelations, and thus to look for ways to improve the outcome, which is the cost to the public, without making the participants worse off, i.e., by reaching a "Pareto optimal" solution, in economists' parlance.

6.3.1 Relationship Between Costs and Engineer's Utility

The influence diagram shown in Figure VI-2 portrays the different variables affecting this problem. The authors' basic assumption is that all paths from "level of conservatism", which is defined by the designer's technical decisions, to "engineer's utility" are positive - i.e., more conservatism will increase the engineer's utility. Level of conservatism is associated with a set of technical decisions discussed in Chapter 4. Another basic assumption is that those technical decisions are influenced by non-technical variables discussed in Chapter 5, in addition to the existing geotechnical conditions.

By looking at Figure VI-2 and Table VI-1 it can be seen that an increase in the level of conservatism due to a change in the non-technical state variables (i.e., setting any one of them at its worst extreme) would lead to:

1) Decreases in the expected "cost of failure" and "cost of maintenance" because of the use, for example, of a double support system, thicker linings and other considerations.
2) The decrease in both these types of costs is negatively correlated with the "firm's reputation," i.e., it will increase.
3) The expected "cost of failure" is positively correlated with the "firm's share of damage," i.e., the latter variable will decrease upon a decrease in the expected "cost of failure."
4) The decrease in the "firm's share of damage" is

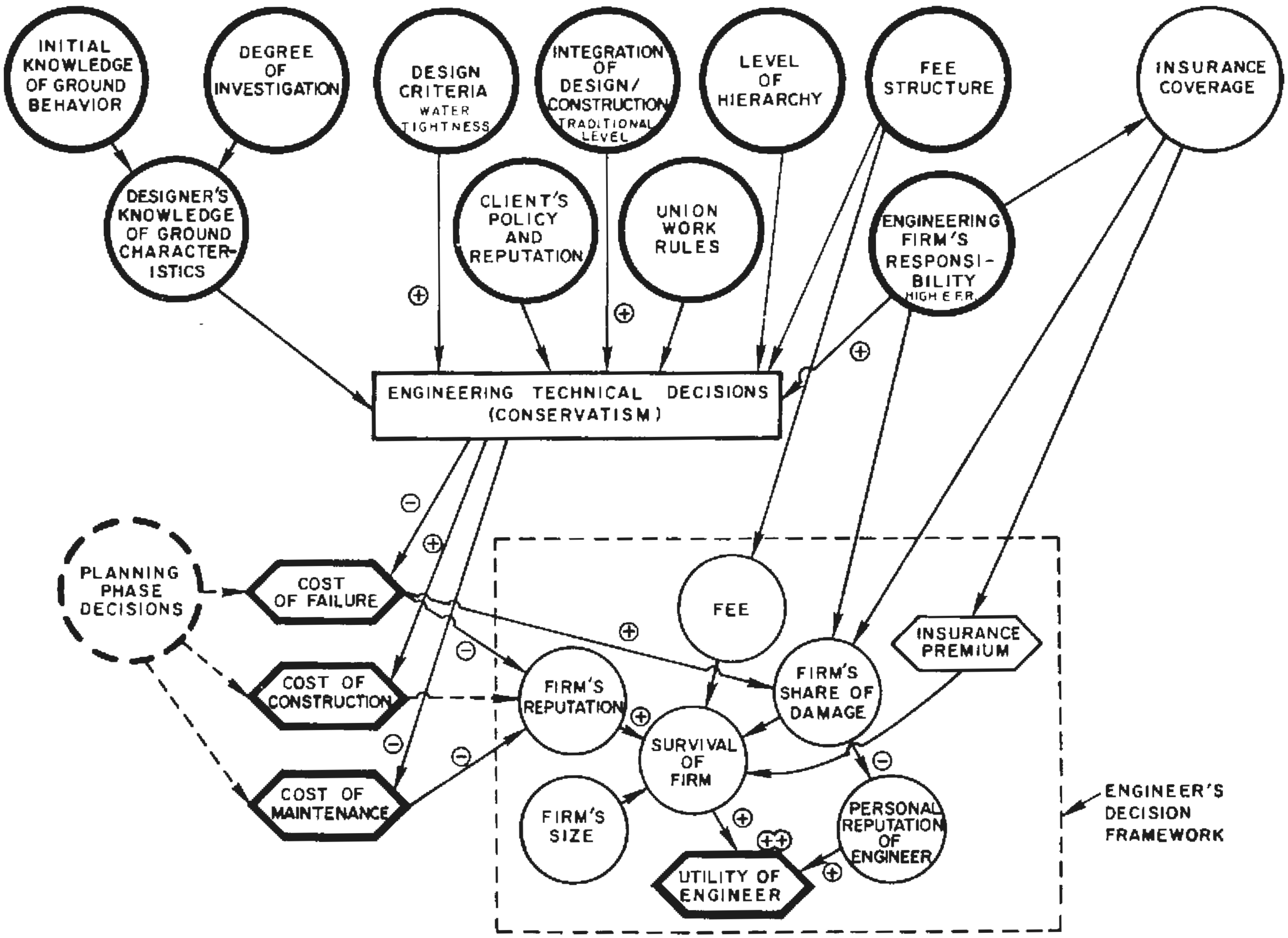

FIGURE VI-2
Designer's Model Showing Correlation between Changes in Non-technical Variables and Utility of Engineer

Correlation between costs of failure and maintenance to engineer's utility.

Variable	Precedence	Correlation
"Level of Conservatism"	Non-Technical Variables	+
"Cost of Failure"	"Level of Conservatism"	-
"Cost of Maintenance"	"Level of Conservatism"	-
"Firm's Reputation"	"Cost of Failure," "Cost of Construction"	-,-
"Firm's Share of Damage"	"Cost of Failure"	+
"Survival of Firm"	"Firm's Reputation," "Firm's Share of Damage"	+,-
"Personal Reputation of Engineer"	"Firm's Share of Damage"	-
"Utility of Engineer"	"Survival of Firm," "Personal Reputation"	+,+

Correlation Matrix

	"Level of Conser-vatism"	"Cost of Fail-ure"	"Cost of Main-tenance"	"Firm's Repu-tation"	"Firm's Share of Damage"	"Survi-val of Firm"	"Personal Repu-tation"
"Level of Conservatism"							
"Cost of Failure"	-						
"Cost of Maintenance"	-						
"Firm's Reputation"		-	-				
"Firm's Share"		+					
"Survival of Firm"				+	-		
"Personal Reputation"					-		
"Utility of Engineer"						+	+

TABLE VI-1

negatively correlated with "survival of firm" and "personal reputation of engineer" variables. That is, both would increase.

5) "Survival of firm" is positively correlated to "firm's reputation" which in this case has increased due to a decrease in the above costs. Therefore, "survival of firm" would increase.

6) Ultimately both "survival of firm" and "personal reputation of engineer" are positively correlated with the "utility of the engineer". The utility in this case is increased and reinforced through two positive paths from "survival of firm" and "personal reputation" as the correlation matrix in Table VI-1 shows.

Through the direction of correlations, it can be seen that an increase in the level of conservatism would lead to increasing the engineer's utility. The only mechanism which could provide a check and balance is that of the increase in "cost of construction" due to an increase in the "level of conservatism". Having thicker linings, or redundant support would lead to increased construction costs. This increase in "cost of construction" is negatively correlated to the "firm's reputation". The decrease in the "firm's reputation" is the counter balance that should maximize the decision-maker's utility when a cost effective design is implemented. This check provides for balanced engineering designs in facilities such as commercial buildings. However, its effect may be diluted in subway design due to the lack of comparability between different tunnels. Hence the link between "cost of construction" and "firm's reputation" is weak in tunnel design, and is shown as a dashed link in Figures VI-1, VI-2.

Hence, designers may not pay any price for over-designing. Thus, it becomes the easy, quick solution. Designers' "status" motives (see Chapter 2) govern their behavior due to the reinforcement of their current assessment and reward system. This system does not incorporate design economy as a criterion for assessment of tunnel designs due to the unavailability of an accurate budgeting system. Hence, excessive conservatism has no negative bearing on the designer's incentives, at the same time that it has a strong positive bearing on their incentives since a failure would have disastrous effects on their reputation.

6.3.2 Causal Relationships Between Non-Technical Variables and Design Decisions

Consider the three variables found to be the most important in influencing the designer's technical decisions (see Chapters 3 and 5). These are:

1) "Integration of Design and Construction";
2) "Design Criteria";
3) "Engineering Firm's Responsibility";

The three variables are shaded in Figure VI-3. The authors' purpose is to explain the links between those variables and the engineering technical decisions. The links are schematically shown as arrows on the influence diagram.

Designers, the authors hypothesized, made decisions that were impacted by the above variables. Causality to them was implicit. The

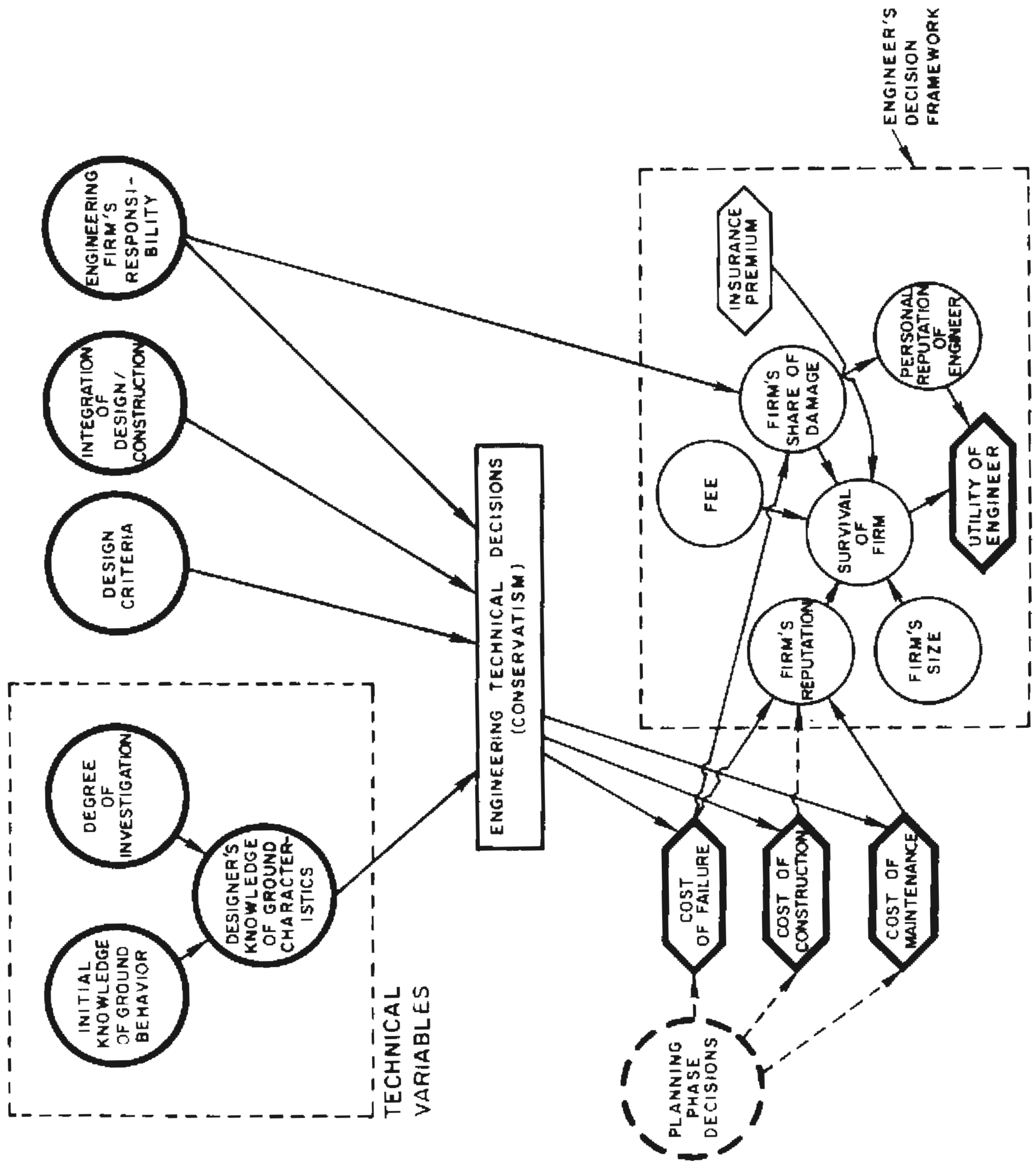

FIGURE VI-3

The Most Important Non-technical Variables Influencing the Designer's Technical Decisions authors' task was to rationalize and explain the causality in terms of:

a) the risks and uncertainties imposed on the designer by the non-technical variables;

b) changes in the levels of these non-technical variables which lead to changes in the levels of uncertainties imposed on the designer;

c) this change in uncertainty perceived by the designer which would lead to changes in design decisions, as will be shown in the following sections.

This procedure and the results of the following analysis have been verified to be correct by designers interviewed and the authors' "sample expert", Mr. Harry Sutcliffe.

Consider the variable "Integration of Design and Construction" and its impact on the design decisions. Figure VI-4 shows how this variable is broken down into two elements:

1. Level of uncertainty about construction method, contractor skill and integrity; and
2. Degree of job supervision the designer has over construction operations.

Figure VI-4 shows how these two element lead to the following uncertainties as perceived by the designer:

a) Level of uncertainty about schedule of project which is a function of construction methods

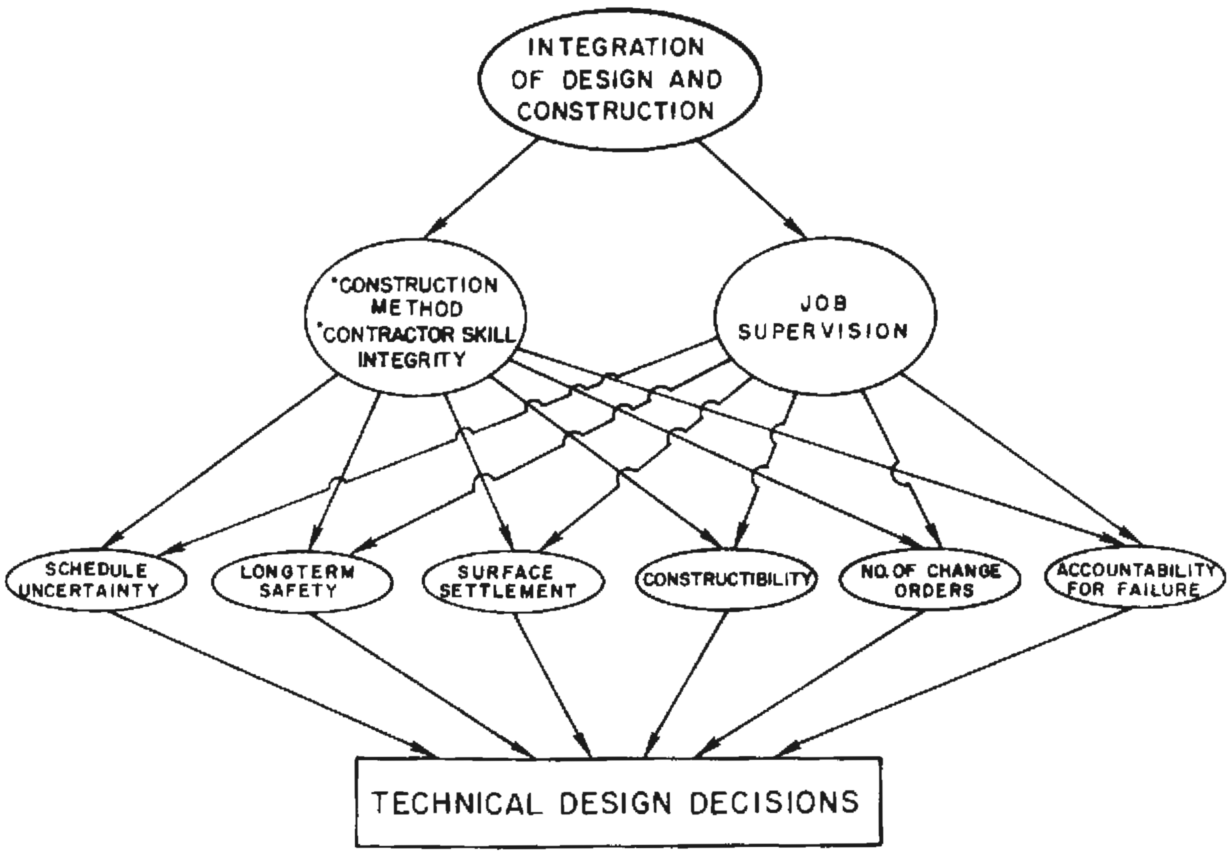

FIGURE VI-4

Causal Relationships--"Integration of Design and Construction" Variable used, contractor's skill and experience, contractor's access to the designer and designer's control over construction. It is evident that this level of uncertainty would vary between the two extreme levels of the variable "Integration of Design and Construction" - i.e., the U.S. traditional approach level and the design/construct level.

b) Level of uncertainty about long term structural safety of the tunnel. This uncertainty relates again to construction methods, contractor's skill and adherence to design specifications. The designer would ensure that the contractor would conform to these specifications through direct supervision.

c) Level of uncertainty about surface settlement due to the use by the contractor of inadequate support or his deviation from design specifications.

d) Level of uncertainty about constructibility or implementation of the engineer's design by the contractor. The engineer fears that introducing new design methods might not be implemented due to the contractor's lack of experience and skill compounded by the designer's lack of supervision authority. This is one of the reasons why designers have been reluctant to use shotcrete systems as final tunnel support.

e) Level of uncertainty about number of change orders resulting from the contractor's inability to implement a new design and designer's lack of supervision authority. As the number of change orders increases the designer's reputation is affected adversely and the designer may even be sued for severe, costly changes.

f) Level of uncertainty about tracing the causes of failure resulting from contractor's methods or engineer's design. Accountability for causes of failure and the responsible party is not readily identified when separation of design and construction operations exists. The legal process to identify blame proves to be very costly and time-consuming.

The designed system is one which minimizes the impact of the above uncertainties. What the authors are saying, therefore, is that a different or changed level of the non-technical state variable would lead to changing the perceived uncertainties and hence impacting the design decisions differently. This is comparable to a situation where changes in perceived ground conditions would lead to different designs.

For illustration, consider that the variable "Integration of Design and Construction" is shifted from its high traditional level to its low design-construct level. Then observe the change in the level of the different uncertainties mentioned previously. Assuming levels of uncertainty approaching unity for the high traditional level, then the corresponding uncertainty levels for the low design-construct case will be significantly reduced or eliminated completely. Table VI-2 shows this relation.

In other words, if the level of uncertainty about contractor's skill, construction method, job supervision, schedule, long term safety, settlement, constructibility, number of change orders, and accountability for causes of failure is very high for the traditional high level of the variable, then consequently by using a design-construct low level of the variable, these uncertainties will be reduced. This drastic change in the level of uncertainty is the causal mechanism that explains the influence of the non-technical state variable on the engineer's technical decisions.

Two points need to be mentioned here:

1. The authors have been looking at the correlation between the uncertainty elements in Figure VI-4 and the low and high levels of the non-technical variable. This does not imply that these uncertainty elements are uncorrelated to each other. For example, schedule uncertainty could be correlated to the constructibility and/or the surface settlement elements. However, the authors' concern is to focus on the vertical correlation of these uncertainty elements to the levels of the non-technical variable. The authors acknowledge the existance of horizontal correlation and its contribution to uncertainty; this would amplify the effect of "Integration of Design and Construction" on the engineering design decisions.

2. When using the nominal joint venture ("design-manage") level of

INTEGRATION OF DESIGN AND CONSTRUCTION

	UNCERTAINTIES							
	Schedule	Long Term Safety	Surface Settlement	Construc-tibility	Number of Change Orders	Accoun-tability for Failure	Supervision	Contractor's Skill & Experience
High Level Traditional Approach (Worst)	100	100	100	100	100	100	100	100
Low Level Design-Const. Approach (Best)	Reduced	Reduced	Reduced	Reduced	Reduced	Reduced	Reduced	Reduced

TABLE VI-2. Uncertainty Reduction Due to Change in Level of Non-Technical Variable the "Integration of Design and Construction" variable, some uncertainties will be decreased while others will remain the same. For example, the level of uncertainty about the constructibility of the engineer's design will be reduced due to the fact that one member of the joint venture ("design-manage") team is a construction manager injecting construction experience and know-how into the design. On the other hand, the level of uncertainty about number of change orders, schedule, failure tracking and others will not be reduced unless the project organization is set so that the construction manager and the design team have complete supervision authority over contractors. This was the case with the "Bay Area Transit Authority" development.

Consider the variable "Design Criteria". This variable has been discussed in Chapter 5. The focus here is on the causality between this variable and the technical design decisions. Looking at Figure VI-5 it can be seen that the "Design Criteria" variable branches into two components:

a) "water tightness requirements";

b) "unbalanced loading requirements".

The "water tightness requirements" component influences the variable "water head build-up". This variable is considered by the engineer in figuring design loads and moments as well as composition of chemicals used in grouting. Similarly "unbalanced loading requirements" influence the choice of design loads and moments. Water leakage and

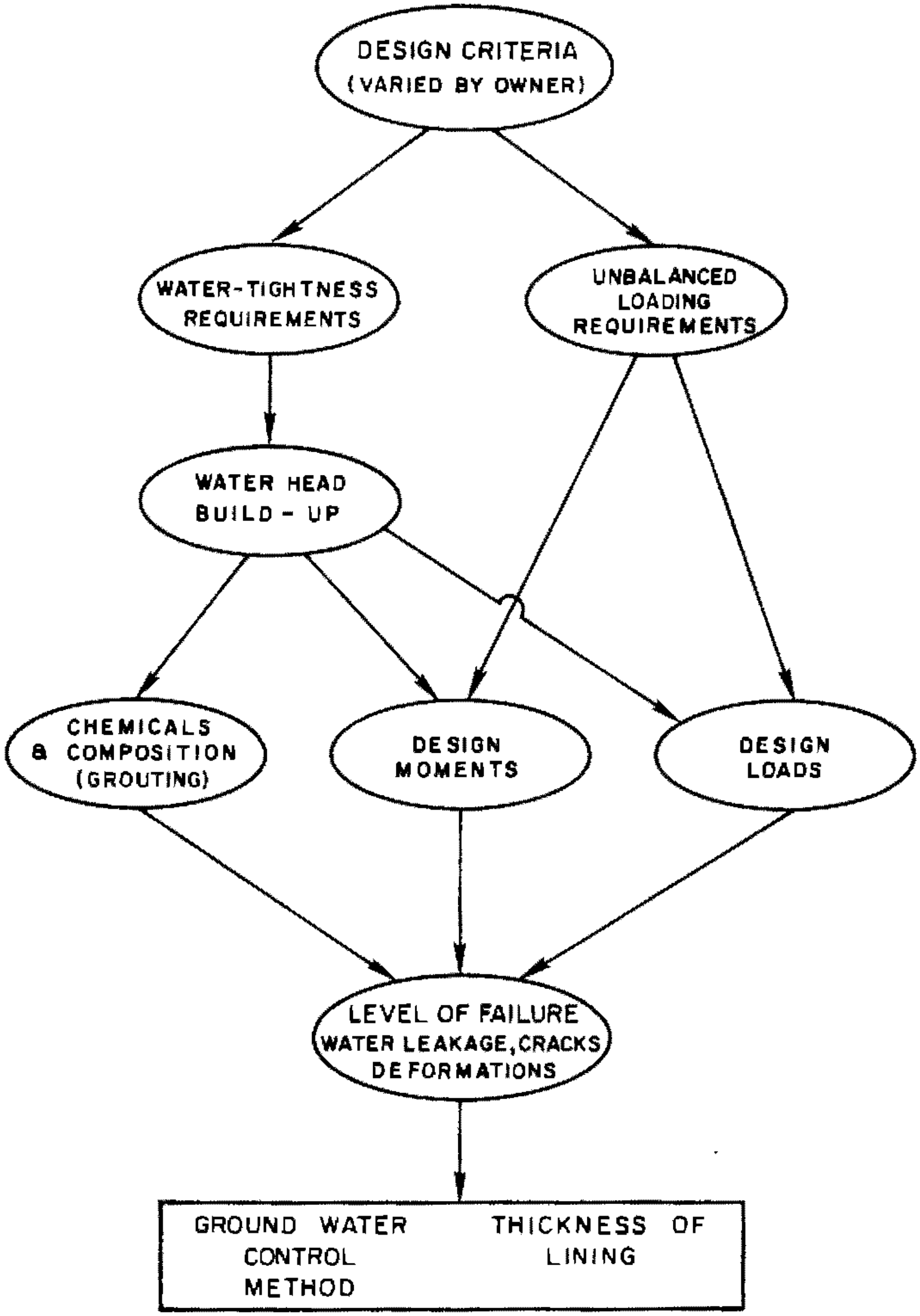

FIGURE VI-5

Causal Relationships--"Design Criteria" Variable cracks in the tunnel are measures of failure considered by the owner and designer. The authors' argument is that the level of failure characterized by water leakage and cracks is determined by the above variables which are a function of the level of the "Design Criteria" variable. Changes in this level of failure due to changes in the level of "Design Criteria" are the reasons behind changes in engineering technical decisions. For example, a strict set of design criteria would imply increased resisting moments and loads to attain a level of performance with no water leakage. Similarly a strict set of design criteria would imply increased resisting moments and loads to counter unbalanced loading conditions and hence maintain a level of performance with no deformations or deflections. This attainment of this level of performance translates into thicker linings, more reinforcement and use of reinforced concrete support as a ground water control method.

Finally, consider the variable "Engineering Firm's Responsibility". The variable is shown in Figure VI-6 and has three elements that contribute to the liability of the engineer. These are:

1) Degree of liability which approaches strict liability for the variable's high level, and which is limited for the low level. The degree of liability includes insurance coverage which is unlimited for the variable's high level. For the low level the owner assumes part of the burden of insurance, by self insurance, or an umbrella insurance policy.
2) Degree of indemnification which is broad for the

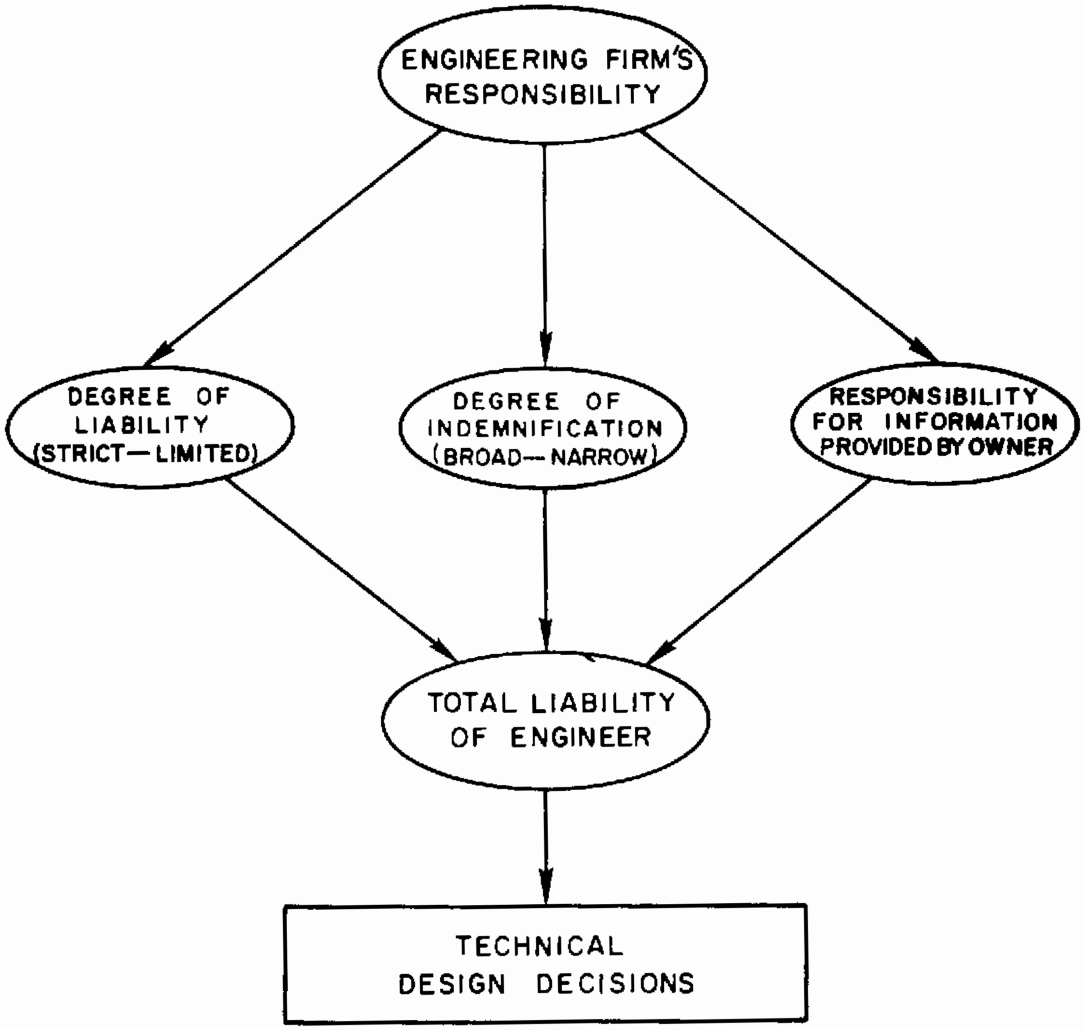

FIGURE VI-6

Causal Relationships--"Engineering Firm's Responsibility" Variable

variable's high level, and narrow for the low level.

3) Responsibility of the owner for the information he provides to the engineer. For the high level the owner is not responsible for the accuracy of information, whereas he assumes responsibility for the low level.

These three variables contribute to the total liability of the engineer. Simply stated, as the level of the variable, "Engineering Firm's Responsibility" is shifted between its two extremes the liability of the engineer changes. Total liability decreases from the high to the low level of the variable. This decrease in liability is the causal mechanism which explains the influence of the non-technical variable on technical design decisions.

6.4 HOW DOES THE MODEL WORK?

The authors' model attempts to capture and rationalize the engineering thinking process. The model does not forecast the exact type of technical decisions made by the designer. These are judgemental and depend on the designer's experience. However, the model does predict changes in the authors' technical decisions due to changes in the non-technical environment. The designer considers the non-technical or institutional variables implicitly in the designer's decision making. The authors tried to show that the designer's decisions reflect the risks or liabilities transferred to him through these variables.

Given geotechnical and institutional scenarios, the authors' model predicts that the decision making process follows this reasoning:

1) the designer's engineering decisions incorporate the influence of geology as well as the risks stemming from institutional or non-technical variables;

2) as geological conditions deteriorate, the design reflects methods that eliminate the uncertainty associated with bad ground conditions such as double support systems, and reinforced concrete linings to fight heavy water inflow. The influence of the non-technical variables on his decisions is reduced because of the bad geology. However, the authors maintain that unfavorable non-technical variables would still influence the design in the form of thicker linings or heavier steel sets as will be shown in the next section;

3) as geological conditions improve the design reflects a reaction to the uncertainty imposed by the non-technical variables rather than actual ground conditions.

4) any one of the most important non-technical variables is capable of influencing the design decisions negatively. Having two variables set at their favorable levels while leaving the third at its unfavorable level does not necessarily

result in improved design decisions (see next section).

In short, the authors attempted to verify the reasoning behind the model and the type of results they expected. This was accomplished through the use of interviews and finally through a structured sensitivity analysis conducted with our "representative expert," Mr. Harry Sutcliffe. The authors have used Mr. Harry Sutcliffe to test changes of design decisions due to changes in institutional variables. The research team is mainly concerned with proving the hypothesis that establishes causal relationships between institutional variables and technical design decisions. The research team is not concerned with whether the expert's decisions are right or wrong under the given conditions, but rather that he perceives the causality between his decisions and changes in those state variables. Nevertheless, the thrust of Mr. Sutcliffe's opinions regarding these causal relationships and the research team's conclusions based upon them, are broadly supported by other designers' published opinions in existing literature, and those expressed in some twenty separate interviews during the course of the research [see Appendix (A)].

6.5 MODELING SENSITIVITY

The authors' modeling sensitivity followed these steps:

a) Changes in the engineering design decisions (i.e., temporary support, final support, excavation method, ground water control) for a change in the levels of each of the non-technical variables were tested for given geotechnical scenarios. This procedure has been discussed in Chapter 3.

b) Changes in the engineering design decisions were also tested for simultaneous change in the levels of pairs as well as triples of the non-technical variables.

The purpose of the test was to show that engineering design decisions are influenced by non-technical variables. Test results are presented next.

6.5.1 Sensitivity Analysis Results

The key to tables VI-3 explains the geotechnical scenario, the non-technical (institutional) variables and the design options available to the designer which are used in the structured sensitivity analysis. Tables VI-3a to VI-3h show the results of the authors' sensitivity analysis. The following is a discussion of each of the mentioned tables:

- Table VI-3a: indicates a geotechnical scenario of extensive investigation with uniform high RQD and low water infiltration. This scenario represents a favorable, known geotechnical situation. Placing the three non-technical variables at their nominal (N) levels yields a rockbolt system for temporary support, an 8 inch reinforced concrete lining, and a drill and blast excavation method (see case 1). Changes are noticed when sweeping one of the variables through its two extreme levels

KEY TO TABLE VI-3 (VI-3a - VI-3h)

Given Scenario

(a) Urban Environment (b) 50ft. - 100ft. Depth (c) One Mile Long Transit Tunnel (d) 20ft. Diameter Round Tunnel

(1) Quality of rock expressed in RQD

(2) Water infiltration level low / high

(3) Amount of subsurface investigation, which is a measure that captures the variability in the quality of the rock. (Uniformity in quality of rock.)

All three combined in:

Little or Minimum Investigation		Extensive Investigation	
(a) Average Low RQD	low water infiltration	(a) Uniform High	low water infiltration
(b) Average High RQD	high water infiltration	(b) Mixed Phase	
		(c) Uniform Low	high water infiltration

Non-Technical Variables*

	MOST SIGNIFICANT NON-TECHNICAL VARIABLES		
Level of Variable	"Integration of Design & Construction"	"Design Criteria"	"Engineering Firm's Responsibility"
Worst (W)	Traditional	Strict	High
Nominal (N)	Joint Venture	Medium	Medium
Best (B)	Design Construct	Loose	Low

* For more detail on these variables and their different levels, refer to Chapter 5.

TEMPORARY SUPPORT	FINAL SUPPORT	EXCAVATION METHOD	DURING & AFTER G.W. CONTROL
(1) Unreinforced	(1) Unreinforced	(1) Drill & Blast	(1) Pumping
(2) Rock Bolts	(2) Shotcrete	(2) TBM	(2) Concrete lining in upper arch
(3) Rock Bolts/ Shotcrete	(3) Concrete lining min. thickness: (a) 6in. (b) 8in. (c) 12in.		(3) Concrete lining complete
(4) Segmental	(4) Reinforced concrete lining min. thickness: (a) 8in. (b) 12in. (c) 14in.		
(5) Ribbed system			

Thicknesses are not a function of structural considerations, but construction tolerances

Minimum Structural Thickness

+

Tolerance

+

Steel Ribs (if used)

TABLE VI - 3a*

SENSITIVITY ANALYSIS SHOWING THE EFFECT OF NON-TECHNICAL VARIABLES ON DESIGN DECISIONS

- Extensive Investigation (Uniform High RQD)
- Low Water Infiltration

CASE #	NON-TECHNICAL VARIABLES			TEMPORARY SUPPORT	FINAL SUPPORT	EXCAVATION METHOD	GROUND WATER CONTROL
	"Integrat. of Design&Const"	"Design Criteria"	"Engin. Firm Responsib."				
1	N	N	N	2	4a	1	1
2	W	N	N	2	4b	1	1
3	B	N	N	2	4a Upper Arch	1	1
4	N	W	N	2	4b	1	1
5	N	B	N	2	4a Upper Arch	1	1
6	N	N	W	2	4b	1	1
7	N	N	B	2	4a Upper Arch	1	1
8	B	W	B	2	2 or 4a Upper Arch	1	1
9	W	B	B	1 or 2	2	1	1
10	B	B	W	2	4a Upper Arch	1	1
11	B	B	B	1	2	1	1

* Refer to key at beginning of this set of tables.

[i.e., from worst (W) to best (B)], while keeping the other two at their nominal (N) levels. This situtation is represented in cases 2 through 7. A change from an 8 inch reinforced concrete final lining in the upper arch for the best level to a 12 inch reinforced concrete lining for the worst level, is noticed. Keeping two of the variables at their best (B) levels and the third at its worst (W) level yields a rockbolt system for temporary support and an 8 inch reinforced concrete final lining in the upper arch (cases 8 and 10). An exception to these cases is case 9 where "design criteria" and "engineering firm's responsibility" variables are set at their best (B) levels while setting "integration of design and construction" variable at its worst (W) level. Case 9 yields an unreinforced or rockbolted tunnel for initial support and a shotcreted final lining. The significance of case 9 is that in favorable ground conditions the designer is willing to introduce cost saving designs, regardless of who the contractor is, if the owner assumes the consequences of risks of failure and liability. Case 11 shows the most significant change which occurs when the three variables are placed at their best (B) levels. This leads to an unreinforced tunnel for temporary support and a shotcrete final lining. Resulting savings are discussed in the next chapter.

- Table VI-3b: indicates a geotechnical scenario of extensive investigation with uniform high RQD and high water infiltration. This scenario represents a less favorable geotechnical situation than the preceding one because of the water infiltration problem.

TABLE VI - 3b*

SENSITIVITY ANALYSIS SHOWING THE EFFECT OF NON-TECHNICAL VARIABLES ON DESIGN DECISIONS

- Extensive Investigation (Uniform High RQD)
- High Water Infiltration

CASE #	NON-TECHNICAL VARIABLES			TEMPORARY SUPPORT	FINAL SUPPORT	EXCAVATION METHOD	GROUND WATER CONTROL
	"Integrat. of Design&Const"	"Design Criteria"	"Engin. Firm Responsib."				
1	N	N	N	2	4a	1	1
2	W	N	N	2	4a	1	1
3	B	N	N	1	4a	1	1
4	N	W	N	3	4b	1	1
5	N	B	N	1	4a	1	1
6	N	N	W	2	4b	1	1
7	N	N	B	1	4a	1	1
8	B	W	B	2	4a	1	1
9	W	B	B	2	4a	1	1
10	B	B	W	2	4b	1	1
11	B	B	B	1	4a	1	1

* Refer to key at beginning of this set of tables.

Case 1, where the three variables are set at their nominal (N) levels, yields a rockbolt system for temporary support, an 8 inch final reinforced concrete lining and a drill and blast excavation method. During construction, water control is performed through pumping and grouting. As in the previous case changes are noticed when sweeping one of the variables through its two extreme levels [i.e., from worst (W) to best (B)], while keeping the other two at their nominal (N) levels. This situation is represented in cases 2 through 7. Setting each of the three variables at its best (B) level while keeping the other two at their nominal (N) levels yields an unreinforced tunnel for temporary support and an 8 inch final reinforced concrete lining. However, setting one of the variables at its worst (W) level while keeping the other two at their nominal (N) levels yields:

- a rockbolt system for temporary support and an 8 inch reinforced concrete final lining for "Integration of Design and Construction" variable;
- a rockbolt system for temporary support and a 12 inch reinforced concrete final lining for "Engineering Firm's Responsibility" variable;
- and a rockbolt/shotcrete system for temporary support and 12 inch reinforced concrete final lining for "Design Criteria" variable.

The impact of using a rigid and strict design criteria (i.e., worst (W) level) is reflected in the use of shotcrete in temporary support. Moreover, the impact of increasing the liability of the firm is reflected in thicker linings. Cases 8, 9 and 10 show the situation when one of the variables is set at its worst (W) level while the other two are set at their best (B) levels. These caes will yield a rockbolt system for temporary support and an 8 inch reinforced concrete final lining, except when "engineering firm's responsibility" is set at its worst (W) level a 12 inch lining is used. Of interest to the authors is the fact that when strict, rigid design criteria exist while the other variables are set at their favorable levels a rockbolt system is used for temporary support rather than the rockbolt/shotcrete system used previously in case 6. The designer takes the risk of water leakage failure in this situation because the owner assumes that risk. Case 11 is one where all the variables are set at their best (B) levels. An unreinforced tunnel for temporary support and an 8 inch concrete lining is obtained. Because of the presence of bad water conditions the designer resorts to a reinforced concrete lining in all the non-technical variables cases.

- Table VI-3c: indicates a geotechnical scenario of extensive investigation with rock of mixed quality along the length of the tunnel and low water infiltration. For rock with bad quality the designer uses a steel ribbed system for temporary support and a final reinforced concrete lining. Steelribs are adaptable to various ground conditions. This system can be effective and economical when provisions are made to adjust the size and spacing of ribs on the basis of field observation in contrast to rigid designs based on conservative interpretation of geological studies, which can be wasteful. While they still find their

TABLE VI - 3c*

SENSITIVITY ANALYSIS SHOWING THE EFFECT OF NON-TECHNICAL VARIABLES ON DESIGN DECISIONS

- Extensive Investigation (Mixed Phase)
- Low Water Infiltration

CASE #	NON-TECHNICAL VARIABLES			TEMPORARY SUPPORT	FINAL SUPPORT	EXCAVATION METHOD	GROUND WATER CONTROL
	"Integrat. of Design&Const"	"Design Criteria"	"Engin. Firm Responsib."				
1	N	N	N	2 or 5 3 or 5	4a	1	1
2	W	N	N	3 or 5	4b	1	1
3	B	N	N	2 or 5	4b	1	1
4	N	W	N	3 or 5	4b	1	1
5	N	B	N	2 or 5	4b	1	1
6	N	N	W	3 or 5	4b	1	1
7	N	N	B	2 or 5	4b	1	1
8	B	W	B	3 or 5	4b	1	1
9	W	B	B	2 or 5	4b	1	1
10	B	B	W	3 or 5	4a	1	1
11	B	B	B	2 or 5	4a	1	1

* Refer to key at beginning of this set of tables.

application in poor rock conditions, their use today, especially in Europe tends to be reduced in favor of rockbolts and shotcrete. When rock is of good quality the designer uses a rockbolt or a rockbolt/shotcrete system for temporary support and a final reinforced concrete lining. Changes from a rock/bolt system to a rockbolt/shotcrete system depend on the levels of the non-technical variables as can be seen in the table.

- Table VI-3d: indicates a geotechnical scenario of extensive investigation with rock of mixed quality along the length of the tunnel and high water infiltration. In this scenario the designer finds himself constrained in his decision making by ground and water conditions. In other words, these geotechnical conditions dominate the influence of changes in the non-technical variables' levels on design decisions. The designer typically chooses a steel set system for temporary support and a final reinforced concrete system. The authors' expert suggested that a rockbolt/shotcrete system could be used for temporary support but the trend is towards using steel sets in U. S. practice. One deviation occurs in case 6 where a 14 inch reinforced concrete lining is used rather than a 12 inch lining, because "design criteria" is set at its worst (W) level while the other two are kept at their nominal (N) levels. This reflects the impact of the "design criteria" variable on the designer's decisions regarding choice and thickness of support.

- Table VI-3e: indicates a geotechnical scenario of extensive

TABLE VI - 3d*

SENSITIVITY ANALYSIS SHOWING THE EFFECT OF NON-TECHNICAL VARIABLES ON DESIGN DECISIONS

- Extensive Investigation (Mixed Phase)
- High Water Infiltration

CASE #	NON-TECHNICAL VARIABLES			TEMPORARY SUPPORT	FINAL SUPPORT	EXCAVATION METHOD	GROUND WATER CONTROL
	"Integrat. of Design & Const"	"Design Criteria"	"Engin. Firm Responsib."				
1	N	N	N	3 or 5	4b	1	1
2	W	N	N	3 or 5	4b	1	1
3	B	N	N	3 or 5	4b	1	1
4	N	W	N	3 or 5	4c	1	1
5	N	B	N	3 or 5	4b	1	1
6	N	N	W	3 or 5	4b	1	1
7	N	N	B	3 or 5	4b	1	1
8	B	W	B	3 or 5	4b	1	1
9	W	B	B	3 or 5	4b	1	1
10	B	B	W	3 or 5	4b	1	1
11	B	B	B	3 or 5	4b	1	1

* Refer to key at beginning of this set of tables.

TABLE VI - 3e*

SENSITIVITY ANALYSIS SHOWING THE EFFECT OF NON-TECHNICAL VARIABLES ON DESIGN DECISIONS

- Extensive Investigation (Uniform Low RQD)
- Low Water Infiltration

CASE #	NON-TECHNICAL VARIABLES			TEMPORARY SUPPORT	FINAL SUPPORT	EXCAVATION METHOD	GROUND WATER CONTROL
	"Integrat. of Design&Const"	"Design Criteria"	"Engin. Firm Responsib."				
1	N	N	N	2 or 5	4b	1	1
2	W	N	N	3 or 5	4c	1	1
3	B	N	N	2 or 5	4b	1	1
4	N	W	N	3 or 5	4c	1	1
5	N	B	N	2 or 5	4b	1	1
6	N	N	W	3 or 5	4c	1	1
7	N	N	B	2 or 5	4b	1	1
8	B	W	B	2 or 5	4b	1	1
9	W	B	B	2 or 5	4b	1	1
10	B	B	W	3 or 5	4c	1	1
11	B	B	B	2 or 5	4b	1	1

* Refer to key at beginning of this set of tables.

investigation with uniform low RQD and low water infiltration. Again, ground conditions dominate and the corresponding temporary support is steel sets with a final reinforced concrete lining. Changes in the non-technical variables levels would only lead to changes in the thickness of the final lining. Changes from a rockbolt system to a rockbolt/shotcrete system occur for changes in the non-technical variables. But the expert mentioned, the use of these as temporary systems for such ground conditions is not the practice in U. S. tunnel design.

- Table VI-3f: indicates a geotechnical scenario of extensive investigation with uniform low RQD and high water infiltration. This is another example of the dominance of ground and water conditions over the non-technical variables. Mainly, steel sets are used for temporary support and reinforced concrete linings for final suppport. The only changes occur in the thickness of the final lining for changes in the non-technical variables.

- Table VI-3g: indicates a geotechnical scenario of minimum investigation and predicted favorable ground conditions (average high RQD). Under such a scenario the designer would resort to a rockbolt system for temporary support, and a reinforced concrete lining for final support. Changes in the levels of the non-technical variables are reflected in changes in the thickness of the concrete lining. Of interest to the reader are cases 9 and 11. In case 9 the designer is willing to substitute the concrete lining in favor of shotcrete. This occurs for the worst

TABLE VI - 3f*

SENSITIVITY ANALYSIS SHOWING THE EFFECT OF NON-TECHNICAL VARIABLES ON DESIGN DECISIONS

- Extensive Investigation (Uniform Low RQD)
- High Water Infiltration

CASE #	NON-TECHNICAL VARIABLES			TEMPORARY SUPPORT	FINAL SUPPORT	EXCAVATION METHOD	GROUND WATER CONTROL
	"Integrat. of Design&Const"	"Design Criteria"	"Engin. Firm Responsib."				
1	N	N	N	3 or 5	4b or 4c	1	1
2	W	N	N	3 or 5	4c	1	1
3	B	N	N	3 or 5	4b	1	1
4	N	W	N	3 or 5	4c	1	1
5	N	B	N	3 or 5	4b	1	1
6	N	N	W	3 or 5	4c	1	1
7	N	N	B	3 or 5	4b	1	1
8	B	W	B	3 or 5	4c	1	1
9	W	B	B	3 or 5	4b	1	1
10	B	B	W	3 or 5	4c	1	1
11	B	B	B	3 or 5	4b	1	1

* Refer to key at beginning of this set of tables.

TABLE VI - 3g*

SENSITIVITY ANALYSIS SHOWING THE EFFECT OF NON-TECHNICAL VARIABLES ON DESIGN DECISIONS

● Minimum Investigation (Average High RQD)

CASE #	NON-TECHNICAL VARIABLES			TEMPORARY SUPPORT	FINAL SUPPORT	EXCAVATION METHOD	GROUND WATER CONTROL
	"Integrat. of Design Const"	"Design Criteria"	"Engin. Firm Responsib."				
1	N	N	N	2	4b	1	1
2	W	N	N	2	4b	1	1
3	B	N	N	2	4a	1	1
4	N	W	N	2	4b	1	1
5	N	B	N	2	4a	1	1
6	N	N	W	2	4b	1	1
7	N	N	B	2	4a	1	1
8	B	W	B	2	4b	1	1
9	W	B	B	2	2 or 4a	1	1
10	B	B	W	2	4b	1	1
11	B	B	B	2	2	1	1

* Refer to key at beginning of this set of tables.

(W) level of the "integration of design and construction" variable and the best (B) levels of the other two variables. The fact that the liability of the engineer is reduced and the design criteria is loosened leads to departures from conventional designs even when the contractor is not known to the designer, when good ground conditions are expected. However, the expert included the concrete lining option under this combination of non-technical variables. The assumption is that he will alternate between the two options depending on the qualifications of the contractor. Case 11 is one where the three variables are set at their best (B) levels. The designer would choose a rockbolt/shotcrete system for support which is less costly than the other options. Many designers indicated that under conditions of uncertainty as to quality of rock, a steel set system is included in the contract as temporary support. Only when the uncertainty is resolved would it be possible to change to a rockbolt system when good ground is encountered.

- Table VI-3h: indicates a geotechnical scenario of minimum investigation with predicted bad ground conditions (average low RQD). Under such scenario steel sets for temporary support and a reinnforced concrete lining are used. Changes in the levels of the non-technical variables would lead to changes in the thickness of the concrete lining.

For poor ground conditions, as discussed previously, the use of the steel ribs in Europe is reduced in favor of other support systems such as rockbolts and shotcrete. The structure of the

TABLE VI - 3h*

SENSITIVITY ANALYSIS SHOWING THE EFFECT OF NON-TECHNICAL VARIABLES ON DESIGN DECISIONS

• Minimum Investigation (Average Low RQD)

CASE #	NON-TECHNICAL VARIABLES			TEMPORARY SUPPORT	FINAL SUPPORT	EXCAVATION METHOD	GROUND WATER CONTROL
	"Integrat. of Design&Const"	"Design Criteria"	"Engin. Firm Responsib."				
1	N	N	N	3 or 5	4c	1	1
2	W	N	N	3 or 5	4c	1	1
3	B	N	N	3 or 5	4b	1	1
4	N	W	N	3 or 5	4c	1	1
5	N	B	N	3 or 5	4b	1	1
6	N	N	W	3 or 5	4c	1	1
7	N	N	B	3 or 5	4b	1	1
8	B	W	B	3 or 5	4c	1	1
9	W	B	B	3 or 5	4b	1	1
10	B	B	W	3 or 5	4c	1	1
11	B	B	B	3 or 5	4b	1	1

* Refer to key at beginning of this set of tables.

liability system discussed in previous chapters makes it hard for the U. S. designers to introduce these techniques. The judicial system which relies on precedent and the unfamiliarity of the U. S. labor force with these techniques compounds the problem of using such methods. However, the trend is changing as can be seen in newly constructed underground transit systems in the U. S. where these methods are being used An article in Engineering News Record (1977) indicated that UMTA has suggested to most of the authorities building transit systems to use a rockbolt and shotcrete system whenever possible, as contractors do in Europe, instead of adding expensive steel liners after the tunnel has been bored. However, only the Metropolitan Atlanta Rapid Transit Authority (MARTA) is trying it.

6.5.2 Discussion of Results

The following conclusions can be derived from the results of the sensitivity analysis:

1) Departure from conventional reinforced concrete lining design is obtained when the three non-technical variables are simultaneously placed at their favorable (B) levels for good ground conditions (i.e., high RQD, low water infiltration). This departure is to a final rockbolts/shotcrete lining system.
2) In general, changes in final lining thickness are obtained for changes in the levels of each

non-technical variable considered separately.

3) When bad rock and/or heavy water inflow conditions exist, the non-technical variables are dominated by these conditions as to the influence on design decisions. The conditions dictate steel sets for temporary support and reinforced concrete linings acting as final support. Variations due to changes in the levels of the non-technical variables are witnessed only in changes of the lining thickness.

4) Setting any one of the three non-technical variables at its unfavorable (W) level would not change the design decisions significantly. This emphasizes the point that these non-technical variables should be manipulated as a group to achieve departures from conventionl, conservative designs.

The next step in the authors' analysis is to translate these changes in design to costs. By doing so the authors will be able to see the cost influence of non-technical variables on design decisions. Hence, the owner who controls these non-technical variables can manipulate them to achieve economic rock tunnel costs.

CHAPTER 7

COST ANALYSIS

In the previous chapter a model was developed that shows the dependence of engineering technical decisions on the non-technical variables. The sensitivity analysis verified this model's structure.

This chapter concludes the research by quantifying the sensitivity analysis results. This quantification is in terms of costs. Based on these results, conclusions and recommendations will be derived in the next chapter.

7.1 OBJECTIVES OF CHAPTER

The change in the engineer's technical decisions for changes in the non-technical variables (given the same geology) was rationalized as the result of changes in the uncertainties and liabilities imposed on the designer. Conceptually, the change in the engineer's technical decisions would imply that he is willing to accept a higher probability of failure provided the owner eliminates the uncertainties and liabilities for which the engineer is responsible. Failure is characterized by water-seepage, cracking, concrete spalling, and defective concrete. Catastrophic failure due to the collapse of the final structural system and which results in loss of lives is not considered for two reasons:

1. No failure of this type and magnitude has been reported in U. S. transit tunnels and, therefore, no statistical data exists in order to estimate a finite probability of failure. Arnold et al (1977:265-299) report such failures in water tunnels, but their service conditions are entirely different from those for transit tunnels.

2. Encoding subjective probabilities for this type of failure through the use of experts proved to be difficult. These experts believed that for transit tunnels, conservative estimates on ground loads and water pressures provided by geotechnical engineers first, and factors of safety used later in structural design, render an overall probability of failure which is very small. In chapter one, it was mentioned that this probability of failure was estimated by VanMarcke (1978:4) to be approximately 0.001 per year for dams. The authors' experts (Kuesel, Sutcliffe, Krumpotic, Birkmyer, Blohm and others) referred to failure of transit tunnels in terms of water leakage and cracking, which are localized types of failure; they considered the probability of catasrophic structural failure, under typical U.S. design practice, to be insignificantly low.

7.2 TYPES OF LOCALIZED FAILURE

The sensitivity analysis on the effect of institutional variables on the engineering technical decisions showed two main types of structural systems used in rock tunnels for transit projects:

1. Steel ribs or rockbolts and shotcrete as temporary support and a final cast-in-place concrete lining (varying in thickness).

2. Rockbolts as temporary support and a final shotcrete lining. This section will focus on localized failure in those two support types.

In cast-in-place concrete linings, unsatisfactory performance was observed from water seepage through concrete cracks, expansion and construction joints [Birkmyer(1978:Chapter 4)]. According to Birkmyer the cracks were parallel to the span of the structure and were generated by shrinkage of the concrete during construction. In themselves, these cracks did not impair the load bearing capacity of the lining, but were undesirable because of water seepage and its long-term multiple effects of this on many of the maintainable items. Cracking can be attributed to:

a) The chemical composition of the concrete mix.
b) Overstresses from differential ground settlement.
c) Construction specifications and engineering design. For example, Kuesel (1979:35-57) indicates that steel ribs provide a preferred site for shrinkage cracking of the lining, with the potential for water leakage.

Another area of failure in cast-in-place linings is the spalling of concrete. Cast-in-place linings in variable ground generally experienced spalling at construction joints because differential ground movements produced excessive shearing forces across the joints

[Birkmyer(1978:Chapter 4)].

In the same chapter, Birkmyer reports that defective concrete was detected in a few of the tunnels inspected in Europe and North America, generally in the form of honeycombed areas. He adds that these were often found at expansion and construction joints. Honeycombing was attributed to inadequate compaction or placing methods during construction. Seepage and spalling generally resulted from this condition.

In shotcrete lined tunnels spalling developed in localized areas because of inadequate bonding to the rock or, occasionally, because of instability of the rock itself.

Birkmyer (1978:Chapter 4) outlines the effect of water seepage into tunnels through cracks and failure of water proofing systems. These effects are on the structure itself as well as on several components and items installed within the undergound system. Examples of these effects are:

a) Effect on drainage and pumping systems: Water that enters the tunnel must be drained into gutters, catch basins and piping to sumps and then pumped out. The cost of maintaining all these items depends on the quantity of water, its chemical composition, the solids content, and the amount of dirt and debris in the track way and other areas, which contributes to clogging of the drainage system. The more water entering the system, the greater will be the compounding of these items and subsequent costs of monitoring the system.

b) Effect of concrete deterioration: Water flowing through cracks contains chemicals that leach free lime and other substances from the cement causing a gradual breakdown in the concrete.

c) Effect of corrosion: Items like re-steel in the concrete structure, track rails and fastenings, train and track control equipment are affected.

d) Effect of stray electrical currents which pass through water and dampness through the structure into the surrounding ground. These currents could corrode the structural and reinforcing steel and metallic components in the tunnel such as utility pipes.

e) Effect of water seepage on architectural finishes. This results in surface discoloration, deterioration of finish materials and corrosion of metallic hangers and light fixtures.

Remedies to the water seepage problem include grouting, use of water proofing barriers (which are used in West Germany), controlling skrinkage of concrete and others. Birkmyer (1978:Chapter 5) deals with this topic in greater detail. The goal of the preceding section is to familiarize the reader with types of localized failure and to show that remedial actions, sometimes involving additional capital cost, taken during the design and construction stages can cut future maintenance costs.

7.3 COST RESULTS

Evaluation of the costs of tunnel structural systems for different institutional and geotechnical scenarios has been based on the sensitivity analysis results presented and discussed in chapter 6. The expected cost of failure has been ignored in the analysis because of the low estimated and experienced probabilities of total failure. Another important aspect of the analysis relates to maintenance costs. Our interest was in detecting differential maintenance costs due to variations in the structural systems employed. The concern of engineers interviewed was focused mainly on the use of a shotcrete final system versus a cast-in-place system as to water seepage potential. The assumption was that a cast-in-place system is a better water sealant than a shotcrete system and, therefore, maintenance costs are higher in the latter. However, documented evidence (refer to Chapter 4), shows that shotcrete is a better sealant for low water infiltration levels (about 20gpm/100 ft.). Moreover, the sensitivity analysis showed that shotcrete was only used in these conditions (low water infiltration). Therefore, maintenance costs are not assumed higher for shotcrete systems and are not evaluated. Secondly, the probability of a localized failure will not increase due to the use of the shotcrete systems. The case is one of perceived higher probabilities of localized failure by U. S. designers for shotcrete systems, rather than of higher real probabilities.

As indicated in the previous paragraph, the cost results and curves are based on the sensitivity analysis presented in Chapter 6. Basically, those sensitivity results show the dependence of engineering technical decisions on non-technical or institutional variables. The costs of different design decisions for different institutional and geotechnical settings are evaluated. Appendix (D) shows the detailed calculations and assumptions used to generate these curves.

The total number of cost curves under consideration is 8 (eight geotechnical scenarios, showing the three most significant institutional variables).

These curves, which are indicative of the cost sensitivity of tunnel design to institutional variables will be presented and discussed here: *

- Figure VII-1 represents an extensive investigation scenario with uniform high RQD and low water infiltration. In other words, this scenario represents a known, very favorable geotechnical setting. Savings up to 13.2% are realized when the non-technical variables are placed at their favorable best (B) levels simultaneously. These savings are apparent because of the shift from a reinforced concrete final lining with rockbolts as temporary support for other combinations of the non-technical varibles to a shotcreted final support system with no temporary support corresponding to the (B) levels of those non-technical variables (Case 11). It would be interesting to note that the authors' "representative

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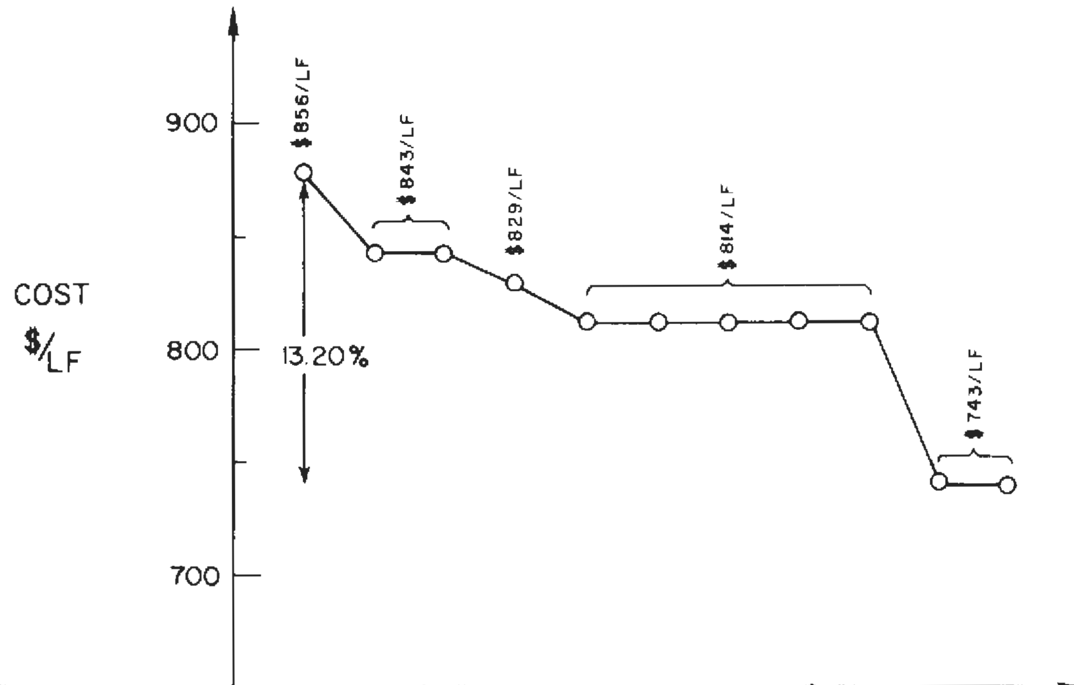
* Notation used in the curves is explained in the key to Table VI-3 as well as Tables VI-3a through VI-3h.

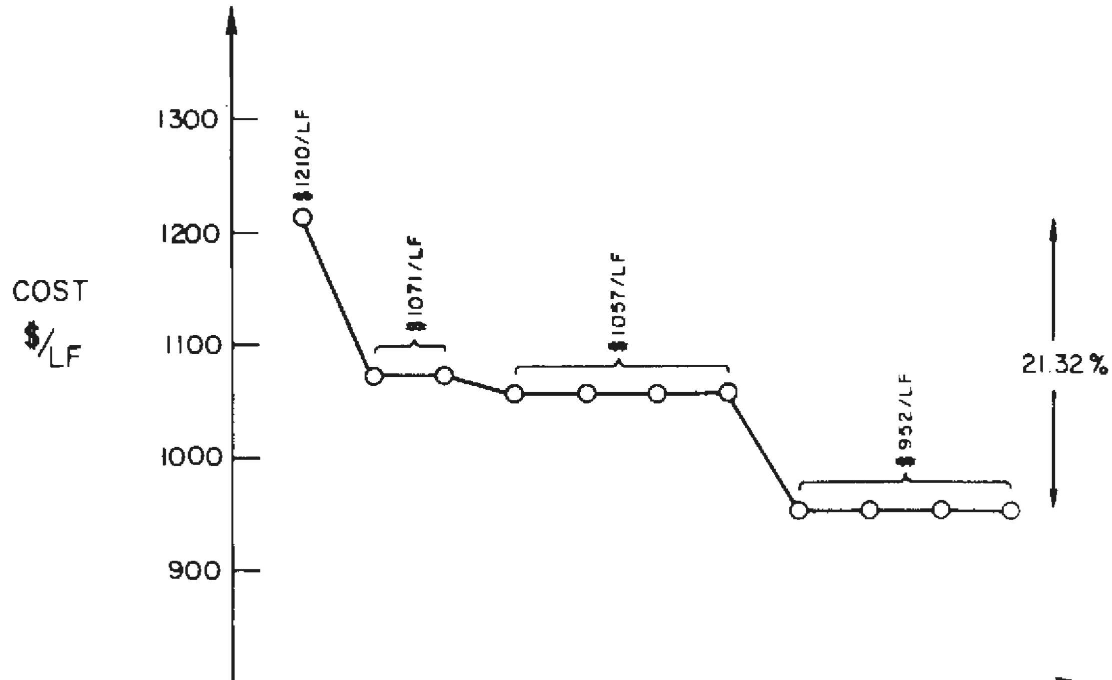


CASE # / VARIABLE	4	2	6	1	3	5	7	8	10	9	11
INTEGRATION OF DESIGN AND CONSTRUCTION	N	W	N	N	B	N	N	B	B	W	B
DESIGN CRITERIA	W	N	N	N	N	B	N	W	B	B	B
ENGINEERING FIRM'S RESPONSIBILITY	N	N	W	N	N	N	B	B	W	B	B

FIGURE VII-1

Cost Curve for Extensive Investigation (Uniform High RQD), Low Water Infiltration, for Different Combinations of Non-technical Variables expert" Mr. Harry Sutcliffe, used rockbolts for temporary support. The "representative expert" as well as several interviewed desingers commented that it would be very likely for other designers to use steelribs for temporary support in lieu of rockbolts when the non-technical variables are shifted to their unfavorable worst (W) levels (e.g.: Cases 2,4,6,8,9, and 10). This would imply greater savings than the 13.2% obtained for this case. Another important point that the "representative expert" raised, relates to the use of shotcrete. He indicated that U.S. designers are becoming aware of its potential and that the existence of a favorable institutional atmosphere would promote its use in the support system.

- Figure VII-2 represents an extensive investigation scenario with uniform high RQD and high water infiltration. The "representative expert" resorted to a rockbolt/shotcrete system for temporary support and a 12 inch reinforced concrete final lining when the "Design Criteria" variable was placed at its strict (W) level. The cost of such an option (Case 4) is $1,210/LF compared to $952/LF for the most favorable (B) levels of the non-technical variables (Case 11). Savings realized as a result of the difference between those two extreme cases are up to 21.32%. This scenario highlights the importance of the "Design Criteria" variable as well as its impact on costs. Moreover the use of concrete linings to control water leakage is emphasized in all the cases. The "representative expert" commented

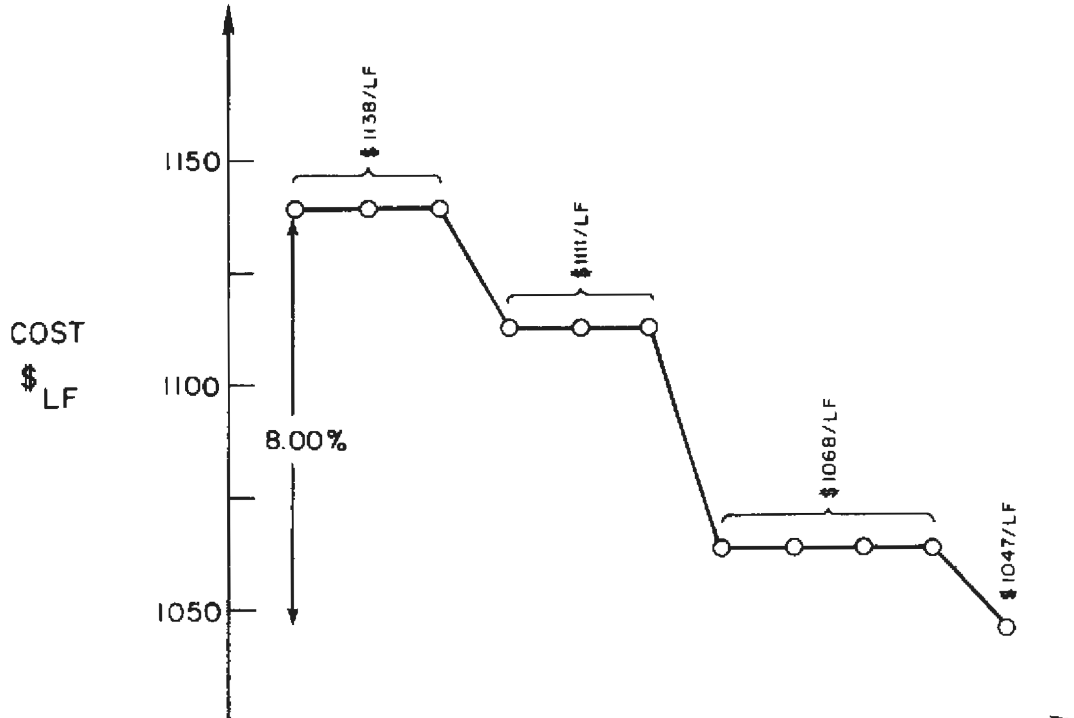


VARIABLE \ CASE #	4	6	10	8	9	2	1	3	5	7	11
INTEGRATION OF DESIGN AND CONSTRUCTION	N	N	B	B	W	W	N	B	N	N	B
DESIGN CRITERIA	W	N	B	W	B	N	N	N	B	N	B
ENGINEERING FIRM'S RESPONSIBILITY	N	W	W	B	B	N	N	N	N	B	B

FIGURE VII-2

Cost Curve for Extensive Investigation (Uniform High RQD), High Water Infiltration, for Different Combinations of Non-technical Variables that he used a support system that other U.S. designers might consider under a similar situation. However, he indicated his confidence in using a rockbolt/shotcrete system under varying geotechnical conditions.

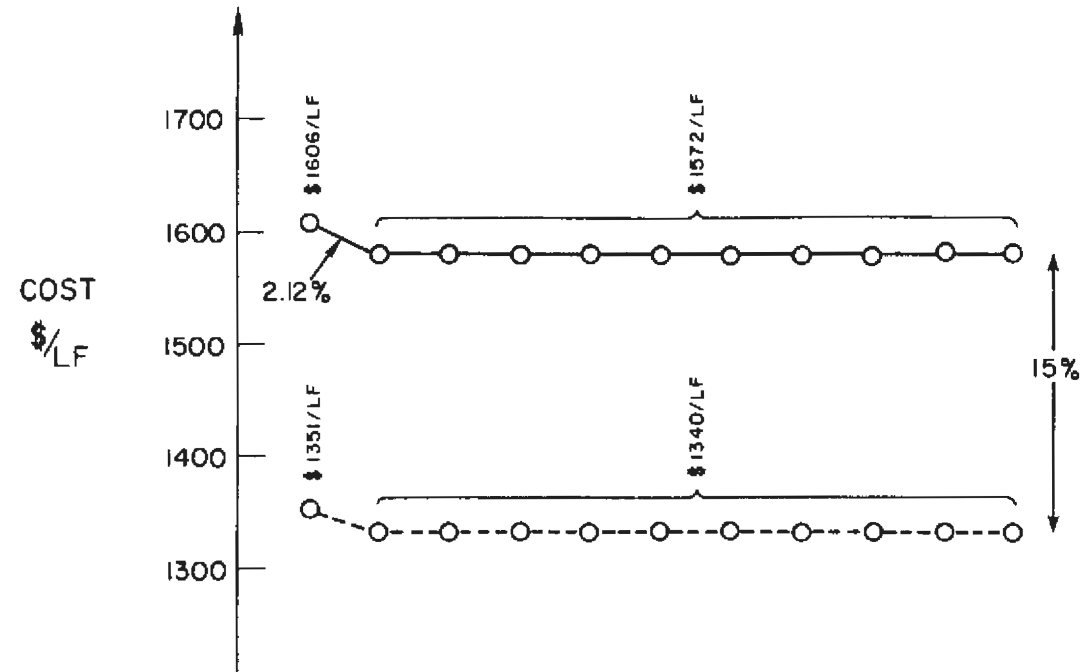
- Figure VII-3 represents an extensive investigation scenario with varying rock quality (mixed phase) and low water infiltration. The "representative expert" resorted to combinations of rockbolts, shotcrete, steel sets for temporary support and varying thicknesses of the final reinforced concrete lining depending on the levels that the non-technical variables assume. Savings up to 8% are realized, when the non-technical variables are placed at their favorable (B) levels.
- Figure VII-4 represents an extensive investigation scenario with varying rock quality (mixed phase) and high water infiltration. The "representative expert" indicated that steel sets for temporary support and concrete linings for final support would be used. When the non-technical variables are placed at their favorable (B) levels, savings occur because of changes in the thickness of the reinforced concrete lining. Savings up to 2.12% are realized. This confirms the authors' hypothesis that savings decline as geotechnical conditions deteriorate. However, there are savings to be achieved for providing a favorable institutional environment. The "representative expert" indicated that a rockbolt/shotcrete system would be used in European practice (dashed line in Figures) and that



CASE # / VARIABLE	2	4	6	8	10	1	3	5	7	9	11
INTEGRATION OF DESIGN AND CONSTRUCTION	W	N	N	B	B	N	B	N	N	W	B
DESIGN CRITERIA	N	W	N	W	B	N	N	B	N	B	B
ENGINEERING FIRM'S RESPONSIBILITY	N	N	W	B	W	N	N	N	B	B	B

FIGURE VII-3

Cost Curve for Extensive Investigation (Mixed Phase),
Low Water Infiltration, for Different Combinations of Non-technical Variables



CASE # / VARIABLE	4	1	2	3	5	6	7	8	9	10	11
INTEGRATION OF DESIGN AND CONSTRUCTION	N	N	W	B	N	N	N	B	W	B	B
DESIGN CRITERIA	W	N	N	N	B	N	N	W	B	B	B
ENGINEERING FIRM'S RESPONSIBILITY	N	N	N	N	N	W	B	B	B	W	B

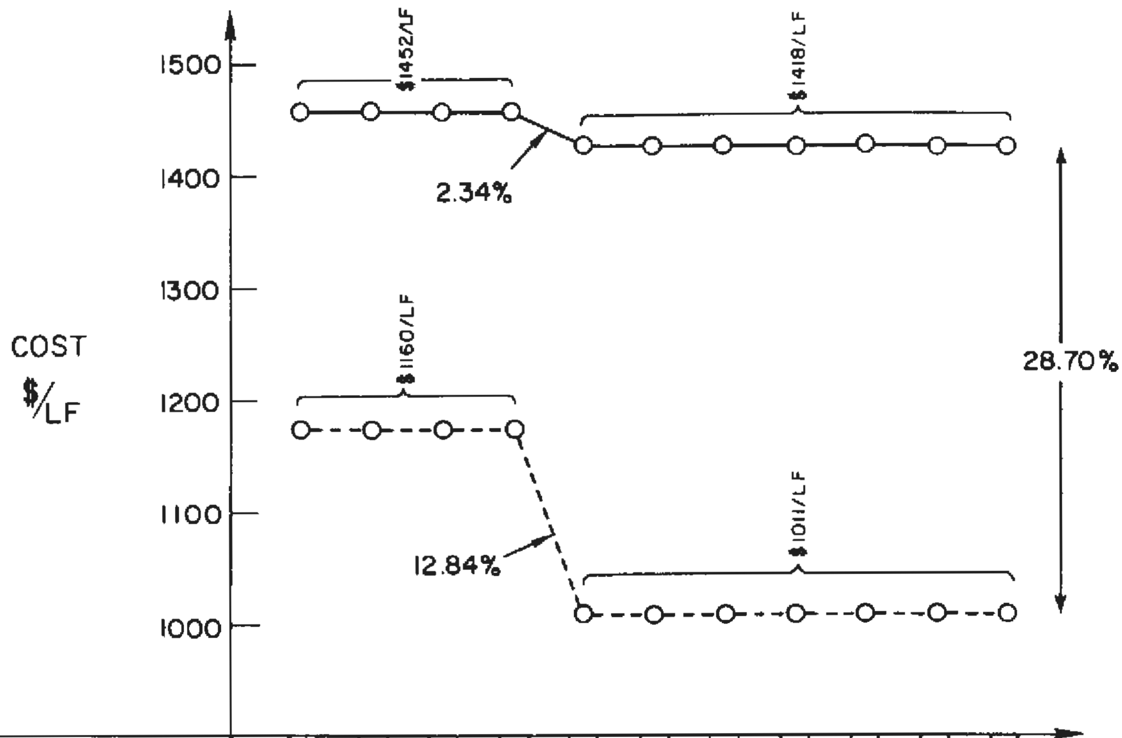
FIGURE VII-4

Cost Curve for Extensive Investigation (Mixed Phase)
High Water Infiltration, for Different Combinations of Non-technical Variables

TYPICAL U S PRACTICE ——
TYPICAL EUROPEAN PRACTICE ----

U.S. designers would resort to its use as a substitute for conventional design if encouraged by the owners of the systems. Using a shotcrete system would yield up to 15% in savings as compared to the use of the conventional system.

- Figure VII-5 represents an extensive investigation scenario with uniform low RQD and low water infiltration. Under such a scenario the "representative expert" indicated that U.S. designers would use steel sets for temporary support and final reinforced concrete linings. Savings up to 2.34% are realized when the non-technical variables assume their favorable (B) levels. The expert's personal preference showed a shotcrete system for temporary support and a final reinforced concrete lining when any of the non-technical variables assumes an unfavorable (W) level (Cases 2,4,6,8, and 10). Otherwise, the expert resorted to a rockbolt system for temporary support and a final reinforced concrete lining. For the expert's choice, savings up to 12.84% are realized when the non-technical variables assume their favorable (B) levels. Savings up to 28.7% are realized because of switching from conventional design to expert's choice, which is typical of European practice.
- Figure VII-6 reprsents an extensive investigation scenario with uniform low RQD and high water infiltration. In other words, this scenario represents a known, very unfavorable geotechnical setting. Under such a scenario the "representative expert" indicated that U.S. designers would use steel sets for temporary support and final reinforced

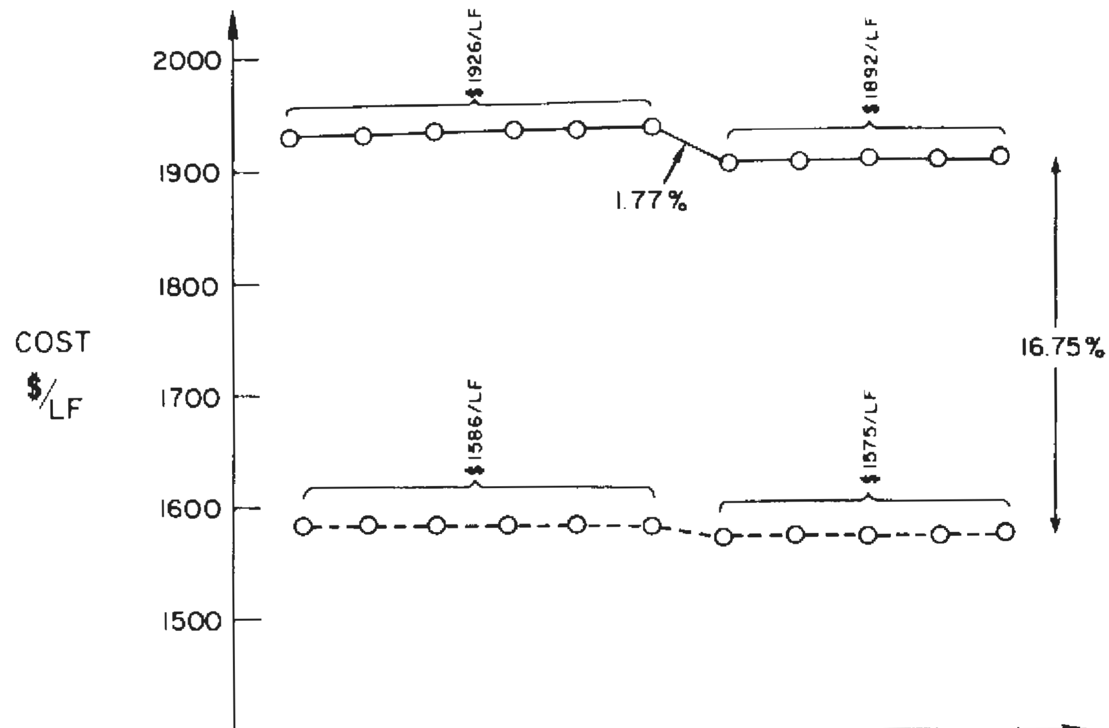


VARIABLE \ CASE #	2	4	6	10	1	3	5	7	8	9	11
INTEGRATION OF DESIGN AND CONSTRUCTION	W	N	N	B	N	B	N	N	B	W	B
DESIGN CRITERIA	N	W	N	B	N	N	B	N	W	B	B
ENGINEERING FIRM'S RESPONSIBILITY	N	N	W	W	N	N	N	B	B	B	B

FIGURE VII-5

Cost Curve for Extensive Investigation (Uniform Low RQD), Low Water Infiltration, for Different Combinations of Non-technical Variables

TYPICAL U S PRACTICE ——
TYPICAL EUROPEAN PRACTICE ----



VARIABLE \ CASE #	2	4	6	1	10	8	3	5	7	9	11
INTEGRATION OF DESIGN AND CONSTRUCTION	W	N	N	N	B	B	B	N	N	W	B
DESIGN CRITERIA	N	W	N	N	B	W	N	B	N	B	B
ENGINEERING FIRM'S RESPONSIBILITY	N	N	W	N	W	B	N	N	B	B	B

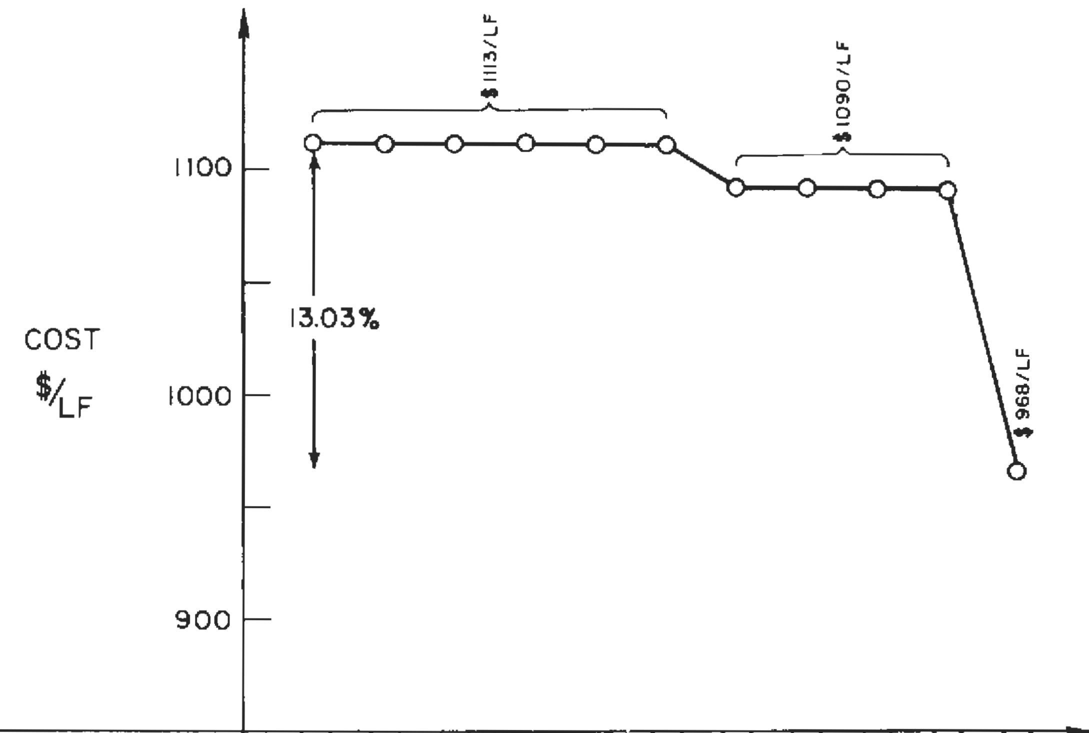
FIGURE VII-6

Cost Curve for Extensive Investigation (Uniform Low RQD), High Water Infiltration, for Different Combinations of Non-technical Variables

TYPICAL U S PRACTICE ———
TYPICAL EUROPEAN PRACTICE -----

concrete linings. Savings up to 1.77% are realized when the non-technical variables assume their favorable (B) levels. This decline in savings as compared to other geotechnical scenarios is indicative of the dominance of ground and water conditions over the non-technical institutional variables. The dashed line in the figure denotes the cost of what the expert thought would be considered under European practice—i.e., a rockbolt and shotcrete system for temporary support and a final reinforced concrete lining. The use of the concrete lining was justified as the result of both high water infiltration conditions as well as the separation of design and construction which is typical of U.S. practice. Nevertheless, savings up to 16.75% are realized if the contractor resorts to the rockbolt/shotcrete system for temporary support.

- Figure VII-7 indicates a geotechnical scenario of minimum investigation and predicted favorable ground conditions (average high RQD). Under such a scenario the designer would resort to a rockbolt system for temporary support and a reinforced concrete lining for final support (Cases 1 through 10). For the favorable (B) levels of the non-technical variables the designer would resort to a final rockbolt/shotcrete system (Case 11). Savings realized are up to 13.03% when those variables are placed at their (B) levels. These savings are lower than the savings realized in the first two scenarios which indicate similar geotechnical conditions (Figures VII-1 and VII-2). The



VARIABLE \ CASE #	2	4	6	8	10	1	3	5	7	9	11
INTEGRATION OF DESIGN AND CONSTRUCTION	W	N	N	B	B	N	B	N	N	W	B
DESIGN CRITERIA	N	W	N	W	B	N	N	B	N	B	B
ENGINEERING FIRM'S RESPONSIBILITY	N	N	W	B	W	N	N	N	B	B	B

FIGURE VII-7

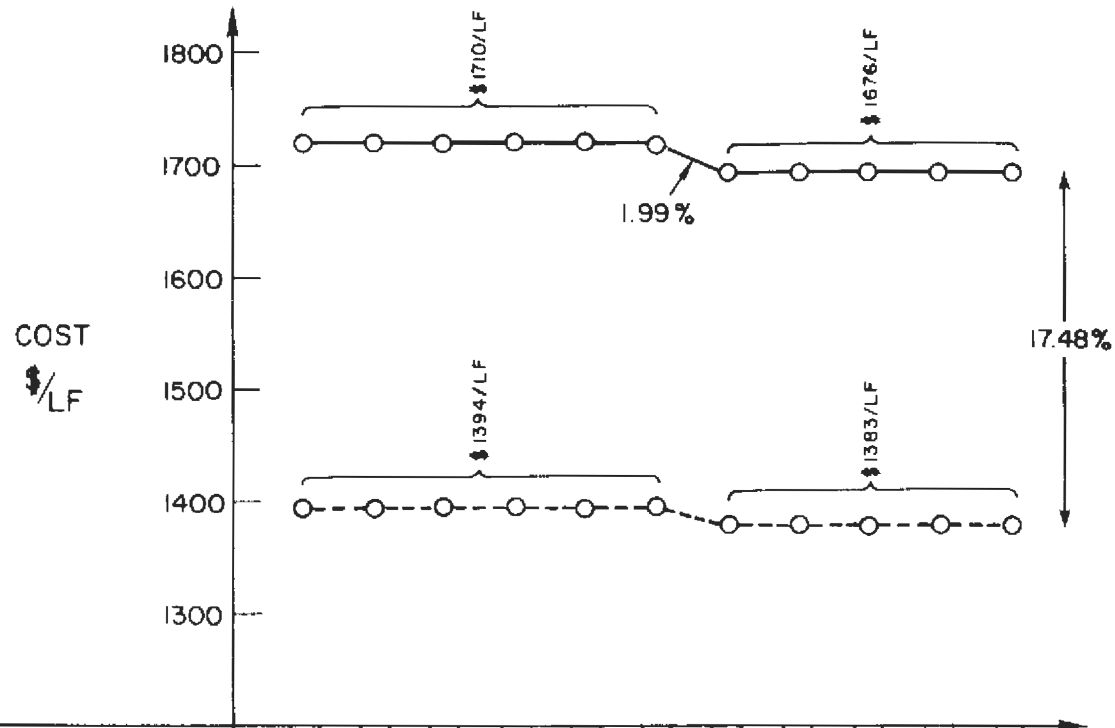
Cost Curve for Minimum Investigation (Average High RQD), for Different Combinations of Non-technical Variables authors attribute this to the lesser degree of sub-surface investigation which characterizes this scenario.

- Figure VII-8 indicates a geotechnical scenario of minimum investigation and predicated unfavorable ground conditions (average low RQD). Under U.S. practice the expert indicated that designers would use steel sets and reinforced concrete linings for structural support. Savings realized are up to 1.99% when the non-technical variables assume their favorable (B) levels. The expert indicated that he would use a rockbolt/shotcrete system for temporary support and a final reinforced concrete lining. This choice is more in line with European practice. The cost savings resulting from the use of the European approach as compared to the conventional U.S. approach are up to 17.48%.

7.4 SUMMARY OF FINDINGS

These cost curves were presented to show that the sensitivity of tunnel designs to institutional variables increases with an increase in the quality of geotechnical conditions. For the best geological conditions, savings of almost 20% could be effected by owners sharing in the designers' risk. Considering a 1 mile tunnel, this translates into 1.4 million, 1981 U.S. dollars. For the most unfavorable rock conditions, however, potential savings were minimal.

These results are very important, because previous research done in this area is characterized by recommendations for cutting costs, by changing isolated variables in the process. The authors' conclusion



VARIABLE \ CASE #	2	4	6	1	10	8	3	5	7	9	11
INTEGRATION OF DESIGN AND CONSTRUCTION	W	N	N	N	B	B	B	N	N	W	B
DESIGN CRITERIA	N	W	N	N	B	W	N	B	N	B	B
ENGINEERING FIRM'S RESPONSIBILITY	N	N	W	N	W	B	N	N	B	B	B

FIGURE VII-8

Cost Curve for Minimum Investigation (Average Low RQD), for Different Combinations of Non-technical Variables

TYPICAL U S PRACTICE ——
TYPICAL EUROPEAN PRACTICE ----

is that owners can only incur savings and cut costs if they manipulate the institutional variables as a group. Table VII-1 presents a summary of cost findings.

GEOTECHNICAL SCENARIO	FIGURE	SAVINGS UNDER BEST INSTITUTIONAL SCENARIO (U.S. PRACTICE)	SAVINGS UNDER BEST INSTITUTIONAL SCENARIO (SHIFT FROM U.S. TO EUROPEAN PRACTICE
EXTENSIVE INVESTIGATION UNIFORM HIGH RQD LOW WATER INFILTRATION	VII - 1	13.20 %	NOT INCLUDED
EXTENSIVE INVESTIGATION UNIFORM HIGH RQD HIGH WATER INFILTRATION	VII - 2	21.32 %	NOT INCLUDED
EXTENSIVE INVESTIGATION MIXED PHASE LOW WATER INFILTRATION	VII - 3	8.00 %	NOT INCLUDED
EXTENSIVE INVESTIGATION MIXED PHASE HIGH WATER INFILTRATION	VII - 4	2.12 %	15.00 %
EXTENSIVE INVESTIGATION UNIFORM LOW RQD LOW WATER INFILTRATION	VII - 5	2.34 %	28.70 %
EXTENSIVE INVESTIGATION UNIFORM LOW RQD HIGH WATER INFILTRATION	VII - 6	1.77 %	16.75 %
MINIMUM INVESTIGATION AVERAGE HIGH RQD	VII - 7	13.03 %	NOT INCLUDED
MINIMUM INVESTIGATION AVERAGE LOW RQD	VII - 8	1.99 %	17.48 %

TABLE VII-1

Summary of Cost Findings

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

In the previous chapter, the authors showed that changing certain institutional variables could have significant impacts on designers' decisions and hence on construction costs for rock tunnels.

This chapter concludes the research by listing the results obtained and the author's recommendations for further research.

8.1 SUMMARY OF CONCLUSIONS

1. The study found that non-technical variables do have a significant effect on design decisions, and hence on the cost of construction for subway tunnels in rock. Sensitivity analysis results to demonstrate this were presented in chapter 6. Specifically, the variables found to have the greatest impact on design decision-making were:

a) Integration of design and construction; where designers had some knowledge of, or input to selecting, the construction contractor, they were willing to specify less costly lining designs. Under a design-construct contract form, significant savings were possible.

b) Design criteria; where requirements for water tightness or unbalanced loadings were decreased, designers were able to design less costly linings.

c) Liability of design firms; where owners required narrow form indemnification, reduced coverage limits, and took responsibility for information provided, designers were willing to adopt lower cost construction procedures and lining designs.

Most importantly, there was interaction between those non-technical (institutional) variables, with two or more being required to change in order to induce design changes for certain ground conditions. This result is very important, because previous research done in this area is characterized by isolated recommendations for cutting costs. The author's conclusion, which was elaborated upon in chapters 6 and 7, is that owners can only incur savings if they manipulate the non-technical variables as a group.

2. The extent of savings from less conservative designs depended on the quality of the rock (as measured by RQD, etc.). The savings were largest, up to 21%, for favorable ground conditions and smallest for poor ground. The implication is that the designer would truly need the conservative design in bad ground, even with the most favorable risk allocation. In good rock, on the other hand, part of the cost of current designs is truly due to overdesign as a result of excessive liability being placed on the designer. This is the situation in which large savings are possible, if owners restructure and share in the project risks. Figure VIII-1 is a schematic representation of the preceding idea. The figure represents a cost surface formed by variations in geology and in institutional conditions. The surface is relatively steeper (implying larger savings) at the end where favorable geotechnical conditions exist. At the other extreme (worsening physical or geotechnical conditions) the surface becomes flat implying minor changes in costs. This fact will assure owners that engineers are not "frivolous" and will still be conservative in bad ground, even if improved institutional conditions exist, so that they are faced

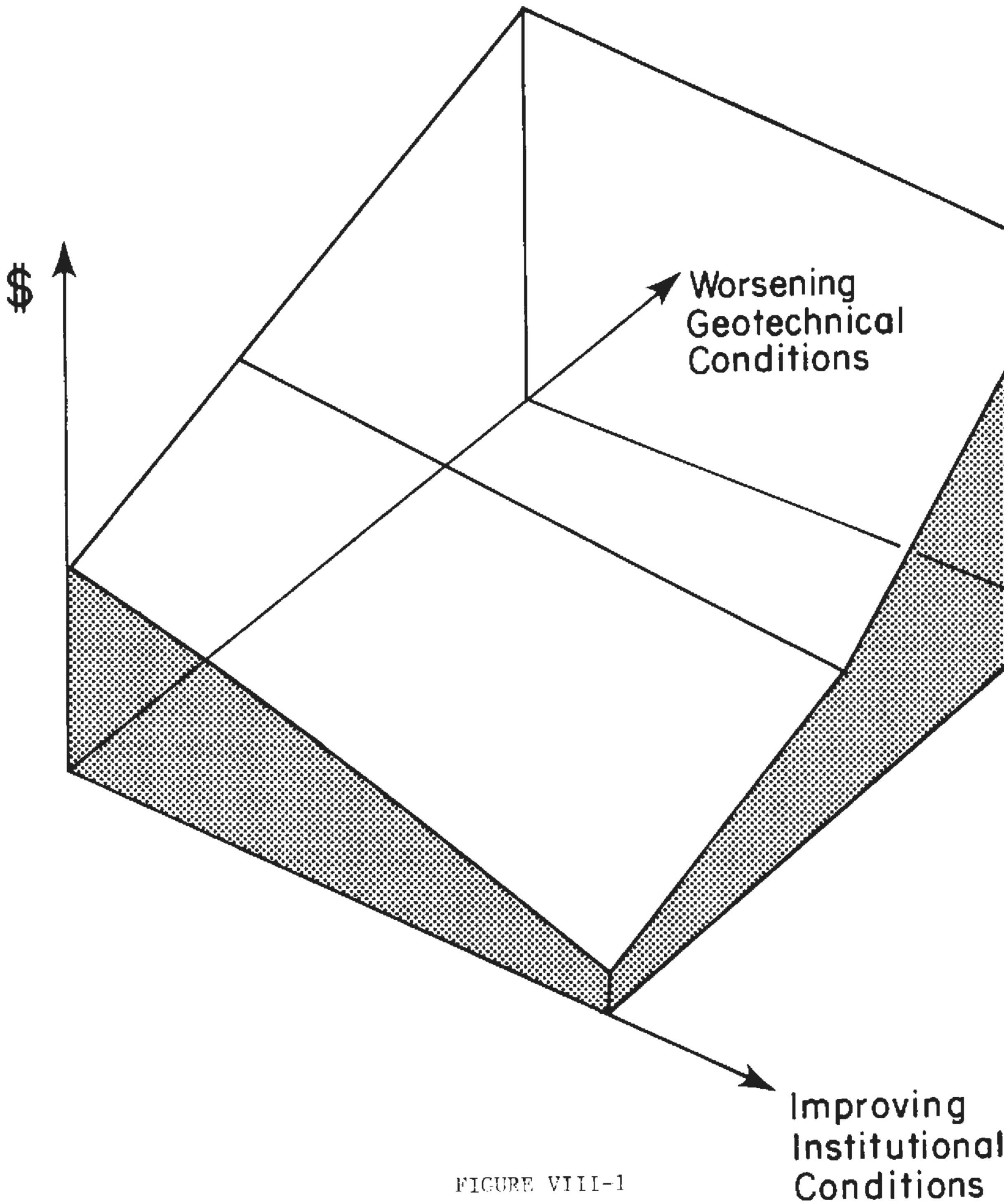


FIGURE VIII-1

Schematic Representation of Potential Cost Savings from Improving Institutional Conditions as a Function of Geotechnical Conditions with less risk.

Consideration was given to the costs of maintenance and to expected failure costs in order to assess the trade-offs between capital costs and life cycle operating and maintenance costs. Since the authors could find no data on any transit tunnel failure in the U. S. and since all of the designers interviewed assured the research team that they were using lining thicknesses far in excess of structural requirements (to control leakage, or for other reasons), it was determined that the expected cost of failures was negligible under current design levels. The costs of pumping water were considered in trade-offs on lining thickness, and in evaluating the use of shotcrete. In some cases no trade-off existed, since lower cost shotcrete linings were also expected to have less water infiltration under low infiltration conditions.

8.2 FURTHER RESEARCH RECOMMENDATIONS

1. The research focused on the design phase of subway tunnels in rock. The construction stage has been dealt with in a previous MIT study [Levitt et al (1978)]. However, extensive research is needed on the planning phase and the decisions involved there (e.g. fixing alignments, constraining construction methods). The economic, social and other impacts of planning stage decisions are not evaluated in existing literature. It was the opinion of designers interviewed in the course of this study that these planning decisions influenced their design decisions and ultimately the cost of the system. This point has been alluded to in Chapter 2 of this study. Morseover, the author looked briefly at the planning phase and the influence of the structuring of the project organization on design decisions in the same chapter.

2. The research focused on the design phase under prevailing

U. S. practice. Changes in the risk allocation structure were departures from this starting point. It might be appropriate to conduct research on the design-construct mode of contracting, as is practiced in some European countries, to assess its feasibility and cost savings in U. S. practice. In an interview with Mr. Sol Ribacoff, a prominent attorney with extensive construction related experience, he expressed the opinion that this mode of contracting is feasible from a legal point of view in U. S. public works, if certain conditions exist. These conditions are enumerated in United States Government Contracts and Subcontracts, [Paul, (undated)]. However, he added, the applicability of this approach is doubtful in the transportation sector because of the traditional attitudes of the different parties involved in such projects and the political structure surrounding them. It should be noted that the Environmental Protection Agency announced in 1972 that it will permit turnkey design/construction procedures for sewage treatment plants. Among the motivations were: single responsibility, reduced design/construction time, guaranteed performance, and closer cost controls. The authors still feel that the application of this approach in the transportation sector needs to be studied in terms of the incentive structure it provides the contractors, in terms of professional liability questions which it raises and how the insurance industry looks at them, and in terms of the availability of firms that can practice this approach.

An extension to the risk-analysis methodology developed here would be to model simultaneously the interaction of the designer and contractor with the owner of a system, in terms of risk allocation, under the design-construct mode. The contractors' interaction with the owner has been modeled in a previous MIT research project. This project looks at the designer separately in his interactions with the owner.

3. The research found that by reducing the liability of designers significant savings were achieved. However, reducing that liability implies that the owner will have to share in the risks. The authors believe that more research should be done in studying the risk behavior of rapid transit systems owners (who in most cases are local agencies) and how that affects planning, design and technical decisions. Will the owners and local authorities accept more risk and would it be feasible for them to do that.

This would require a systematic interviewing approach to establish risk curves and to measure utilities. Seltz-Petrash (1981:42-45), gives an example on an owner sharing in the risk. She reports the use of advanced subway techniques, contracting and management in the newly constructed Baltimore subway. Sharing of risk was the approach of the owner and consultant. Sharing of all geotechnical information and interpretation among the project participants was accomplished. The owner was willing to remove some of the burden of risk from the contractor. Reducing their risk allowed contractors to bid lower (within a range of 2 to 20%). Moreover, designs allowed for flexibility specifying performance standards when possible. This encouraged contractors to seek less expensive ways, and most noticeably on this project, reduced the use of underpinning.

4. The loosening of design criteria is another issue. The owner could impose constraints on how severe these can be. The owner could, for example, establish acceptable levels of water infiltration for certain ground conditions. But since this becomes a question of life cycle costs vs. capital cost, the owner could perform a life cycle study (preliminary study for each tunnel) and determine those maximum levels of design criteria for which they are willing to pay. Anything more could be paid by the local authorities.

5. Finally, the problem of unlimited liability should be tackled. Does

it make sense for transit authorities to require unlimited liability from their consultants. If the result--as this study has indicated--is defensive engineering, they may be unwittingly buying some very costly "insurance" against failures which are very unlikely in the first place.

APPENDIX A

THE PERSONS INTERVIEWED

The authors would like to thank those designers and professionals whose input was valuable to this research. Their names are listed in alphabetical order:

Mr. Art Arnold
Bechtel Incorporated

Professor Amer Azzouz
M.I.T.

Mr. James Birkmyer
Bechtel Incorporated

Mr. Harry Blohm
Bechtel Incorporated

Mr. Tim Cullen
Bechtel Incorporated

Mr. Bill Custer
Kaiser Engineers

Mr. Don D'Eramo
Sverdrup and Parcel

Professor Herbert Einstein
M.I.T.

Mr. Chris Gardner
Bechtel Incorporated

Mr. Vern Garret
WMATA

Mr. David Hammond
DMJM Associates

Mr. Robert Harvey
Parsons, Brinckerhoff, Quade and Douglas

Mr. Mike Hayes
Bechtel Incorporated

Mr. Richard Howell
Risk Analysis and Research Corporation

APPENDIX A CON'T

THE PERSONS INTERVIEWED

Mr. Matthew Krumpotic
Guy F. Atkinson & Co.

Mr. Thomas Kuesel
Parsons, Brinckerhoff, Quade and Douglas

Mr. Morris Levy
Parsons, Brinckerhoff, Quade and Douglas

Mr. Leo Moll
Bechtel Incorporated

Mr. Youssef Nassar
Multi-Systems, Inc.

Mr. Bill Paris
Bechtel Incorporated

Mr. Ziad Ramadan
Multi-Systems, Inc.

Mr. Sol Ribakoff
Attorney

Mr. Harry Sutcliffe
Bechtel Incorporated

Mr. David Thompson
Haley and Aldrich, Inc.

APPENDIX B

THE MEMBERS OF THE WORKSHOP

1. Mr. Bill Custer, Project Manager with Kaiser Engineers. Mr. Custer is now involved in the cut and cover extension of the Orange Line and he has been involved in the design of deep bore tunnels in the past.

2. Mr. Morris Levy, Parsons, Brinckerhoff, Quade & Douglas. Mr. Levy is an experienced designer of tunnels.

3. Mr. Harry Sutcliffe, Project Manager with Bechtel, Inc. Mr. Sutcliffe advised the research team on what kind of geotechnical input the research team should provide at the workshop.

APPENDIX C

FINDINGS OF THE WORKSHOP

The non-technical variables identified as the most significant on the engineer's decision making and consequently on design conservatism were the following (in order of importance)*:

1. Integration of Design/Construction (designer's role in prequalification and/or selection of contractor; construction management input into the design phase).
2. Engineering firm's responsibility (degree of designer's indemnification; owner's responsibility in the information he provides).
3. Design criteria (rules and specifications imposed on the designer by the general design consultant or the owner).
4. Level of hierarchy (designer is either general design consultant or section designer with/without direct contract with the owner).
5. Fee structure (cost plus fixed fee, lump sum, fee adjustments).
6. Insurance coverage (limited/unlimited liability).

The summary of the preceding results is presented in Table C-I.

*See Chapter 5 for more detailed discussions of these variables.

TABLE C-1. SUMMARY OF RANKING

Variables	BEST CASE				WORST CASE				Average
	Participant 1	Participant 2	Participant 3	Total	Participant 1	Participant 2	Participant 3	Total	
Integration of Design/Construction	3	1.5	1	5.5	2	1	1.5	4.5	1
Level of Hierarchy	4	3.5	3.5	11	3	3	3.5	9.5	4
Engineering Firm's Responsibility	1	1.5	2	4.5	1	3	3.5	7.5	2
Fee Structure	5	5.5	5	15.5	5	5.5	5	15.5	5
Insurance Coverage	6	3.5	6	15.5	6	5.5	6	17.5	6
Design Criteria	2	5.5	3.5	11	4	3	1.5	8.5	3

OTHER VARIABLES WITH INCOMPLETE DATA:
Client's Policy and Reputation
Union Work Rules

The participants of the workshop were asked to provide the research team with a rough tunnel design for the given ground conditions under both the worst and the best cases.* These rough designs were subsequently used for estimating the cost difference between the two cases. Due to the fact that the research team was not provided with detailed information on each design, and since the aim of this cost comparison was to look at the range of potential differences in cost, the team decided not to use detailed estimation techniques. Instead, the team decided to use approximate estimating techniques drawn from existing publications (Mayo, 1968; Spittel, 1971) on tunnel cost estimating and to check the results with data provided by Multisystems, Inc., who are concurrently developing a subway estimating model under a contract with DOT.

Costs were estimated for excavation, support and lining of a rock tunnel, assuming that other costs remained the same in both the worst and the best cases. Cost calculations are presented in Ioannou (80, Appendix D).

The general tunnel characteristics were the following:

Tunnel shape: circular

Tunnel's finished internal diameter: 19 ft.

Depth of tunnel: 100 ft.

Length of tunnel: 8,500 ft.

Rock Quality Designation: 60~75%

Rock Strength: 20,000 PSI

In both cases, cost figures were established assuming two methods of excavation, i.e. drill and shoot or a tunnel boring machine (TBM), in order to control for the impact of the construction method on relative costs.

The results are presented in the following table. Costs are given for only one tunnel, so all figures have to be doubled for twin tunnels.

*These two cases relate to two sets of the same non-technical variables where those are placed at their least and most favorable levels. See Ioannou (80, Chapter VI) for more detail.

UNIT COST	EXCAVATION METHOD			
	TBM		DRILL & SHOOT	
	BEST	WORST	BEST	WORST
$/LINEAL FOOT	830	1,600	1,700	2,690
$/MILE	4,382,400	8,448,000	8,976,000	14,203,200
DIFFERENCE $/MILE	4,065,600		5,227,200	

It has been assumed that when a TBM is used, the contractor is writing off the complete cost of the machine on one project and that he is the only contractor on the specified length of subway. The first assumption serves to make a cost comparison from a conservative point of view. The second assumption is made because breaking up the project into overly small contracts makes the TBM uncompetitive.

Assuming a current total system cost of about $50 million per mile it could be stated that shifting from the worst case to the best case would at least result in a 20% savings (for twin tunnels = 2x5/50=20%).

It should also be pointed out that the "best" and "worst" cases do not represent highly improbable extremes. The worst case represents what is used in current U.S. practice whereas the best case is something similar to European practice.

The following geotechnical information was provided to the workshop's participants:

1. A diagram showing the vertical alignment of the tunnel, the borings and the unified soil classification of the strata encountered.
2. Laboratory soil test results:
   2.1. Natural water content
   2.2. Atterberg limits
   2.3. Unit weight
   2.4. Unconfined strength-strain test results
   2.5. Consolidation curves
   2.6. Coefficient of permeability
3. Laboratory rock test results:
   3.1. Megascopic identification
   3.2. Unit weight
   3.3. Unconfined compression test curves
   3.4. Hardness
4. Piezometer in situ results.

For more detail on workshop's proceedings please refer to Ioannou (80).

APPENDIX D

COST CALCULATIONS

The cost calculations are based on the sensitivity analysis results discussed in Chapter 6. Few considerations have to be mentioned before conclusions can be drawn. These considerations are:

- The costs used are relative rather than absolute costs. The author acknowledges the effect of economic, regional, union requirements and other factors in determining bid prices. These factors are assumed to be fixed when calculating the costs of different support options. The author is interested in showing the relative savings of using different support options when the institutional variables change under fixed geotechnical scenarios (See Chapters 6 and 7). The costs are extracted from the references that are listed on page 240.

- According to the "representative expert," design is the setting up of the contract conditions to be as flexible as possible. He sites as an example both Red Line contracts where the rock proved better than expected and the contractor was permitted to use far fewer supports than the designer anticipated--(a sort of NATM on a crude scale). The "representative expert's" answers reflect those cost savings. However, he believes that some designers would rigidly stick to the contract, and such savings would not then be made.

- Some contracts would normally include provisions for rock bolts, shotcrete and steel sets. The "representative expert's" answers were based on the predominant methods that he would expect to use for certain ground conditions.

- The TBM vs. drill and shoot decision was ignored in the analysis because of the length of the tunnel (i.e., 1 mile). Breaking up the project into overly small contracts makes the TBM uncompetitive.

The different support options available to the designer (under varying geotechnical conditions) as discussed in the sensitivity analysis results (Chapter 6, Table VI-3) are listed in the following paragraph. The costs of these options are calculated in this appendix.

DESIGN OPTIONS

* Rockbolts + Reinforced Concrete (8 inch lining) + Drill & Blast
* Rockbolts + Reinforced Concrete (12 inch lining) + Drill & Blast
* Rockbolts + Reinforced Concrete (14 inch lining) + Drill & Blast
* Rockbolts/Shotcrete + Reinforced Concrete (8 in.lining) + Drill & Blast
* Rockbolts/Shotcrete + Reinforced Concrete (12 in.lining) + Drill & Blast
* Rockbolts/Shotcrete + Reinforced Concrete (14 in.lining) + Drill & Blast
* Ribbed System (Steel Sets) + Reinf. Conc. (8 in.lining) + Drill & Blast
* Ribbed System (Steel Sets) + Reinf. Conc. (12 in.lining) + Drill & Blast
* Ribbed System (Steel Sets) + Reinf. Conc. (14 in.lining) + Drill & Blast
* Rockbolts + Reinforced Concrete (8 in.lining-Upper Arch)+ Drill & Blast
* Unreinforced + Reinforced Concrete (8 inch lining) + Drill & Blast
* Rockbolts + Shotcrete + Drill & Blast
* Unreinforced + Shotcrete + Drill & Blast

COST CALCULATIONS

References	Corresponding Page in Bibliography
1. Tunnel and Station Cost Methodology Volume I - Mined Tunnels Multisystems, Inc. Prepared for D.O.T. (1980)	266
2. Means - Building Construction Cost Data (1981)	262
3. Tunnelling Technology - Appraisal of the State of the Art for Application to Transit Systems	265
4. Economic Factors in Tunnel Construction	263
5. The Impact of Structural Design Conservatism on the Cost of Rapid Transit Tunnels - Photios G. Ioannou, Plus his Costing Working Papers	264
6. Tunnelling - The State of the Industry	265
7. Tunnelling Cost Analysis - Spittel	266
8. Harry Sutcliffe - Bechtel (Project Manager)	
9. Krumpotic, M. - G.F. Atkinson (Chief Estimator)	

EQUIPMENT USED IN BUILDING ROCK TUNNELS

Reference 6, Pp. 11-2, 11-3

* Haulage:	Mine Cars Car Dumpers Rails, Turnouts LHD (Load-Haul-Dump)
* Muck Hoist:	Mine Hoist Cage-Skip-Bins Measuring Pocket Inclined Shafts
* Breaking Rock:	Drills, Booms & Drill Steel Explosives Air Compressors - High Drill Jumbo
* Loading Muck:	Mucking Machines
* Ground Support:	Ribs-and-Wood Lags Steel Ribs Rock Bolts Shotcrete
* Concrete Lining:	Steel Forms Concrete Pump or Gun Agitator Cars Concrete Cars Pneumatic Grouters Grout Mixer & Pump Mixing or Batch Plant

CREW COMPOSITIONS

* For Drill-and-Blast Excavation

1 Shift:

Supervisors:	
Walker	1
Shifter	1
Laborers:	
Miner	6
Chuck Tender	3
Nipper	1
Powderman	1
Operating Engineers:	
Muck Operator	1
Mechanic in Tunnel	1
Oiler in Tunnel	1
Muckers	4
Foreman	1
Electricians:	
Electrician	1
Bull Gang (1 Foreman, 3 Laborers)	4
Installing Support:	
Miners (Ribs & Lagging)	5
Miners (Rockbolts & Shotcrete)	5

References: 1, Tables E-6, E-7
6, Exhibit 4-H (Pp. 4-17)

* <u>For Poured Concrete Operations</u>

1 Shift:

Shifter (Walking Boss)	2
Foreman	1
Miner (Installing Cast-in-Place Concrete)	8
Pumpman (Concrete)	1
Oiler	1
Operator (Hydraulic Form Traveler)	1
Rodman	4

Reference: 1, Table E-8

* <u>For De-Watering Operations</u>

1 Shift:

Pump Operator	1
Mechanic	1

Reference: 1, Table E-9

* Assume an average hourly wage rate of $12/hr. including fringe benefits for all preceding crew composition labor classifications.

Reference: 1, Tables G-1, G-2, G-3

RATES OF ADVANCE

* Drill & Shoot Method

	Extensive Investigation			Minimum Investigation	
	Uniform High R.Q.D.	Mixed Phase	Uniform Low R.Q.D.	High R.Q.D.	Low R.Q.D.
R.O.A. (Low Water Inflow)	60ft/day	45ft/day	30ft/day	50ft/day	30ft/day
R.O.A. (High Water Inflow at Crown of Tunnel)	30ft/day	22ft/day	15ft/day		

References: 3, P. 60, Figure 38 (P61)
8, 9

* Steel-Ribs (Steel sets) Spacing

Rule of Thumb (Krumpotic)
Not more than 5ft spacing

	Extensive Investigation			Minimum Investigation	
	Uniform High R.Q.D.	Mixed Phase	Uniform Low R.Q.D.	High R.Q.D.	Low R.Q.D.
Spacing	5ft	4ft	3ft	5ft	3ft

References: 3, Pp. 104-105, Table 29
8, 9

EQUIPMENT COSTS

☆ Drill and Blast Excavation

- Drill Jumbo, Spare Drills

  JUMBOWIL 2052, 20 ft. diameter Jumbo on wheels, electric/hydraulic drilling, 5 face drills, 2 rock bolt drills = $1,120,000 (Reference 1, Appendix F). Write-off value = 80% (Reference 1, Appendix D).

  Cost = .8 x $1,120,000 = $896,000 ≅ $170/ft.

- 4 LHD

  8 cubic yards capacity @ $225,000 each (Reference 1, Appendix F) (Mucking). Write-off value = 50%.

  Cost = 4 x $225,000 x .5 = $450,000 ≅ $86/ft.

- Crane for Muck Lifting

  Crane 100C, 100 ton hydraulic crawler crane.

  1 month = 22 working days. Cost = $245,000 (Reference 1, Appendix F)

  Monthly Rental Cost = $245,000 x 0.03 (Reference 1, Page 38)

Number of Months - Duration

		With Excessive Water Inflow	Cost	
High R.Q.D.	$\frac{5280}{60}$ = 88 days 4 months	8 months	$6/LF	$12/LF
Mixed Phase	$\frac{5280}{45}$ = 118 days $5\frac{1}{2}$ months	11 months	$8/LF	$16/LF
Low R.Q.D.	$\frac{5280}{30}$ = 176 days 8 months	16 months	$12/LF	$24/LF

- Flat Cars for Moving Support

  4 x \$8,000 = \$32,000 $\cong$ \$6/LF (Reference 1, Appendix F)

- Dynamite & Miscellaneous (Blasting equipment, magazines, warning system, gas detector)

High R.Q.D.	6.4 lbs/CY	(Reference 1, Page 35)
Mixed	4.3 lbs/CY	
Low R.Q.D.	2.8 lbs/CY	

<u>Excavation</u>

	Excavated Volume
8in. conc. lining = (19ft.(I.D.) + 8in. + 12in.) x $\sqrt{1.11}$ $\simeq$ 22ft. = (steel ribs lagging) (over breakage, Ref. 1, P.35)	75,000CY
12in. conc. lining $\simeq$ 22.5ft. =	78,000CY
14in. conc. lining $\simeq$ 23ft. =	82,000CY
4in. shotcrete $\simeq$ 20.5ft. =	65,000CY

<u>Dynamite Cost</u>

	8 inches	12 inches	14 inches	4 inches
High R.Q.D.	\$60/LF	\$63/LF	\$65/LF	\$52/LF
Mixed	\$41/LF	\$42/LF	\$44/LF	\$35/LF
Low R.Q.D.	\$26/LF	\$28/LF	\$29/LF	\$23/LF

Dynamite @ \$0.65/lb (Reference 1, Appendix F)

☆ Muck Transportation

Two mile distance assumed.

Concrete lining 8 inches	\$75/ft.
Concrete lining 12 inches	\$80/ft.
Concrete lining 14 inches	\$85/ft.
Shotcrete 4 inches	\$68/ft.

Reference 5 (Working Papers), 7

☆ Temporary Support

$$\text{Steel Ribs} \Rightarrow \text{Cost/LF} = \frac{\overset{\text{circumference}}{(\text{O.D.} \times \pi)}}{\text{spacing}} \times \text{Weight} \times \$/\text{wt.}$$

$\frac{\text{Length}}{\text{Spacing}}$ = # of Ribs		8 in.	12 in.	14 in.
1056	High R.Q.D.	\$131/ft.	\$134/ft.	\$137/ft.
1320	Mixed R.Q.D.	\$164/ft.	\$167/ft.	\$172/ft.
1760	Low R.Q.D.	\$218/ft.	\$223/ft.	\$229/ft.

Assume 8 inch WF Steel (21 lbs.) (Reference 8)

\$0.45/lb. (Reference 1, Appendix H)

☆ Lagging

\$150/ft. (References 4,5)

☆ Rock Bolts

1 5/8 inch diameter rock bolt (10-15 ft. long) @ \$2.60/ft.

Reference 1, Appendix H

10 ft. rock bolts @ 2 ft., pattern spacing @ 4 ft.

$$\text{Cost/LF} = \frac{20.5 \times \pi}{2 \times 2 \times 4} \times 10 \text{ ft.} \times 2.6 = \$105/\text{LF}$$

☆ Ribs Installer

\$75,000 = \$14/LF (Reference 1, Appendix F)

* <u>Permanent Lining</u>

- Steel Forms = \$18/LF

Cost of Concrete 14 inch lining $= 2/3 \times \pi \times \dfrac{(23^2-19^2)}{4 \times 27} = 3.26 \times 46.8 = \$153/LF$

Cost of Concrete 12 inch lining $= 2/3 \times \pi \times \dfrac{(22.5^2-19^2)}{4 \times 27} = 2.82 \times 46.8 = \$132/LF$

Cost of Concrete 8 inch lining $= 2/3 \times \pi \times \dfrac{(22^2-19^2)}{4 \times 27} = 2.39 \times 46.8 = \$112/LF$

CY of Concrete (material) @ \$46.80/CY (4000psi) (Reference 2, P.64)

* <u>Reinforcing Steel</u>

(Ref.1, Appendix H)

14in. lining Cost/ft. of Re-steel $= 0.07\% \times 3.26 \times 27 \times 490$ lb/Cuft. $\times \$0.4/lb = \$12/ft.$

12in. lining Cost/ft. of Re-steel $= 0.07\% \times 2.82 \times 27 \times 490$ lb/Cuft. $\times \$0.4/lb = \$11/ft.$

8in. lining Cost/ft. of Re-steel $= 0.07\% \times 2.39 \times 27 \times 490$ lb/Cuft. $\times \$0.4/lb = \$10/ft.$

* <u>Curing Compound</u>

Sq.ft. of Concrete to be treated with curing compound $= 2/3 \times \pi \times 19 \times 5280 = 210110$ (Reference 1, P.42)

1 gallon for 300 sq.ft.

1 gallon @ \$3.4 (Reference 1, Appendix H)

Cost/ft. $= \dfrac{210110}{300} \times \dfrac{3.4}{5280} = \$1$

☆ Equipment for Poured Concrete (Reference 1, Appendix F)

Hydraulic Form Traveler	\$25,000
Concrete Pump	80,000
Vibrators (6)	8,000
Agitator Cars (2)	50,000

\$163,000 - 50% Write off = \$80,000 ≅ \$15/ft.

☆ Shotcrete

- Square footage of shotcrete to cover surface area $= 2/3 \times \pi \times 20.5 \times 1 = 43$ sq.ft.

  (material cost, Ref. 2, P.67)

  Cost/ft. = 43 x 2.35 = \$102/ft.

  Assume 20% wasted ⇒ \$123/ft.

- 2 Shotcrete pumps @ \$31,000 (50% Write off) = \$6/ft.

  (Reference 1, Appendix F)

☆ Placing Concrete & Finishing (invert & sidewalk) = \$45/ft.

(Reference 1, Appendix I)

☆ Excessive Water Infiltration (100 Gallons/Minute/100 ft.)

(See Reference 1, P.54)

(Ref.1, Appendix F)

(2) 6in. Pumps @ \$20,000 (50% Write off) = \$10/ft.

(Including Piping & Operating Costs)

Deep Wells = \$15/ft. (Reference 1, Appendix I)

Leak Stoppage During Excavation = \$10/ft. (Reference 1, Appendix I)

☆ Low Water Infiltration

2in. Submersible Pump @ \$1,000 + Leak Stoppage = \$5/ft.

LABOR COSTS

* Drill & Blast Excavation, Ribs & Lagging, Concrete Lining

Labor Force = 45/shift x 3 = 135 employed/day

Hourly Rate = $12/hr.

High R.Q.D.		Mixed		Low R.Q.D.	
High Water Inflow	Low Water Inflow	High Water Inflow	Low Water Inflow	High Water Inflow	Low Water Inflow
$432/ft.	$216/ft.	$594/ft.	$297/ft.	$864/ft.	$432/ft.

Example: For High R.Q.D., High Water Inflow

Duration = 8 months = 8 x 22 = 176 days

Labor Cost/ft. = $135 \times 12 \times 8 \times 176 \times \frac{1}{5280}$ = $432/ft.

* All Other Scenarios

Labor Force = 40/shift x 3 = 120 employed/day

Hourly Rate = $12/hr.

High R.Q.D.		Mixed		Low R.Q.D.		Average R.Q.D.	
High Water Inflow	Low Water Inflow	High Water Inflow	Low Water Inflow	High Water Inflow	Low Water Inflow	Average High R.Q.D.	Average Low R.Q.D.
$384/ft	$192/ft	$528/ft	$264/ft	$768/ft	$384/ft	$\frac{384+192}{2}$ = $288/ft	$\frac{768+384}{2}$ = $576/ft

EXCAVATION COSTS

* Fixed for All Scenarios, Ribs & Lagging & Re-Concrete

Drill Jumbo	$160/ft.
4 LHD	86/ft.
Flat Cars	6/ft.
Lagging	150/ft.
Rib Installer	14/ft.
Steel Forms	18/ft.
Curing Compound	1/ft.
Equipment for Poured Concrete	15/ft.
Invert & Sidewalk Concrete	45/ft.
	$495/ft.

* Fixed for All Scenarios, Rockbolts & Re-Concrete

Drill Jumbo	$160/ft.
4 LHD	86/ft.
Flat Cars	6/ft.
Steel Forms	18/ft.
Curing Compound	1/ft.
Equipment for Poured Concrete	15/ft.
Invert & Sidewalk Concrete	45/ft.
Rockbolts	105/ft.
	$436/ft.

COSTS OF STEEL SETS & RE-CONCRETE OPTION FOR VARYING GEOTECHNICAL CONDITIONS

Dollars/ft.	High R.Q.D.						Mixed						Low R.Q.D.					
	High Water			Low Water			High Water			Low Water			High Water			Low Water		
Items	8in	12in	14in	8in	12in	14in	8in	12in	14in	8in	12in	14in	8in	12in	14in	8in	12in	14in
Crane	$12	$12	$12	$6	$6	$6	$16	$16	$16	$8	$8	$8	$24	$24	$24	$12	$12	$12
Dynamite	60	63	65	60	63	65	41	42	44	41	42	44	26	28	29	26	28	29
Muck Transpor.	75	80	85	75	80	85	75	80	85	75	80	85	75	80	85	75	80	85
Steel Ribs	131	134	137	131	134	137	164	167	172	164	167	172	218	223	229	218	223	229
Concrete	112	132	153	112	132	153	112	132	153	112	132	153	112	132	153	112	132	153
Re-Steel	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12	10	11	12
Water Control	35	35	35	5	5	5	35	35	35	5	5	5	35	35	35	5	5	5
Labor Costs	432	432	432	216	216	216	594	594	594	297	297	297	864	864	864	432	432	432
Fixed	495	495	495	495	495	495	495	495	495	495	495	495	495	495	495	495	495	495
TOTALS	$1362/ft	$1394/ft	$1426/ft	$1110/ft	$1142/ft	$1174/ft	$1542/ft	$1572/ft	$1606/ft	$1207/ft	$1237/ft	$1271/ft	$1859/ft	$1892/ft	$1926/ft	$1385/ft	$1418/ft	$1452/ft

COSTS OF ROCKBOLTS & RE-CONCRETE OPTION FOR VARYING GEOTECHNICAL CONDITIONS

Dollars/ft	High R.Q.D.						Mixed						Low R.Q.D.					
	High Water			Low Water			High Water			Low Water			High Water			Low Water		
Items	8in	12in	14in	8in	12in	14in	8in	12in	14in	8in	12in	14in	8in	12in	14in	8in	12in	14in
Crane	$12	$12	$12	$ 6	$ 6	$ 6	$16	$16	$16	$ 8	$ 8	$ 8	$24	$24	$24	$12	$12	$12
Dynamite	52	54	55	52	54	55	35	36	37	35	36	37	23	24	25	23	24	25
Muck Transport.	70	71	72	70	71	72	70	71	72	70	71	72	70	71	72	70	71	72
Concrete	63	73	83	63	73	83	63	73	83	63	73	83	63	73	83	63	73	83
Re-Steel	5	6	7	5	6	7	5	6	7	5	6	7	5	6	7	5	6	7
Water Control	35	35	35	5	5	5	35	35	35	5	5	5	35	35	35	5	5	5
Labor Costs	384	384	384	192	192	192	528	528	528	264	264	264	768	768	768	384	384	384
Fixed	436	436	436	436	436	436	436	436	436	436	436	436	436	436	436	436	436	436
TOTALS	$1057/ft	$1071/ft	$1084/ft	$ 829/ft	$ 843/ft	$ 856/ft	$1201/ft	$1214/ft	$1227/ft	$886/ft	$ 899/ft	$ 912/ft	$1424/ft	$1437/ft	$1450/ft	$ 998/ft	$1011/ft	$1024/ft

CONSIDER THE DESIGN OPTION OF ROCKBOLTS/SHOTCRETE & RE-CONCRETE

Excavated Diameter		Excavated Volume
8in re-concrete = $\left[19ft(ID) + 8in(lining) + 4in(shotcrete)\right] \times \sqrt{1.11}$	= 21ft =	68,000CY
12in re-concrete =	21.4ft =	71,000CY
14in re-concrete =	21.6ft =	72,000CY

Dynamite Cost

	8 inches	12 inches	14 inches
High R.Q.D.	$54	$56	$57
Mixed	$36	$38	$39
Low R.Q.D.	$24	$25	$26

Muck Transportation

$71/ft (8 inch lining)
$73/ft (12 inch lining)
$74/ft (14 inch lining)

Shotcrete

- Square footage of shotcrete to cover surface area (14 inch concrete lining) $= 2/3\times\pi\times21.6\times1 = 45$ sq.ft.

  Square footage of shotcrete (12 inch concrete lining) $= 2/3\times\pi\times21.4\times1 = 45$ sq.ft.

  Square footage of shotcrete (8 inch concrete lining) $= 2/3\times\pi\times21\times1 = 44$ sq.ft.

  Cost/ft. (14 inch lining) = $45\times2.35\times1.2$ = \$127/ft.

  Cost/ft. (12 inch lining) = $45\times2.35\times1.2$ = \$127/ft.

  Cost/ft. (8 inch lining) = $44\times2.35\times1.2$ = \$124/ft.

- 2 Shotcrete pumps @ \$31,000 (50% write off) = \$6/ft.

Permanent Lining

Steel Forms = \$18/1.ft.

Cost of Concrete 14 inch lining $= 2/3\times\pi\times\left[\frac{(21.6-0.33)^2-19^2}{4\times27}\right] = 1.77\times\$46.8/CY = \$83/1.ft.$

Cost of Concrete 12 inch lining $= 2/3\times\pi\times\left[\frac{(21.4-0.33)^2-19^2}{4\times27}\right] = 1.60\times\$46.8/CY = \$75/1.ft.$

Cost of Concrete 8 inch lining $= 2/3\times\pi\times\left[\frac{(21-0.33)^2-19^2}{4\times27}\right] = 1.29\times\$46.8CY = \$60/1.ft.$

Reinforcing Steel

14 inch lining @ \$7

12 inch lining @ \$6

8 inch lining @ \$5

* Fixed for All Scenarios, Rockbolts/Shotcrete & Re-Concrete

Drill Jumbo	$160/ft.
4 LHD	86/ft.
Flat Cars	6/ft.
Steel Forms	18/ft.
Curing Compound	1/ft.
Equipment for Poured Concrete	15/ft.
Invert & Sidewalk Concrete	45/ft.
Rockbolts	105/ft.
Shotcrete Pumps	6/ft.
	$442/ft.

COSTS OF ROCKBOLTS / SHOTCRETE & RE-CONCRETE OPTION FOR VARYING GEOTECHNICAL CONDITIONS

Dollars/ft.	High R.Q.D.						Mixed						Low R.Q.D.					
	High Water			Low Water			High Water			Low Water			High Water			Low Water		
Items	8in	12in	14in	8in	12in	14in	8in	12in	14in	8in	12in	14in	8in	12in	14in	8in	12in	14in
Crane	$12	$ 12	$ 12	$ 6	$ 6	$ 6	$ 16	$ 16	$ 16	$ 8	$ 8	$ 8	$24	$24	$24	$ 12	$12	$ 12
Dynamite	54	56	57	54	56	57	36	38	39	36	38	39	24	25	26	24	25	26
Muck Transport.	71	73	74	71	73	74	71	73	74	71	73	74	71	73	74	71	73	74
Shotcrete	124	127	127	124	127	127	124	127	127	124	127	127	124	127	127	124	127	127
Concrete	60	75	83	60	75	83	60	75	83	60	75	83	60	75	83	60	75	83
Re-Steel	5	6	7	5	6	7	5	6	7	5	6	7	5	6	7	5	6	7
Water Control	35	35	35	5	5	5	35	35	35	5	5	5	35	35	35	5	5	5
Labor Costs	384	384	384	192	192	192	528	528	528	264	264	264	768	768	768	384	384	384
Fixed	442	442	442	442	442	442	442	442	442	442	442	442	442	442	442	442	442	442
TOTALS	$1187/ft.	$1210/ft.	$1221/ft.	$ 959/ft.	$ 982/ft.	$ 993/ft.	$1317/ft.	$1340/ft.	$1351/ft.	$1015/ft.	$1038/ft.	$1049/ft.	$1553/ft.	$1575/ft.	$1586/ft.	$1127/ft.	$1149/ft.	$1160/ft.

CONSIDER THE DESIGN OPTION OF ROCKBOLTS & RE-CONCRETE

Excavated Diameter			Excavated Volume
(8in re-concrete) = $(19ft(ID)+8in(lining))\times\sqrt{1.11}$ =	20.75ft.	=	66,000CY
(12in re-concrete) =	21 ft.	=	68,000CY
(14in re-concrete) =	21.25ft.	=	69,000CY

Dynamite Cost

	8 inches	12 inches	14 inches
High R.Q.D.	\$52/lf	\$54/lf	\$55/lf
Mixed	\$35/lf	\$36/lf	\$37/lf
Low R.Q.D.	\$23/lf	\$24/lf	\$25/lf

Muck Transportation

\$70/ft (8 inch lining)

\$71/ft (12 inch lining)

\$72/ft (16 inch lining)

Permanent Lining

Steel Forms = \$18/lf

Cost of Concrete 14 inch lining $= 2/3 \times \pi \times \frac{(21.25^2-19^2)}{4 \times 27} = 1.76 \times \$46.8/CY = \$83/lf$

Cost of Concrete 12 inch lining $= 2/3 \times \pi \times \frac{(21^2-19^2)}{4 \times 27} = 1.55 \times \$46.8/CY = \$73/lf$

Cost of Concrete 8 inch lining $= 2/3 \times \pi \times \frac{(20.75^2-19^2)}{4 \times 27} = 1.35 \times \$46.8/CY = \$63/lf$

Reinforcing Steel

14 inch lining @ \$7/lf

12 inch lining @ \$6/lf

8 inch lining @ \$5/lf

CONSIDER THE DESIGN OPTION OF UNREINFORCED & RE-CONCRETE (8 inch lining)

This option is encountered in the geotechnical scenario of:

- Extensive Investigation (Uniform High R.Q.D.)
- High Water Infiltration

Cost of this option for the above scenario:

Drill Jumbo	$160/ft.	
4 LHD	86/ft.	
Flat Cars	6/ft.	
Steel Forms	18/ft.	
Curing Compound	1/ft.	
Equipment for Poured Concrete	15/ft.	
Invert & Sidewalk Concrete	45/ft.	
Dynamite	52/ft.	(Refer to option of rockbolts & re-concrete
Muck Transportation	70/ft.	
Concrete	63/ft.	
Re-Steel	5/ft.	
Crane	12/ft.	
Water Control	35/ft.	
Labor	384/ft.	
	$952/ft.	

CONSIDER THE DESIGN OPTION OF ROCKBOLTS & RE-CONCRETE (8 Inch Lining - Upper Arch)

This option is encountered in the geotechnical scenario of:

- Extensive Investigation (Uniform High R.Q.D.)
- Low Water Infiltration

Looking at cost table of Rockbolts & Re-Concrete under High R.Q.D., Low Water and 8 inch lining, the total cost would be equal to $829/ft.

For an 8 inch concrete lining in the upper arch, the cost will be:

$63/ft. x 3/4 = $48/ft., $15/ft. less.

Therefore, cost of this option = $829 - $15 = $814/ft.

CONSIDER THE DESIGN OPTION OF UNREINFORCED & SHOTCRETE

This option is also encountered in the geotechnical scenario of:

- Extensive Investigation (Uniform High R.Q.D.)
- Low Water Infiltration

Cost of this option for the above scenario:

Drill Jumbo	$160/ft.
4 LHD	86/ft.
Crane	6/ft.
Dynamite	52/ft.
Muck Transportation	68/ft.
Shotcrete	123/ft.
Shotcrete pumps	6/ft.
Invert & Sidewalk Concrete	45/ft.
Water Control	5/ft.
Labor	192/ft.
	$743/ft.

CONSIDER THE DESIGN OPTION OF ROCKBOLTS & SHOTCRETE

This option is encountered in the geotechnical scenarios of:

Table VI - 3a

- Extensive Investigation (Uniform High R.Q.D.)
- Low Water Infiltration

Table VI - 3g

- Minimum Investigation (Average High R.Q.D.)

Cost of the option for scenario VI - 3a:

Drill Jumbo	\$160/ft.
4 LHD	86/ft.
Crane	6/ft.
Dynamite	52/ft.
Muck Transportation	68/ft.
Rockbolts	105/ft.
Shotcrete	123/ft.
Shotcrete pumps	6/ft.
Invert & Sidewalk Concrete	45/ft.
Water Control	5/ft.
Labor	192/ft.
	\$848/ft.

Cost of the option for scenario VI - 3g:

Drill Jumbo		\$160/ft.
4 LHD		86/ft.
Crane	$\frac{6+12}{2}$	9/ft.
Dynamite		52/ft.
Muck Transportation		68/ft.
Rockbolts		105/ft.
Shotcrete		123/ft.
Shotcrete pumps		6/ft.
Invert & Sidewalk Concrete		45/ft.
Water Control	$\frac{5+35}{2}$	20/ft.
Labor		288/ft.
		\$962/ft.

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