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SUBSURFACE EXPLORATION METHODS FOR SOFT GROUND RAPID TRANSIT TUNNELS
Volume I: Sections 1-6 and References

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FINAL REPORT

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16. Abstract

The objectives of the Urban Mass Transportation Administration (UMTA) Tunneling Program are to lower subway construction costs and reduce construction hazards and damage to the environment. Some measure of each of these objectives for bored tunnels and deep excavations can be achieved through a more detailed knowledge of the subsurface and of how changes in soil types or characteristics will affect construction.

This study assesses subsurface exploration methods with respect to their ability to provide adequate data for the construction of rapid transit, soft-ground bored and cut-and-cover tunnels.

Geophysical and other exploration tools not now widely used in urban underground construction are investigated, their potential is discussed, and performance specifications and ideas for future development are presented. The effect of geotechnical variations on construction costs is modeled, and the effect of the prior knowledge of variations estimated. Requirements for the best methods of site investigation, including preliminary designs, specifications, cost estimates, and development plans, are formulated.

Volume one contains Sections 1-6 and all references. Volume two contains Appendixes A-F.

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PREFACE

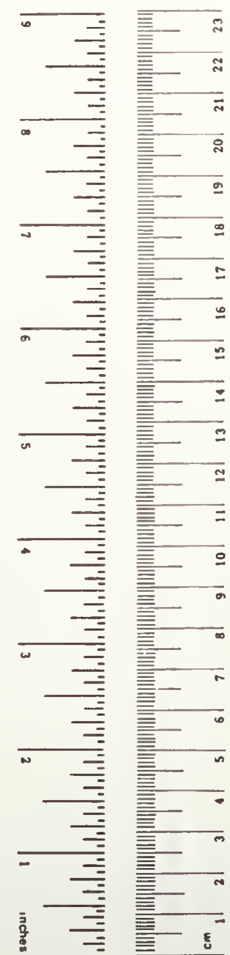
The study investigation of subsurface exploration methods for soft ground rapid transit tunnels, described in this two-volume report, was sponsored by the Rail Technology Division of the Urban Mass Transportation Administration, Office of Research and Development. The effort was conducted under contract with the Transportation Systems Center, contract DOT-TSC-654, for the Urban Rail Supporting Technology Program.

George Kovatch and Andrew Sluz were contract technical monitors for TSC. Birger Schmidt of Parsons, Brinckerhoff, Quade & Douglas, Inc. was Project Manager responsible for overall coordination and the principal writer of the sections 1 through 4. Bruno Matarazzi, Economist with Parsons, Brinckerhoff, Quade & Douglas, developed the economical analyses in Appendix A, assisted by Robert D. Budd of Mason and Hanger. The inventories and the detailed development of new methodologies, sections 5 and 6, were largely in the hands of C. John Dunnicliff, Chief Engineer, and Stephen A. Alsup, Geophysicist, both of Soil and Rock Instrumentation, Inc., with consultation services provided by Seismograph Services Corporation, Inc.

METRIC CONVERSION FACTORS

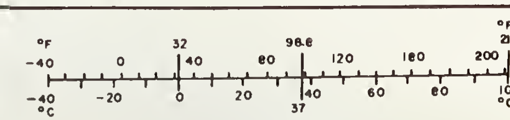
Approximate Conversions to Metric Measures

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



Approximate Conversions from Metric Measures

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



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1. INTRODUCTION

1.1 WHY EXPLORATION TECHNOLOGY SHOULD BE IMPROVED

A typical rapid transit tunnel contract in soil includes some 6,000 feet of single-track running tunnel and costs $18 to $24 million, including track and other finish work. Most of this cost is incurred for shaft and tunnel excavation, temporary and permanent ground stabilization and support, utilities relocation, or support or protection of existing structures.

For geotechnical explorations, tests, and analyses for such a tunnel contract, the owner typically expends $60,000 to $70,000 or about one-third of one percent of the construction cost.

Selection of ground support systems, optimization of excavation and construction processes, underpinning of structures, utilities relocation, and other significant construction cost items are to a greater or lesser extent influenced or dictated by geotechnical data developed by the geotechnical exploration program.

Based on adequate subsurface information, a tunnel alignment or elevation can often be selected to avoid or minimize problems such as may be associated, for example, with pervious and waterlogged cohesionless soils, or with boulders and bedrock. Since tunnel construction costs can be four times greater in a soil-rock mixed-face situation than in either soil or rock full-face conditions, potential cost savings are very substantial.

The roof stand-up time of soil in a tunnel is a function of geotechnical parameters measurable during the exploration phase, and may indicate the feasibility of a liner system expanded directly against the soil rather than one erected within a shield, at a very significant cost saving.

Where ground stabilization is needed, the selection of ground stabilization technology - dewatering, compressed air, grouting, or a combination - depends greatly on measurable soil and groundwater parameters. The proper selection has a great effect on the overall economy of the tunnel construction. For example, the use of compressed air, where dewatering is judged technically unfeasible, could increase the tunnel driving cost, particularly for short sections.

Since expenditures for geotechnical data acquisition for rapid transit tunnels currently are an insignificant one-third of one percent of the construction costs, and since potential savings from adequate interpretations of an adequate geotechnical data can be substantial, the cost/benefit ratio of improved subsurface exploration technology can be very high. Even a doubling or tripling of exploration costs would be justified if it would result in a construction cost improvement of only a few percent.

A soft ground tunneling system - excavator, immediate face and wall support, lining, muck removal - may be designed either to cope with a limited range of ground conditions, or to handle nearly every type of ground condition conceivable. Considerable discussion has been expended on which type of design is most feasible. Clearly, a system with unlimited capabilities obviates the need for accurate forecasting of tunneling conditions. In a systems study by Fenix & Scisson, Inc. and A.D. Little, Inc. (1970), the conclusion was reached that "the most cost-effective system choice is the unlimited system where there exists a risk of greater than 10% of encountering bad ground conditions." These researchers admitted, however, that none of their proposed unlimited systems could cope economically with a large amount of boulders or soil-rock mixed-face conditions. R.J. Robbins (1972), a tunneling equipment supplier, reached a somewhat similar conclusion: "Maintaining reasonable and planned advance rates through unpredicted and varying geologic conditions should be identified as the major development frontier." Mr. Robbins also concludes, however, that "the universally adaptable dream system ... does not seem to be a very serious likelihood for at least many years to come."

The possibility of one day having this universally adaptable dream system available is real, but such a system will, no doubt, have a high initial cost and may only be applied economically to long tunnels. A tunnel shield without a mechanical excavator but including hydraulic jacks costs $300,000 to $500,000. The addition of a mechanical excavator increases the cost to $800,000 to $1,000,000. Several attempts have been made to produce a universally adaptable machine; some were successful but most were not. One of the most successful machines, the BADE tunneler, costs about $1,800,000. It is evident that universality comes at a significant cost penalty.

For a few years to come, then, most tunnels will be driven with equipment of limited capability, designed to deal with specific ranges of ground conditions as determined by geotechnical explorations. Even when the universal equipment is available, many tunnels will be driven most economically with more limited equipment.

Thus, it makes good economic sense to develop and employ tools that will improve our capabilities to predict the conditions and adversities of tunneling so that the most appropriate construction technology may be employed with little risk of encountering costly unanticipated adverse conditions.

1.2 SCOPE OF THIS STUDY

The basic objectives of this research and development project are to develop techniques for reducing tunneling costs, enhancing the safety of urban tunneling, and minimizing the adverse impacts of tunnel construction on the urban environment. This project is one of several projects whose combined goal is to make urban mass transit tunnels an environmentally and economically attractive solution to urban transportation problems.

Specifically, this project deals with the development of new or improved subsurface exploration technology and methodology for use before and during excavation and tunneling. Requirements, specifications, and preliminary designs of subsurface investigation tools have been prepared that should improve both the measurement of in-situ properties of geologic materials and the prediction of geologic and groundwater conditions, anomalies, and natural or man-made obstructions.

In this study, problems of urban soft ground tunneling in the United States have been emphasized. A typical urban transit tunneling contract involves shield-driven twin tunnels, 15 to 20 feet in diameter, at depths less than 150 to 200 feet. Cut-and-cover tunnels are generally shallower, with a maximum depth of 90 feet. Cut-and-cover and bored tunnels in soil above and below the ground water level have been considered, including soil-rock mixed-face conditions.

In spite of these basic restrictions, the results are equally applicable and the methodologies developed equally useful for many underground structures constructed for other purposes, with different geometries and in other environments.

In view of the need for immediate improvements in tunneling technology, the studies have emphasized those developments that may be implemented within a three-year time frame, but considerations regarding longer-term developments of other systems without immediate potential are also presented.

The studies have considered improvements or developments of borings and in-situ soil testing, geophysical methods applied from the ground surface, borehole geophysical tools. Techniques for investigations from the tunnel face have been discussed briefly.

The success of an engineering or scientific innovation or development can be measured only by its future use. A novel methodology, however theoretically well founded, is of no value if it is too expensive for practical use, if it provides information only marginally useful for the practicing engineer, if it provides highly ambiguous information, or if interpretation is excessively complex and cumbersome. In other words, a novel or improved methodology must be reliable and credible and provide data of real use in a useful format. Even then, user's incentives may have to be employed to accomplish a rapid acceptance by the profession.

1.3 STUDY APPROACH AND BASIC CRITERIA

Three stages of research are logically pursued; during the first stage the significant geotechnical parameters are identified and the methods currently in use or potentially available for their determination are inventoried. In the second stage the potentials for development are defined and the feasibility and possible cost impact of development are assessed. In the third stage specific requirements for selected systems, preliminary designs, specifications, cost estimates, and development plans are evolved.

The relationship between the different tasks and phases of the effort is suggested in figure 1-1.

Simply stated, the approach adopted on this research project has been as follows:

a. Determine the most significant typical problems in soil tunnel construction, based on literature reviews and personal experiences.

b. Perform economic analyses to determine and verify the cost effect of these typical problems, using model cost estimating, backed up by factual data.

c. Define in detail the parameters of soil and geology responsible for or indicative of these typical problems.

d. Inventory present practice and potential candidates for technology or methodology transfer or improvement.

e. Assess the feasibility of improvement or development of candidate technologies and methodologies for subsurface explorations.

f. Select potentially most useful and cost effective candidates for development.

g. Develop and present requirements, preliminary designs, and specifications for candidate developments, together with a plan and schedule for development and testing.

Basic criteria for the acceptability of candidate developments in terms of this research are:

a. The parameter measured must be associated with an important type of tunnel construction problem, that is, a problem imposing a substantial cost or time delay on tunneling, or posing a significant safety or environmental hazard.

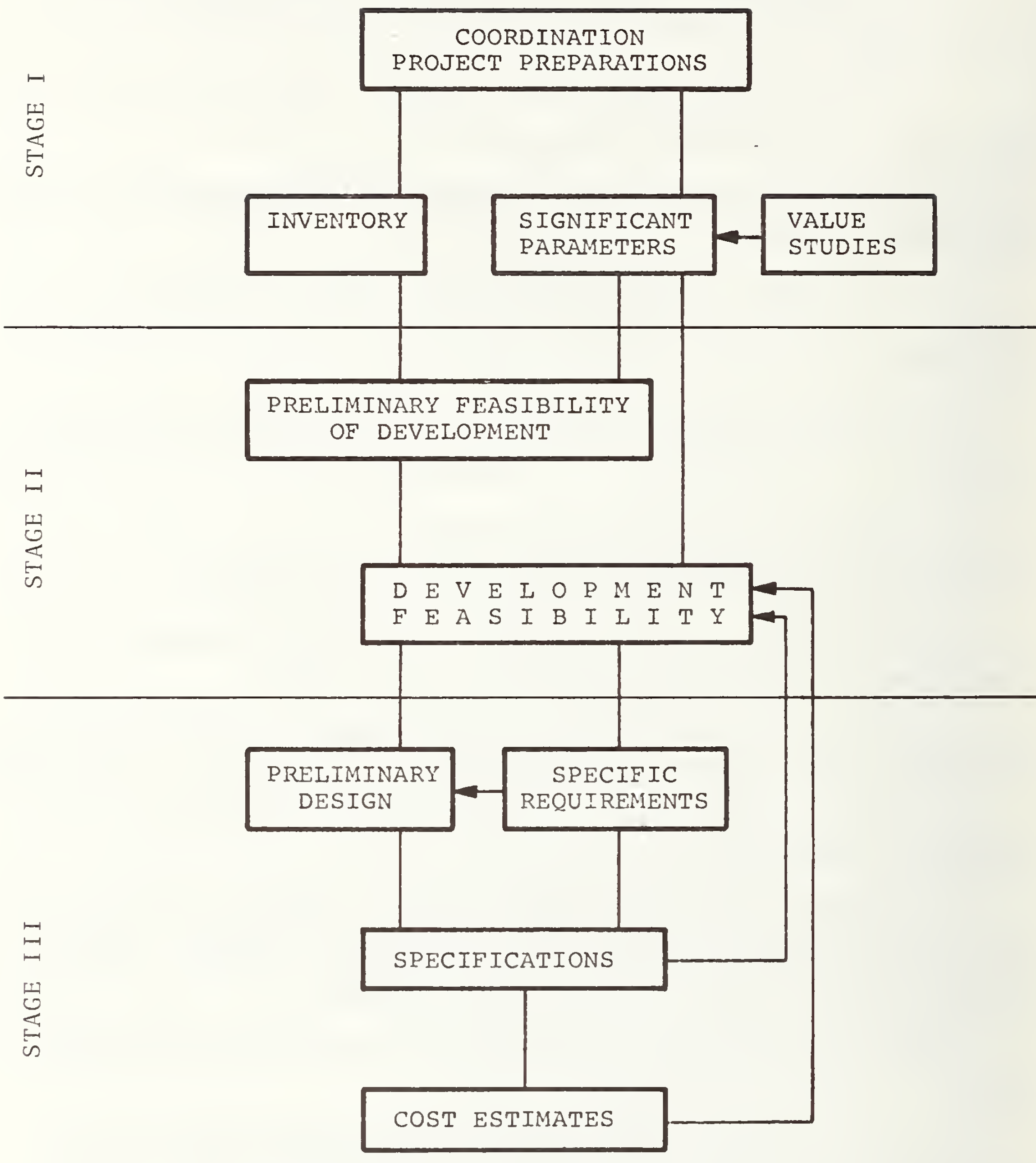


Figure 1-1. Progress Flow Chart.

b. The parameter must be associated with a relatively common problem.

c. Improved quality or quantity of data should result in a likelihood of reducing cost, risk or impact of tunneling. It makes no sense to gather data on a significant parameter if the data is useless, as for example, if no applicable and acceptable theories or methods of analysis exist, to employ the data.

d. The state of technology as regards measurement of particular parameters must be so well developed that prototype (sets of) instruments may be developed and tested within a three-year time frame. This means that no wholly new concepts are likely to be among the successful candidates.

e. The method must be practicable, reliable, and give credible results in engineering language; that is, it must be attractive to the engineer. The cost of its use in practice is of secondary importance, because, as was discussed previously, the cost of geotechnical explorations, even if tripled, would still be a very minor cost item for an urban rapid transit tunnel.

A number of possible developments fulfill these criteria, including direct methods of in-situ measurements as well as indirect methods employed from the ground surface and from boreholes. The items of highest priority are (1) in-situ measurement of permeability; (2) borehole geophysical tools; and (3) surface seismic development.

In paragraph 2.2 the recommended development schemes are briefly presented. The recommended developments are discussed in detail in section 6 and specifications are presented in appendices D and E. Some conclusions of general interest are presented in section 2.1.

In the course of our research, emphasis was placed on development of improved seismic techniques for subsurface explorations. Because such developments were not completed in this study at our sponsors' request, the allotted time was employed instead on an elaboration of the economic studies. It is anticipated that future efforts in seismic research will be conducted by the Federal Highway Administration, consequently the lack of emphasis in this work.

An elaborate, though not time-consuming, effort was also expended on an analysis of the effects of geotechnical parameters on soft ground tunneling. Though only the main results of this analysis are needed in this report, the full analysis, with case histories, is presented in section 4.

Our study has concentrated on bored tunnels. However, the recommendations and most of the general conclusions are equally applicable to cut-and-cover structures.

2. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

2.1 SOME GENERAL CONCLUSIONS

Before presenting the recommended developments, it is worthwhile to describe some of the most important findings that have led to these schemes. These findings are of general interest and not all are original with this project.

a. Geotechnical parameters have a great direct impact on tunnel construction but only a minor direct impact on tunnel design. Indirectly, however, geotechnical parameters have a significant impact on the selection of alignment and depth, optimization of the design, and preparation of contract documents.

b. By far the most severe construction problems in soil tunneling are face and wall stability problems associated with granular soils below the water table. Hence, the most useful geotechnical data relate to the ground water:

1. Soil stratigraphy, identifying aquifers, sources and storage quantities of water, and recharge conditions.
2. Soil permeability, necessary for estimating water flow quantities and gradients.
3. Ground water table, including perched water, or piezometric heads.

c. In granular soils below the water table, a small cohesion or cementation has a significant stabilizing effect. A good knowledge of the available cohesion may allow the use of less expensive construction methods. Unfortunately, this parameter is very difficult to measure by any known conventional or innovative means.

d. In cohesive soils, the most useful parameter for direct or diagnostic use is the undrained shear strength; this may be measured adequately by existing methods.

e. A potentially very important parameter for which much future use is foreseen is the soil modulus of deformation (equivalent to Young's modulus). Directly or indirectly, modulus data provide information about cementation, strength, and other important parameters.

f. Bouldery soils present some of the worst excavation problems for a shield tunnel, and no technological breakthrough is in sight that might improve the economic influence of slow advance rates in bouldery soils. It is desirable to avoid or minimize tunneling in such soils. Unfortunately, conventional and most innovative exploration tools will tell little about the critical parameters: the frequency and size of large boulders in the soil mass.

g. A significant cost item in tunneling is the labor insurance cost (Workmen's Compensation). This is a fact known to contractors and insurers but little appreciated among engineers and owners. Increasing the predictability of tunneling conditions will, in the long run, reduce insurance costs through the elimination of most accidents related to unanticipated soil problems.

h. At present, tunnel designers, tunnel contractors, and dewatering or grouting contractors make little use of sophisticated methods of analysis to optimize their designs and construction procedures. While some will argue that this is because of the inherent unpredictability of tunneling conditions in general, we believe that a prime reason has been the unavailability of adequate geotechnical data commensurate with the complexity of such analyses. Specifically, analyses of the future will include:

1. Slurry-trench wall and support design using finite elements or other appropriate method, considering in detail the soil/structure interaction problem; such analyses will require soil modulus data as functions of stress state and time.

2. Analyses of groundwater flows and gradients under natural and imposed conditions of dewatering and tunneling; such analyses require accurate soil stratigraphy and permeability data.

3. Tunnel face and wall stability analyses; these require soil strength and cohesion data, and input from groundwater flow and gradient analyses.

4. Ground movements and settlements analyses, using finite elements; these require input from face and wall stability analyses, and soil modulus data as functions of stress state and time.

Though such analytical procedures can be developed under the present state of theories and computer technology, they cannot yet be implemented in practice. Development and use of adequate data acquisition methods must first provide improved input data for these analytical procedures. A difficult step in the development will also be a full appreciation of the effects of the construction process itself.

i. With appropriate development of methods of exploration from the ground surface or through boreholes, it will not be necessary to develop or use exploratory tools from the face of a tunnel. Most conceivable methods applied from the face will cause costly interference with tunnel progress; most soil tunnels are sufficiently shallow that explorations from the ground surface are more economical than explorations from the face; and most important decisions regarding tunneling must be made long in advance, before the basic tunneling scheme is decided on. Hence, explorations from the face are of use only to warn against unanticipated danger, and as such are likely to be heeded only if very reliable. These circumstances are rather different from those of deep rock tunnels, where face probing is potentially very valuable. In the few instances where face probing is of real use in soil tunnels, simple tools will do the job.

j. With regard to man-made obstructions, or utilities, the existence or location of deep utilities are normally known in advance. Shallow utilities pose problems primarily where shafts or cut-and-cover construction require their relocation. They will then generally be exposed by careful uncovering and their exact location is frequently immaterial. Only in instances where blind driving, excavation, or drilling occurs is it necessary to have assurances of the location of utilities: for example, when drilling exploratory borings, driving soldier piles, or constructing slurry-trench walls (upper five feet usually pre-excavated in the open). Current technology is judged reasonably adequate and no major breakthrough is expected to improve methods significantly. Such methods, however, are not used to their full extent, and some are not used at all in this country.

k. The techniques for drilling and sampling, and standard penetration testing, need no major development at this time. It should be pointed out, however, that current industry practices do not always guarantee the employment of the best and most suitable tools and methods for exploratory borings with undisturbed sampling. Several methods are available and at a moderate state of development for in-situ testing of soil strength, modulus, and relative density. These include vane shear test devices, several versions of the dilatometer, and several varieties of pseudostatic penetrometers. Except for the vane shear devices, none of these tools have seen significant use in the United States; and before they are developed further, it is suggested that their use be implemented. The interpretation of data from these devices requires considerable experience, which U.S. engineers can obtain only through increased familiarity with the techniques.

l. Direct measurements of soil permeability currently are performed through expensive pumping tests, yielding gross averages of soil permeabilities, or through relatively crude borehole percolation tests, which are not very reliable. In view of the great effect of permeability on water problems in tunneling, methods for in-situ permeability measurements should be improved.

m. Except under very special circumstances, gravity and magnetic surveys show little promise for producing useful and sufficiently accurate data regarding soil stratigraphy. Electric resistivity surveys are of limited use in urban areas where abundant utility lines obscure the effect of soil properties and stratigraphy. Nuclear methods have too shallow a penetration. In view of the difficulties of interpretation, it is not likely that short-term developments can make these tools very useful for stratigraphic purposes. It should be pointed out, however, that some of these tools have applicability for the location of shallow utilities. It is also noted that electromagnetic subsurface profiling, currently under development, shows considerable promise, though its depth of penetration appears to be limited.

n. The state of the art of seismic explorations is well advanced, but the methods currently employed for shallow work in soil are crude. One reason why seismic methods are not extensively used for soil explorations is that the crudeness of both the methodology and the principles of interpretation does not provide sufficient assurance of positive and accurate results. The hardware, electronics, and principles of computerized interpretation now employed for deep seismic work in the oil and mining industries may be used for shallow soft-ground explorations, with some modifications and developments. As a valuable by-product, such methods will also, under the proper circumstances, make it possible to determine the location of relatively deep utilities. Another valuable by-product would be a relatively crude determination of soil modulus. Preliminary assessments backed up by interviews with industry representatives indicate that an appropriate system may be developed and tested within a three-year time frame, and within a total cost of the order of $1,000,000.

2.2 RECOMMENDED DEVELOPMENTS

A future system of subsurface explorations is envisioned, in which a variety of tools are employed to acquire a redundancy of geotechnical data. Traditional borings, sampling, and testing will not be obsolete but will become one series of a larger package of tools available to the exploration engineers. Stratigraphy will be studied in three dimensions by surface geophysical tools, especially varieties of seismic techniques, correlated with conventional borings or borings logged by geophysical logging tools. These tools will also be used to study groundwater conditions. Soil properties, in particular permeability, strength, and cohesion, will be measured either directly by borehole permeability tests and in-situ strength tests, or indirectly by borehole logging tools correlated with some direct tests. Table 2-1 shows a possible future full-range exploration program for a rapid transit tunnel.

TABLE 2-1. EXPLORATION PROGRAM OF THE FUTURE

<u>SURFACE GEOPHYSICS</u> New seismic methods, possibly supplemented by electromagnetic subsurface profiling; to map stratigraphy in three dimensions; to trace significant soil-soil and soil-rock boundaries. Other surface geophysical methods as needed to find utilities.
<u>CONVENTIONAL BORINGS WITH STANDARD PENETRATION AND UNDISTURBED SAMPLING</u> A small number to acquire samples for accurate identification and laboratory testing to correlate with surface and borehole geophysics.
<u>IN-SITU TESTING</u> In boreholes to determine soil strength and permeability, using shear devices, penetrometers, dilatometers, and permeability devices.
<u>BOREHOLE GEOPHYSICS</u> To be logged in conventional borings for correlation purposes, and in a large number of holes, drilled without sampling for the express purpose of logging; to be used for correlating surface geophysics, and for logging certain soil properties and their variations.
<u>COMPUTER ASSISTANCE</u> Needed for interpretation of surface and borehole geophysics, eventually for complete storage, interpretation and retrieval of all exploration data.

Computers will be used, to analyze seismic and borehole geophysical data, and may display the results, and analyze the effects on construction of soil and water conditions.

Geophysical tools do not measure soil properties directly but must be correlated with direct data. As experience is accumulated, however, these correlations will improve and the need for taking large quantities of direct measurements for correlation purposes on a specific project will diminish. In the future, perhaps only a handful of borings will be taken with extensive sampling and direct testing, but a large number of borings will be drilled quickly for geophysical borehole logging, and the regions between bore holes will be mapped by seismic or other surface geophysical methods.

It is too optimistic to expect that such procedures can be fully established in a few years, but the system is certainly feasible. Tools, methodologies, and theories are now available that may be adapted for use in soil. These tools have been used for oil and mineral explorations for many years, and the problem is one of technology transfer rather than technology invention.

Seismic methods are important in this future system, but are not treated in detail here. These are being studied under other Department of Transportation contracts. The following summarizes the recommended developments of direct permeability measurements and geophysical borehole logging systems.

Geotechnical engineers have had dreams about the universal exploratory tool that will enter the soil without a borehole but with simple penetration, and will measure - directly or indirectly - soil density, strength, modulus, moisture content and permeability. This universal sensor now seems near realization. Penetrometers have long been accepted tools, at least abroad, and new developments are on the way to produce a piezometer probe capable of measuring porewater pressures generated by penetration, and their time response, and to produce an accurate moisture sensor. As soon as these developments are finished, the universal exploratory penetrometer may be put together. This instrument could also find use in probing from the tunnel face.

The tools recommended for immediate development fall in two groups: tools and methodologies for direct in-situ measurement of soil permeability, and geophysical borehole logging tools. Recommendations are presented in detail in section 6, and specifications are presented in appendices D and E. The recommendations are briefly summarized here.

a. <u>Direct Permeability Measurement</u>

1. Borehole Permeability Probe: Present borehole permeability tests are often inaccurate and misleading, and a simple, accurate and standardized test is needed. A simple borehole permeability test is proposed. Development efforts will require hardware design and fabrication, some theoretical work, field testing and preparation of a Manual or Test Specification.

2. Perforated Casing Permeability Test: This is a new methodology which uses a special perforated casing section introduced in a standard cased hole, in conjunction with a seal or packers, to perform infiltration and/or drawdown tests through the borehole wall. Development efforts here will include a minor design effort, theoretical work on interpretation methods, fabrication and field testing, and Manual or Test Specification preparation.

3. Modification and Standardization of Large Scale Pumping Tests: This type of test, though expensive, is most reliable for determining large scale permeability and drawdown effects. There is a need to modify and standardize such tests to suit the problems of tunneling in soil. This effort will be mostly analytical, and will involve the development of suitable methodologies.

4. Full Scale Dewatering Test: A test to be performed only at critical locations, consisting of actual installation and testing of prototype system in the design stage. This effort would be carried out in conjunction with the effort above and will include development of interpretation and implementation techniques.

5. Improved Theoretical Methodology: To make optimum use of improved permeability data, to interpret pumping tests, and to analyze dewatering situations,

computer techniques are proposed. The effort will involve a transfer of analytical methodologies known from groundwater resources to highlight the specific problems of dewatering and tunnel stability.

6. Data Bank: Analytical case histories are required to follow up on these developments and to verify the validity of the proposed theoretical analyses.

It is estimated that the first two developments, if carried out jointly, will involve an expenditure of $70,000, and take 18 months. Items 3 and 4 are estimated at $40,000 and 12 months, and items 5 and 6, $120,000 over 24 months.

b. Borehole Logging System. The proposed borehole logging system consists of a set of logging tools to be employed in boreholes, ancillary surface mechanical and recording systems, and computerized methods of interpreation and data display. None of the tools alone would provide meaningful and worthwhile data for tunneling purposes. A set of data from several tools must be interpreted together. The tasks involved in the development of the complete package are the following:

1. Develop, test, and verify automatic interpretation techniques.

2. At selected sites, test those tools that are already available, and correlate with directly measured data, to develop and verify interpretation techniques and demonstrate viability of the system.

3. Develop and Modify Tools: Six borehole logging tools are recommended for repackaging or development. Of these, only two tools need major innovative developments; for the remainder, it is primarily a question of repackaging into a smaller diameter.

4. Field Test of New Tools: All tools developed under 3 will be tested in the laboratory and in standard facilities, but a field test under prototype conditions is also needed.

5. Test of Complete System: The complete system must be tested for verification purposes and as a demonstration project.

The total estimated cost of the borehold logging system development is $1,581,000, expended over a period of three years. Tasks 1, 2, and 3 may proceed immediately and concurrently.

The complete set of recommendations, including both the permeability tools and the borehole logging system, would involve an expenditure of approximately $1.8 million. A return on the investment may be expected to accrue, beginning already after one year. To accelerate the implementation of the methodologies, a concerted effort should be made to disseminate information to users, and to support or even to enforce the use of some or all of these methods on government funded projects.

3. GEOTECHNICAL PARAMETERS SIGNIFICANT TO TUNNELING

3.1 CRITERIA FOR SIGNIFICANCE

Tunneling is one civil engineering endeavor where the engineer does not select his own major structural component, the geologic material, but must accept the conditions nature has provided for him. Hence, material properties, distributions, and variabilities must be obtained for each individual project. Tunnel design is different from most other types of design in that a plausible construction method must be assumed before a basic tunnel structure can be selected and designed. For very few other civil engineering works must the design engineer know as much about construction problems and methods as for tunnel works.

A great many geotechnical parameters influence tunneling in one way or another, and most of them exert their influence on several fronts. A number of significant, common tunnel problems can be identified, each of which is governed by a set of geotechnical variables. To establish the total overall influence of a given parameter, through its combined influence on several different problems, is a very complex matter.

In this section the process of decision making in tunnels is briefly discussed to ascertain at which stages of planning or design geotechnical parameters should ideally be available. Paragraph 3.3 lists the parameters that may have an impact on tunneling. Section 4 discusses the influence that variations in the geotechnical parameters have on tunneling and presents summaries and final assessments of the important geotechnical parameters.

In the context of this study, the importance of a geotechnical parameter for tunneling or deep excavations must be assessed by at least the following criteria:

a. The parameter must be a meaningful physical parameter (property, state, boundary location, etc.) that is measurable directly or indirectly by a tool or a set of tools, or by observation and deduction.

b. The parameter must significantly influence the cost, safety, or environmental impact of a rapid transit tunnel (planning, design, construction, maintenance); that is, it must be associated with an important problem.

c. The parameter must occur in adverse range or condition in a reasonable percentage of tunneling contracts in the United States; that is, it must be associated with a common problem.

d. The problem(s) to which the parameter applies must be analyzable in terms of this parameter, perhaps in combination with others, by known analyses or analyses that may be developed. That is, one should be able to use this parameter in the analysis of, or solution to the problem.

e. Increased or improved parameter data must be likely to affect tunneling beneficially.

Ideally, all of these criteria should be fulfilled to a reasonable degree for a particular parameter. For the successful employment of any tool, instrument, or methodology in practice, several additional criteria must be considered. These criteria apply to the methods of obtaining, interpreting, and presenting parameter data:

a. The data must be credible and reliable; the engineer must have sufficient confidence in them to use them as a basis for judgments and analyses. Verification should be possible through repetition or redundancy.

b. The data must be presented in civil engineering terms. It cannot be expected, for example, that a sufficient number of qualified geophysicists will be available to perform complex interpretations of geophysical data.

c. The equipment and methodology must be attractive to the user and the procurer, economically and otherwise; it must be marketable.

d. In the terms of this contract, the development and testing of new or adapted systems must be possible within a three-year time frame. The development cost, though perhaps a secondary consideration, should be reasonable.

3.2 THE PROCESSES OF PLANNING, DESIGN, AND CONSTRUCTION

The implementation of a rapid transit tunnel can logically be separated into five processes: planning, design, construction planning, construction, and maintenance of the finished structure. There are, of course, many subtasks within each process. Further, the maintenance phase is included primarily for the sake of completeness; apart from corrosion and water tightness problems, geotechnical considerations have little influence on maintenance. The complete implementation process is discussed here to insure that all phases and problems are considered, and to find at what stage the availability of geotechnical data is most critical.

As a rule, a tunnel contractor spends much time and money in mobilizing shields, excavation and mucking equipment, hoists, and other tools, and in setting up his project plant. Also, a good deal of the construction materials (for example, specially manufactured tunnel lining elements) and expendables are ordered at an early stage. Once the tunneling operation is underway, it is extremely difficult and costly to make significant modifications to the construction plant, primarily because the essential parts, the shield and excavator, are quite inaccessible.

For these reasons, it is essential that the contractor prepare in advance his construction plant for the anticipated conditions. Since, in contrast with other types of construction, he only has one point of production - the tunnel face - he is subject to severe cost penalties if misjudgment of tunnel conditions causes delays in his progress.

The planner and the designer must also anticipate tunneling conditions. Some of the important decisions relating to geotechnics, which the planner must make at an early stage, are indicated in table 3-1, which briefly enumerates the most significant tunnel design decisions related to geotechnical parameter investigations. In particular, the selection of construction method - cut-and-cover versus tunnel - and the vertical and horizontal alignment, are cost significant. As will be demonstrated in appendix A, a choice of alignment to avoid specific trouble spots may save the owner

TABLE 3-1. DECISION MAKING IN TUNNEL PLANNING, DESIGN, AND CONSTRUCTION

Type of Decision	Planning & Feasibility Study	Phase During Which Made: Design	Construction Planning	Construction
1. Type contracts, legal, insurance etc.	Final	-	-	-
2. Selection, tunnel vs. cut-and-cover	Preliminary or final	Final	-	-
3. Alignment, horizontal and vertical	Within range of feet or tens of feet	Final	-	-
4. Purchase of property	General	Detailed plan and execution	-	-
5. Determine role of monitoring	General policy	Specific	-	-
6. Underpinning and utilities relocation	General policy	Specific mandatory or optional	Decide on optional items	-
7. Type of support	General terms only	Select and design one or several types; eliminate others	Select one type	-
8. Installation of support	-	Restrictions may be imposed	Select method	Field modifications
9. Shield type	Possible yes/no decision	Possible yes/no decision restrictions	Selection	-
10. Face support	-	Criteria	General decision, availability of tools	Field decisions
11. Excavation and mucking tools	-	-	Detailed design	-
12. Dewatering	-	Possible restrictions and requirements	Yes/no detailed design	Monitoring and field changes
13. Compressed air	General policy	Possible restrictions and requirements	Yes/no design	Select air pressure
14. Ground treatment (grouting, freezing)	-	Note possibility, possible design	Yes/no final design	Field changes

several millions of dollars on a single contract. It is realized, of course, that environmental implications, functional requirements, and other factors may occasionally dictate or limit construction methods or alignments, but value engineering requires that construction cost (highly influenced by potential trouble spots) be included as a planning parameter. Once basic alignments are set in the planning stage, they are difficult to change because of end restraints and other considerations. Unless the geotechnical problems have been properly accounted for, the designers are fixed in what may not be the most economical alignment.

Basic policy decisions regarding types of contracts to be employed, distribution of liabilities and responsibilities, right-of-way acquisition, underpinning criteria, and the specific role of tunnel construction monitoring, are all to some extent influenced by predictions of the types and severity of tunneling problems, environmentally objectionable ground movements, and other geotechnically related problems.

The designer must prepare construction documents that will produce an economical tunnel structure under safe conditions, minimizing the environmental impact. This means that he must determine in advance which types of construction methodology, including ground support and soil stabilization, may be successfully employed. He must also consider the effects of tunneling on the environment so that decisions regarding underpinning, real estate acquisitions, etc., may be made. He must write construction specifications and prepare drawings including all specific limitations and criteria that the contractor must fulfill. If a monitoring program is necessary to insure the safety of the construction, eliminate underpinning, or serve other purposes, the designer must provide a monitoring program with all appropriate measures for the implementation of results and directives based on instrumentation data. If it is possible that compressed air will be used, he must determine if this is a requirement or if economic considerations using risk analysis indicate that standby air equipment is desirable.

On the whole, the design engineers must foresee all significant construction conditions and potential problems, and evaluate all significant risks - environmental, economical, and safety - on the basis of geotechnical data acquired for these purposes.

A very important duty of the design engineer is to provide fully sufficient data to allow the contractor to assess his risks and to select his construction methodology. The contractor's contingency depends almost entirely on the adequacy of geotechnical data, and his success depends on the reliability of these data.

Based in part on geotechnical data, the contractor selects his tunnel excavation and muck-handling systems, his temporary support (shield), his face and wall stabilization procedures if required, his method of lining, and many other items. For preparation of his bid, the contractor usually has about 60 days, during which time it is usually not possible for him to collect additional geotechnical data. A U.S. National Committee for Tunneling Technology report (1974) recommends that the owner make available to bidders, as official opinions but not as guaranteed facts, geological and geotechnical reports interpreting the physical data obtained in the field.

Almost all important construction decisions must be made in advance of construction. Once construction is underway, it is usually practical to implement only minor field changes and modifications to the construction plant and methodology; most major modifications may be implemented only at severe cost penalties. Possible field modifications include, for example:

a. Changes in pumping effort in dewatering wells, or use of additional wells, based on dewatering systems success and/or ground water monitoring data.

b. Selection of air pressure to be used at any given time in a compressed air tunnel.

c. Use of face breasting or other simple modifications of face support systems.

d. Modifications of schedules for filling or grouting tail void space.

e. Implementation of ground stabilization schemes such as freezing or grouting.

f. Use of air pressure or dewatering where not originally planned.

g. Removal of excavation equipment and resorting to hand digging to cope with boulders or bedrock.

The need for implementing modifications of the types a through f would be judged during construction on the basis of direct observations of ground behavior and water flows within the tunnel, and monitoring primarily of ground movements above the tunnel. Items a through d may usually be implemented at little additional cost or time delay; items e through g involve significant time delay and cost.

3.3 MEASURABLE PARAMETERS

Geotechnical parameters of significant influence on urban tunnel construction are of four types: geological, geohydrological (groundwater), soil properties, and cultural features.

Table 3-2 lists virtually all conceivable geotechnical parameters that might have an influence on urban soft ground tunneling, and that might be measured, discovered, or deduced through explorations and research. In most instances, a single parameter does not have a major impact; rather, certain combinations of parameters must be analyzed. Several parameters are clearly of secondary importance, yet under given circumstances they may be critical.

While many parameters may be measured directly, most involve indirect measurements and deductions. The geological and geohydrological parameters may be safely assessed only with due consideration to general geological principles and local geological history and morphology.

Section 4 describes typical problems in tunneling and relates these problems to governing parameters.

TABLE 3-2. GEOTECHNICAL PARAMETERS RELEVANT TO SOFT GROUND TUNNELING

1. Geological Parameters:
   - Soil Strata Boundaries p. 3-8
     - Vertical stratification, extent of soil type and varves or laminations
     - Horizontal extent of problem soils
     - Existence of water-bearing sand seams or pockets in cohesive soils
     - Existence of natural obstructions, boulders
     - Location (in three dimensions) of each surface
   - State of stress
   - Presence of natural toxic or flammable gases

2. Geohydrological Parameters:
   - Groundwater table elevation
   - Hydrostatic head, if artesian
   - Existence of perched water
   - Reservoir of water (quantity, recharge, etc.)
   - Water chemistry

3. Soil Properties:
   - Properties of essentially cohesive soils
     - Undrained shear strength, consolidation characteristics (including preconsolidation pressure), fissuredness, brittleness, stickiness deformation modulus, effective strength parameters, and classification characteristics
   - Properties of essentially non-cohesive soils
     - Existence and magnitude of cohesion or cementation (if any), permeability, relative density, Grain Size Distribution, and deformation modulus
   - Properties of silts and organic soils
     - Cohesion or undrained shear strength, permeability, density, consolidation characteristics, classification characteristics, and Deformation modulus
   - All soils
     - Presence of boulders, if any, size distribution quantity, and degree of dementation

4. Cultural Features (man-made):
   - Utilities, shallow and deep (all types: location, sensitivity to ground movements)
   - Structures with shallow foundations (sensitivity)
   - Structures with deep foundations (location)
   - Underground structures (basements, tunnels other than sewers, etc.)
   - Other, e.g., piling, buried seawalls, rubble, etc.

4. THE INFLUENCE OF VARIATIONS IN THE GEOTECHNICAL PARAMETERS ON SOFT GROUND TUNNELING

4.1 GENERAL

Tunneling in soft ground is an endeavor that calls for great expertise and ingenuity on the part of the contractor. Even under simple and favorable conditions, it is a difficult task, and adverse and changing conditions compound the difficulties.

When such difficulties are encountered with little or no warning, hazard and great cost are often the result. In the worst instance, accidental loss of ground or face collapse may bring about loss of life, burial or destruction of equipment, loss of parts of the finished tunnel structure, and destructive subsidence of the ground surface. Unexpected adverse conditions, even if less severe, always carry the risk of such losses to some extent, and frequently require the replacement or repair of tools and substantial delays for clean-up and retooling. Further, they may well affect the integrity of the finished tunnel structure and of existing surface or subsurface structures. In most instances, prior knowledge of unfavorable conditions would, in theory, allow the contractor to select the construction methodology that would produce the finished structure at the least risk and at the smallest cost. The planner and the designer would also be able to select the alignment, the structural units, and the general specifications and constraints to minimize the problems. In brief, combatting the unfavorable, unexpected conditions will usually be costly; but with prior knowledge of these conditions, adverse situations may be avoided or at least cost penalties may be minimized.

The most severe problems are those associated with instability of the face, roof, or walls of a tunnel, but excessive settlements on occasions lead to equally unfavorable conditions. Less severe are excavation, steering and mucking problems, though obstructions are frequently very costly to negotiate. Toxic or flammable gases, while of rarer occurrence, pose severe problems when they do occur.

In the following, the most common tunneling problems are identified and analyzed for the purpose of defining the responsible geotechnical parameters. The problems are classified as follows:

a. Stability problems above groundwater table.

b. Stability problems below groundwater table, soils with little or no cohesion.

c. Stability problems in soft cohesive soils.

d. Stability problems in stiff cohesive soils.

e. Boulders and soil-rock mixed-face problems.

f. Problems associated with man-made structures.

g. Other geotechnical problems.

Item g includes settlements due to dewatering, flammable and toxic gases, corrosion problems, and problems due to clay stickiness. Finally, cut-and-cover and shaft construction problems are treated separately.

In each instance, the geotechnical parameters responsible for the problem are identified, and the mechanism of the problem is described. The possible effects of the problem, within the tunnel itself and on the surroundings, are assessed. Methods of avoiding or minimizing the effects are then described. These methods may be employed either at the planning, design, or construction stages. They are discussed here to show that a prediction of the problem based on geotechnical data may be put to good use, and that data gathering would not be futile. It is realized that the problems here analyzed are based on locally uniform conditions with a single soil type present throughout the height of the tunnel face. In mixed soil faces, problems commonly associated with any one or all of the soils present may occur. Case histories illustrating a number of tunnel problems and their effects are presented in appendix B. They are listed by number and referred to in the text.

On the basis of this technical assessment of tunneling problems and the economical assessment in appendix A, the overall effects of the critical parameters are summarized, with a priority rating, in paragraph 4.4.

4.2 GEOTECHNICAL PROBLEMS ENCOUNTERED IN TUNNELING

4.2.1 Stability Problems Above Groundwater

Responsible Parameters. Geology and Groundwater: Strata boundaries and the existence or possibility of perched water. Soil Properties: Cohesion or cementation, gradation, and relative density.

Problem Description. The most common problems are face, crown, and wall instability which occur primarily in natural soils or fills with little or no cohesion. (See Case History No. 1, appendix B.) Problems may initiate in soil which may be firm, cohesive raveling, or running ground - the severity increasing with decreasing cohesion and density and more uniform gradations. Soil-water flows may occur due to perched water. Instability may cause the tail void to fill with entering soil, resulting in loss of ground as much as two to four percent of the volume of the excavated soil. Face instability may cause severe local settlements, with potential risk to utilities, buildings, and surface traffic. Risks to tunnel workers are usually small to moderate, depending on tunnel diameter.

4.2.2 Stability Problems Below Groundwater Table, Soils with Little or No Cohesion

Responsible Parameters. Geology and Groundwater: Location of groundwater table (pore water pressure), soil strata boundaries, continuity of aquifers, recharge of aquifers, and groundwater storage in aquifers. Soil Properties: Permeability, cohesion or cementation (if any), and relative density.

Problem Description. The seepage gradient toward the tunnel face, walls, and roof may cause erosion or piping, or create quicksand conditions -- flowing ground in tunnel parlance. The gradient depends on the geometry of the tunnel and the soil boundaries, as well as the head of groundwater and the spatial distribution of permeabilities. The detrimental effect of the seepage gradients is greatest in uniform fine sands and silts without cohesion. In well-graded soil, erosion and piping are significantly less likely, partly because removal of fines by flowing water tends to generate a natural filter. This eventually arrests erosion; however, quicksand conditions are still possible. Cohesion or cementation of the soil, even if of small magnitude, reduces or eliminates the dangers of erosion and quicksand conditions. For a demonstration of some of these problems, see Case History No. 2, appendix B.

If not controlled, erosion or flowing ground at the tunnel face may cause limited to severe loss of ground and chimneying to the ground surface. Where a cohesive stratum exists above the crown, chimneying may be arrested but soil may enter the tunnel from far-reaching horizontal soil flow. This may result in local excessive settlements or collapse, or widespread settlements, depending on the stratigraphy. Unlike running conditions in dry sand, flowing soil does not stop moving at a natural angle of repose but may fill many tens or even hundreds of feet of tunnel before the erosive forces subside due to flow resistance in the tunnel or exhaustion or close-off of the groundwater reservoir.

With an adequate seal between liner and shield, instability of the soil in the tail void is less severe; in theory, soil flow can fill only the tail void, resulting in moderate settlements.

A fairly common problem occurs when a tunnel heading moves from impermeable or cohesive soils upwards into a more permeable stratum. This soil interface is particularly difficult to dewater, and flows are commonly experienced. Frequently, pockets or lenses of pervious or cohesionless material in otherwise impervious soils contain water that will generate flows. In these instances, the exposure in the tunnel and the groundwater reservoir is often limited, and effects are less severe than for a full face flow. Often, however, they still result in unacceptable settlements.

Under unfavorable circumstances, the hazard to tunneling personnel, and to surface traffic and structures, must be considered moderate to severe.

4.2.3 Stability Problems in Soft Cohesive Soils

Responsible Parameters. Geology and Groundwater: Three dimensional soil boundaries and inclusions of permeable soils. Soil Properties: Undrained shear strength, soil modulus, gradation (of silt); sensitivity, and permeability (of silt).

Soft cohesive soils include soft, normally consolidated or moderately overconsolidated clays, silty or sandy clays, and soft organic or inorganic silts. These soils are generally below the groundwater table. Case History 2 includes a length of tunnel in such soils.

Problem Description. The governing parameter combination for stability and ground movement magnitudes is the ratio of total overburden pressure to undrained shear strength, p_o/c. For values greater than about 6, full face support by air pressure or other means must be provided to prevent face collapse; for values smaller than unity, ground movements are essentially elastic and small. For values increasing from unity to about 6, ground movements become progressively more significant, and ground control must usually be provided for high values when in an urban area.

At the face, ground movements take the form of primarily horizontal displacements into the tunnel. For low p_o/c values, the movement is moderate and occurs during excavation; for higher p_o/c values, movements can become quite large and may continue even if the excavation process is temporarily stopped. The tail void may be completely filled by soil squeezing into the void when p_o/c is large; for smaller values, it is often possible to grout before the soil fills the void.

Ground losses and movements of soil toward the tunnel create a surface settlement trough whose shape is fairly predictable. Hence, with proper knowledge of geometry and p_o/c ratios, the need for underpinning and other protection, or for face stabilization, can be ascertained. Only in the rare instances where a high p_o/c ratio cannot be predicted would there be a significant safety hazard within the tunnel. The environmental hazards are restricted to those associated with excessive but not catastrophic settlements.

4.2.4 Stability Problems in Stiff Cohesive Soils

Responsible Parameters. Geology and Groundwater: Soil stratigraphy, geologic history, discontinuities, and fissures. Soil Properties: Undrained shear strength, modulus (short-term, and long-term), overconsolidation ratio, and coefficient of lateral earth pressure at rest (K_o).

Problem Description. Stiff cohesive soils are usually considered very good tunneling media. Slow raveling from the face or the roof may occur when the soil is closely fissured, setting limits to the maximum possible unsupported span. In the long term, swelling of soil may occur, leading to a slow increase in lining stress and distortion. In areas with a very large in-situ horizontal stress, both the stand-up time and the long-term effects are adversely influenced. Both safety hazards and environmental impacts are generally minor in these soils.

4.2.5 Boulders and Soil-Rock Mixed-Face Problems

Responsible Parameters. Geology and Groundwater: Strata boundaries, groundwater table, and geological history. Soil Properties: Maximum size, frequency, and strength of boulders, strength and permeability of the soil matrix, and strength and fissuredness of top of bedrock.

Problem Description. Excavation and removal require the use of hydraulic splitters or blasting when individual boulders are greater than can be handled by the mucking system. Splitting is often required (in smaller diameter tunnels) for boulders larger than about two feet. The associated time delay is very costly. Mixed face conditions often require blasting to loosen rock for handling by the soft ground mucker. The soils immediately above bedrock are often very permeable and unstable against a hydraulic gradient.

Boulders encountered around the periphery of the tunnel occasionally cause damage to the shield cutting edge. When a boulder is removed from the tunnel periphery through manipulation, the void that remains is very hard to fill properly. This frequently results in excessive ground movements and settlements. Steering is also adversely influenced. Some of the problems described here were encountered in the tunnel of Case History No. 3.

4.2.6 Problems Associated with Man-made Structures

Responsible Parameters. Horizontal location and elevation of structure relative to tunnel and features related to the structure such as type, use, sensitivity to ground movements, and value.

Problem Description. Man-made structures include foundations, piles, sea wall structures, basements, tunnels, utilities, building rubble, etc. Obstructions interfering with tunneling usually require manual handling and removal, causing costly delay. Frequently associated disturbance of soil results in settlements. If tunneling is in compressed air, a disturbance may create a path for air to escape. If the obstruction is a sewer, the pipe must usually be plugged before the section interfering with tunnel excavation may be removed. If the obstruction is not expected, a sewer break may cause tunnel flooding, or even a catastrophic compressed air loss. In brief, hazards to tunnel workers are greatly variable. Case Histories No. 4, 5 and 6 describe the encounter with different types of man-made structures.

4.2.7 Other Geotechnical Problems

Compressible Soft Soils. When dewatering is selected as a means of stability control in water-bearing granular soils, the lowering of the water table causes an increase in the effective vertical stresses in the soil, with consequent compression of the soil. In many instances, the soils are of only moderate compressibility, and the widespread and relatively uniform resulting settlements are of little or no concern. However, where normally consolidated or slightly overconsolidated clays, silts, or organic materials are present, settlements may reach magnitudes of several inches, occasionally more than a foot. Where there are existing structures and utilities in the region of influence, such settlements are often intolerable. Even where structures are on piles, settlements may not be tolerated because of excessive downdrag on the piles. Timber piles may rot.

The governing factors for these problems are the stratigraphy and groundwater conditions, and the compressibility and preconsolidation pressure of the soft soils. Under severe conditions, the contract documents may prohibit dewatering or require recharging of groundwater.

Gases. In certain geologic environments, natural gases may cause safety hazards by accumulating in explosive concentration in tunnels.

When hazardous gas is known or suspected to exist, special precautions may be made to remove the gas by ventilation and to monitor the gas level in the tunnel atmosphere at all times, perhaps with automatic alarms or automatic regulation of the ventilation effort. In a compressed air tunnel, the gas hazard is virtually eliminated because the air overpressure tends to displace the gas away from the tunnel, though the fire hazard, generally speaking, is greater.

Gases are potentially more hazardous in a tunnel that is unlined or lined with temporary linings pervious to gas (ribs and lagging) than in a tunnel lined with tight segments. Hence, they are more hazardous in rock tunnels than in soil tunnels. Where the lining is tight, the only gas entry would be from the face; but with a pervious lining, gas may enter anywhere. Indeed, the number of incidents associated with the presence of gas reported for tunnels in soil appears to be much smaller than for tunnels in rock, presumably because of the difference in tunnel supports and because gas traps are less frequent in soils than in rocks. There are, of course, exceptions. The explosion that took place in the San Fernando (California) tunnel in 1970 and took the lives of 17 miners was in a tunnel through essentially unconsolidated materials.

In urban areas, gases from leaks in the gas distribution system are always possible. Such leaks may in fact be generated by ground movements due to tunneling. Gases may occur from other types of human endeavor as well, as Case History No. 7 will suggest.

Corrosion Problems. During planning and design, decisions must be made as to what extent corrosion protection of steel or iron linings must be provided. Corrosion-retarding paints may be provided, with provision for protecting the paint cover until segments are installed. Cathodic protection may be provided; or, more commonly, special provisions are made to prepare the structure, by insuring appropriate electric continuity, for future cathodic protection.

Although general appraisals of the corrosion danger can be obtained from soil and groundwater chemistry and from well logging, the problem is the effect of the tunnel structure itself on the electric conditions around the tunnel. The tunnel constitutes a very large conductor; it carries third rail and other power, leakage from which may have a major influence on corrosion rates. Grout surrounding the tunnel may have some effect in retarding corrosion, and the groundwater conditions may be permanently altered by the tunnel. Hence, there is almost always a need to test the corrosion potential of the final structure, and to prepare for cathodic protection, since such protection becomes more expensive if provided as an afterthought. For case histories of corrosion protection problems, see Case History No. 8.

Clay Stickiness. Though the selection of cutting tools for a wheel excavator is usually fairly simple and not overly critical, the wrong selection can occasionally generate problems. Very stiff or hard clays usually break into lumps that are easily managed, and soft clays will usually slide off cutting blades without extra efforts. But clays of intermediate strength, with a liquidity index of the order of 0.5, especially highly plastic clays, often will not break into lumps but will tend to adhere strongly to cutting teeth. Anticipation of this problem will allow engineers and contractors to estimate the monetary effects in advance, and to make a proper cutting tool selection.

This difference in clay behavior during excavation was noted during construction of the D2 Section of the Toronto Subway. The slowest progress was recorded in an area where hand clearing of the rotating buckets was required; the sticky clay here had a water content midway between the plastic and liquid limits (Bartlett, et al, 1965).

A similar problem occurred during the drilling of caissons to rock through old San Francisco Bay mud for the Golden Gateway in San Francisco. The plastic, stiff clay here had to be removed from the augers by pneumatic clay spades, and the slow progress eventually forced the unhappy caisson contractor to abandon the job and let the remainder be founded on piles.

4.3 CUT-AND-COVER AND SHAFT CONSTRUCTION

4.3.1 General

The previous sections of this report have dealt specifically with tunneling. Shafts and cut-and-cover construction involve essentially the same parameters but to a different degree. Since cut-and-cover techniques were the subject of an extensive state-of-the-art analysis (Sverdrup, Parcel & Associates, Inc., 1973), they will not be treated in detail here.

The basic problems of ground movements and ground control are quite similar for deep cuts and for tunnels, but different means are employed to excavate and support the soil, and the economic impact of some parameters is different.

4.3.2 The Groundwater Problem

Excavation bottom instability occurs when upward water flow creates gradients large enough for piping or quicksand conditions to develop. The parameters governing this phenomenon are the same as those governing face instability in granular soils below groundwater. Where tunnels are often driven in compressed air under severe instability conditions, shafts are usually not, because the cost of plant is more easily amortized over a length of tunnel than a depth of shaft, and because dewatering locally for a shaft is easier than dewatering over a length of tunnel.

On the whole, the same parameters required for evaluating constructability problems in tunneling apply to cut-and-cover: stratigraphy, groundwater elevation, groundwater storage and recharge, permeability distribution, and cohesion of granular soils.

4.3.3 Retaining Walls

Loads on temporary and permanent walls depend on the soil strength parameters. Some savings could be realized in the design and construction of temporary walls by a better knowledge of soil strength. But the design of such temporary walls is frequently not very sophisticated, reflecting either the contractor's lack of incentive to save on temporary walls, or his willingness to take risks. It is, therefore, quite possible than an improvement in strength data will not result in significant cost savings on temporary walls.

Permanent walls are usually quite conservatively designed. It is generally assumed that temporary walls, even if they remain in place, do not contribute in carrying earth loads. More often, quite arbitrary assumptions are made regarding groundwater elevations and differential elevations from one side to the other. Further, to allow for all future eventualities (for example, the possibility of deep adjacent excavations), cut-and-cover structures are designed for cases of large differential earth pressures, one side to the other. Under these circumstances, if improved geotechnical data are to effect any savings in design and construction of conventional cut-and-cover structures, a change of philosophy in cut-and-cover design is first required.

Modern and future design methods and methods of ground movements prediction will require a detailed knowledge of stress-strain relations of the soils, as well as accurate strength data, while methods currently in use circumvent the need for stress-strain relations except in a qualitative way. Finite element analyses under development require the use of elastic moduli and plastic behavior over a wide range of stress conditions. Before such methods can be generally employed, technology to provide these data must be developed.

4.3.4 Natural Obstruction

Natural obstructions, such as boulders and bedrock, are much more easily handled in open excavations than in a tunnel. Natural obstructions do, however, interfere with the placement of soldier piles or sheet piles and substantially increase the cost of slurry trench walls. Case History No. 9 describes how natural and man-made obstructions interfered with soldier pile placement in a Toronto project. In some instances, ordinary sheet piles cannot be driven, and soldier piles require predrilling of one kind or another. Slurry trench wall construction in such instances must often employ special drilling equipment and suffer delays. Where bedrock is encountered, walls of any type must generally be socketed into rock and specially anchored or strutted against toe kick-out, a common type of failure under such circumstances.

It would appear, then, that natural obstructions and the location of bedrock are as important parameters for design, specifications, cost estimating, and selection of construction methods for cut-and-cover as for tunneling, though for somewhat different reasons.

4.3.5 Man-made Obstructions

Man-made obstructions, particularly shallow utilities, are more important for cut-and-cover work than for tunneling. Shallow utilities crossing cuts may be severed and relocated, or supported without service interruption. Either alternative involves a significant cost and the risk of interfering with the function of the utility.

Excavation in city streets and uncovering of utilities are usually carried out with sufficient care such that disruption does not occur even if a utility is uncovered at an unexpected location. The drilling of exploratory borings and the driving of soldier piles, however, are sometimes performed without preexcavation or prior utilities relocation, and occasionally results in severing of a utility.

Severing of telephone, telegraph, water, or sewer lines, while unpleasant and frequently costly, usually does not carry with it a significant risk to life. Cutting a high-tension cable, however, is dangerous. Except for sewers, these types of utilities usually are metallic elements, and metal detectors may be employed for their location. In general, the horizontal location of near surface utilities is the most important. However, for structures that include tiebacks or anchors, the elevation of these utilities is required.

4.3.6 Slurry Walls

Instability of a slurry-trench can occur under two conditions: if the slurry is drained from the wall, such as by intercepting a sewer; or if a relatively high differential water pressure exists from one side of the wall to the other. Dilution of the slurry -- for example, from a broken water line -- may also result in instability. Fortunately, almost all utilities are close to the ground surface, and a collapse would include only insignificant, near-surface soils. Really severe collapses only occur when the drained slurry wall extends deep below groundwater. Such collapses are so rare that several interviews and a literature review have disclosed but a single instance. As a rule, exposure of all utilities is made during preexcavation of the trench at a nominal cost. The risk of utilities disruption is generally much greater in the case of steel sheet piles.

The cost of slurry wall is about evenly split between materials and construction costs. The total cost, however, depends on the rate of excavation. When excavation is easy to moderately hard, the rate is governed largely by the time it takes for the bucket to make a round trip. Digging becomes hard in dense soils (with N-values greater than 80-100), where the loosening of the soil begins to take an appreciable time. Small boulders, of a size 40 to 80 percent of the trench width, may slow down excavation and increase total costs up to about five percent. If boulders are larger than about 80 percent of the trench width, they must be destroyed individually by special tools, causing appreciable delays.

Thus, boulders larger than about two feet can have an important influence on cost. Prediction of their existence in significant numbers is desirable, so that appropriate equipment can be on hand when required. Old footings and piles affect construction and cost in much the same manner.

Since a fairly large part of the cost of slurry walls is in the materials, it is clearly advantageous to generate an economical concrete and steel design. For this reason, soil strength and deformability are frequently important parameters for slurry walls.

4.4 ASSESSMENT OF IMPORTANT PROBLEMS AND PARAMETERS

In the following, the different types of tunnel problems and cost components are put together in groups that are meaningful for a derivation of parameter effects. A rating of importance is applied through the use of relative weight numbers, recognizing the results of the economic analyses (in appendix A) regarding relative costs and sensitivities of the various types of problems. Not all types of problems have been treated in detail by the economic analyses. The relative weights have, therefore, in part been assigned subjectively on the basis of the technical analyses. The problem groups and their relative rating are described in table 4-1.

Each group of problems is affected by a large number of geotechnical parameters. Many of the parameters affect several or all of the problem groups, but with different weight. To obtain the overall weight of a particular parameter, a summation must be made of products of relative weight for all the problem groups.

The three most complex groups of problems must first be examined; those problems associated with water and those associated with stability and ground movement. These are rated in tables 4-2 to 4-4, which show the general importance of particular geotechnical parameters for the solution of specific problems or selection between construction options. The remainder of the problem groups can be rated directly against the pertinent geotechnical parameters; this is done in table 4-5.

TABLE 4-1. RELATIVE RATING OF TUNNELING PROBLEMS

Water Associated Problems:

Face instability - tail void instability - ground movements and settlements - compressed air - dewatering - grouting - the surprise factor - effects of groundwater lowering - underpinning requirements based on risk analysis. Relative weight: 15

Excavation Problems:

Boulder removal - soil rock interface - clay stickiness - overexcavation - soil resistance to cutters - excessive water in soil. Relative weight: 7

Other Stability Problems:

Ground loss at face - ground loss in tail void - slabbing and raveling in firm ground - long term displacements and stresses - ground movements, settlement and underpinning requirements. Relative weight: 5

Safety Problems:

Soil-water flows - stones and soil falling from face or roof - explosives - gases - working ahead of shield cutting edge - compressed air hazards. Relative weight: 2

Lining Design:

Thrust - moment - flexibility - corrosion - watertightness requirements - designs to reduce ground movements during installation - erection within shield, behind shield, no shield at all. Relative weight: 2

Steering Problems:

Vertical steering problems in soft soil - differential resistance to cutting edge - boulders - rocks - soil adhesion to shield. Relative weight: 1

TABLE 4-2. PARAMETER ASSESSMENT: THE COMPLEX OF GROUNDWATER PROBLEMS

Construction Problem or Selection of Option	Geological Parameters							Soil Properties						Other	Relative Weight
	Stratigraphy	Natural Obstructions	Rock Surface	Gases	Stress State	Water Pressures	Water Chemistry	Permeability	Shear Strength, Undrained	Cohesion of Granular Soil	Modulus, Short-Term	Modulus, Long-Term	Classification	Man-made Obstructions	
Relocation to Avoid Problem	3	1	2	0	0	2	0	2	0	2	1	1	1	1	Items have equal weight.
Dewatering	3	2	2	0	0	3	2	3	0	2	2	3	2	2	
Full Face Support	2	2	2	0	0	2	0	1	0	2	1	0	1	2	
Compressed Air	2	1	1	0	0	2	0	2	0	2	1	0	1	1	
Ground Improvement	2	1	1	0	0	1	1	3	0	1	1	0	2	1	
Ground Movement Prediction	2	1	1	0	0	1	0	1	0	2	3	3	1	1	
Summation	14	8	9	0	0	11	3	12	0	11	9	7	8	8	
Overall Weight	3	1	1	0	0	2	1	3	0	2	1	1	1	1	

Note: 3 for greatest influence, 0 for no influence.

TABLE 4-3. PARAMETER ASSESSMENT: STABILITY PROBLEMS OTHER THAN WATER RELATED

Stability and Ground Movement Problem	Geological Parameters							Soil Properties						Other	Relative Weight
	Stratigraphy	Natural Obstructions	Rock Surface	Gases	Stress State	Water Pressures	Water Chemistry	Permeability	Shear Strength, Undrained	Cohesion of Granular Soil	Modulus, Short-Term	Modulus, Long-Term	Classification	Man-made Obstructions	
In Granular Soil	3	2	2	0	0	0	0	2	0	3	1	1	2	2	5
In Soft Cohesive Soil	3	1	1	0	1	0	0	1	3	0	2	2	1	1	5
In Firm Soil	3	2	2	0	2	0	0	1	2	1	2	1	1	2	3
Product Summation	39	21	21	0	11	0	0	18	21	18	21	18	18	21	
Overall Weight	3	2	2	0	1	0	0	1	2	1	2	1	1		

Note: 3 for greatest influence, 0 for no influence.

TABLE 4-4. LINING DESIGN PROBLEMS

Design Consideration	Geological Parameters							Soil Properties						Other	Relative Weight
	Stratigraphy	Natural Obstructions	Rock Surface	Gases	Stress State	Water Pressures	Water Chemistry	Permeability	Shear Strength, Undrained	Cohesion of Granular Soil	Modulus, Short-Term	Modulus, Long-Term	Classification	Man-made Obstructions	
Construction Stresses	1	1	1	0	0	0	0	0	1	1	1	0	1	1	
Watertightness	2	0	0	1	0	2	0	2	0	0	0	0	1	0	
Corrosion	1	0	0	1	0	2	3	1	0	0	0	0	1	0	
Loads	2	0	0	0	1	2	0	0	1	1	0	1	1	1	
Distortions	2	2	2	0	1	1	0	0	1	1	1	1	1	1	
Summation	8	3	3	2	2	7	3	3	3	3	2	2	5	2	
Overall Weight	3	2	2	1	1	3	2	2	2	2	1	1	2	1	

Note: 3 for greatest influence, 0 for no influence

TABLE 4-5. PARAMETERS ASSESSMENT SUMMARY

Construction Problem or Selection of Option	Geological Parameters							Soil Properties						Other	Relative Weight
	Stratigraphy	Natural Obstructions	Rock Surface	Gases	Stress State	Water Pressures	Water Chemistry	Permeability	Shear Strength, Undrained	Cohesion of Granular Soil	Modulus, Short-Term	Modulus, Long-Term	Classification	Man-made Obstructions	
Water Associated Problems	3	1	1	0	0	2	1	3	1	2	1	1	1	1	15
Excavation and Mucking	2	3	3	0	1	1	0	1	2	2	1	0	1	3	7
Stability Not Covered Above	3	2	2	0	1	0	0	1	2	1	2	1	1	2	5
Safety	2	2	2	3	0	0	1	0	1	1	0	0	1	2	2
Lining Design	3	2	2	1	1	3	2	2	2	2	1	1	2	1	2
Steering	2	2	2	0	1	0	0	0	1	1	0	0	0	2	1
Product Summation	86	56	56	8	15	43	21	61	46	56	34	22	33	54	
Overall Rating	A	A	A	C	C	B	C	A	B	A	B	C	B	A	

Notes: (1) 3 for greatest influence, 0 for no influence
(2) A: 50-96; B: 30-50; C: 0-30

As a result of these exercises, the priorities of the various important parameters can be rated in a subjective fashion:

PRIORITY A:

- Stratigraphy
- Permeability
- Rock surface
- Obstructions, man-made or natural
- Cohesion of granular soils

PRIORITY B:

- Shear strength of cohesive soil (undrained)
- Water pressure
- Modulus, short term
- Soil classification, in general

PRIORITY C:

- Modulus, long term (Consolidation characteristics)
- Water chemistry
- Stress state (At-rest pressure)
- Gases

The general results of these ratings have been used in a slightly modified form for the evaluation of possible and proposed methods of subsurface explorations in the following sections.

But before entering this stage, it is necessary to discuss the important parameters in some detail, so that a more precise definition of the specific parameters can be formed to classify and summarize the effects of the parameters, and to demonstrate that the parameters can, indeed, be put to use in the analysis of tunneling problems.

4.5 GEOLOGIC AND GEOHYDROLOGIC PARAMETERS

4.5.1 Strata Boundaries

The stratigraphy of the subsurface is of paramount importance for soft ground tunneling. The geometric configurations which are the horizontal and vertical boundaries of different soil types, determine the character of the groundwater problem and the size of the groundwater reservoir. Hence, a detailed knowledge of the stratigraphy has an important bearing on the groundwater problems in tunneling.

Tunneling in mixed soil faces carries with it the problems of all the soils encountered over the height of the face, and also a few compounded problems. The prior knowledge of strata boundaries, therefore, allows potential cost reductions by realignment to avoid the most severe problems, or by preparing the contractor for the mixed face condition.

Geological boundaries of particular importance are:

1. The interface between soil and bedrock. Soil/rock mixed faces are particularly difficult and expensive, often requiring two different excavation and support techniques. The soil/rock interface is often associated with bad weathering and fracturing of the rock or with a gravel or boulder bed above the rock, both of which could lead to severe water problems.

2. The boundary between an upper, permeable soil and a lower, impermeable soil below the natural water table. The water above such an impermeable soil is particularly difficult to remove by dewatering. This boundary can be particularly troublesome when the tunnel is driven from beneath the boundary, causing both potential face and roof instability.

3. Boundaries of waterlogged permeable soils within impermeable soils, especially if continuous or of large horizontal extent. Such seams or pockets frequently are especially difficult to locate and evaluate, and may cause severe stability problems if not properly dewatered.

Even a good knowledge of the stratigraphy will not usually suffice for an accurate prediction of soil behavior during tunneling. A variety of other types of data are required depending on the specific conditions. The stratigraphy, however, supplies the basic skeleton of information, to which all other types of data must be applied. Stratigraphy must be given the highest priority among the parameters affecting soft ground tunnels.

4.5.2 Natural Obstructions

Natural obstructions must be included among the geologic parameters. These include, first and foremost, boulders large enough to interfere with or hamper the advancement of a shield, or excavation and mucking,and also any other natural construction hindrance such as an exceptionally hard localized cementation of the soil.

When the frequent occurrence of boulders is anticipated, a shield may be designed extra strong, with a hardened cutting edge to minimize shield damage. Excavation tools may be selected to provide access to the heading for manual stone removal (full face wheel support may be eliminated from consideration), and muck handling systems may be designed to handle the boulders. If a significant quantity of boulders is encountered by a tunnel excavation system that is not designed for it, substantial costs will be incurred.

It may be possible to obtain an approximation of the boulder problem by ordinary exploratory borings. However, a statistical evaluation of the problem indicates that even in an instance where a significant boulder is encountered every one or two feet of actual tunneling, the frequency of boulders that would be encountered in exploratory borings might be as low as one in every 100 feet of boring. Hence, while exploratory borings might give a hint of a potential boulder problem, they cannot, with a reasonable exploration expenditure, show the severity of the problem.

The best tool that is currently available for prediction of a boulder problem is an accurate geologic interpretation of the soil profile. Boulders are encountered in quantity only in glacial tills, residual soils above bedrock, in alluvial and colluvial soils, and frequently in a layer above bedrock. Thus, if these geologic features are properly identified using geologic deduction, the likelihood of encountering a potential boulder problem can be ascertained with some confidence.

4.5.3 State of Stress

The state of stress in a body of soil is determined by the geological history of the soil body. It can sometimes be deduced from an analysis of the geological history.

In nearly all instances, the driving of a tunnel through soil releases the in-situ stress in such a fashion that the original stresses are never restored. The removal of soil at the tunnel face reduces the horizontal stress in the direction of the tunnel axis to zero, or to the support pressure if air pressure or full face breasting is applied. This stress reduction is felt to a distance of several diameters from the face. Before a temporary or permanent support is installed, the roof and the walls of the tunnels are nearly always exposed to zero or low stress for some time, allowing some soil movement. A support or lining is installed with or without an effort to jack the lining against the soil and most often grout is applied under pressure to fill any voids left between lining and soil or within the soil. Therefore, the stresses that act in the interface between the tunnel structure and the soil - the loads on the lining - immediately after construction, are greatly dependent on the details of construction.

In most soils, the magnitude of the loads on the tunnel lining depends in some fashion on the depth of cover, or the original vertical in-situ stress. This dependency, however, varies greatly with the soil types, and attempts to quantify the relationship theoretically or empirically have often faltered. In almost all instances it is sufficiently accurate to assume that the original vertical in-situ stress is equal to the weight of a column of soil above, even if there is a substantial topographic variation of the ground surface. An important point is that the design of a tunnel lining depends much more on the distribution or irregularity of the earth pressure than on its intensity.

In soils where no significant creep or long-term moisture changes take place after tunneling, the loads on the liner change little with time, and they are therefore determined largely by the overburden pressure and the construction details. In soft, normally consolidated, or slightly overconsolidated clays and silts, some reconsolidation of the disturbed soil around the tunnel takes place with time, sometimes influenced by drainage into a leaking tunnel. Some theories would indicate the load changes taking place during this reconsolidation depend on the original horizontal stress in the soil or the coefficient of lateral earth pressure at rest (K_o). However, in these soils, K_o is known almost always to be between about 0.6 and 1.0. Furthermore, the disturbance of the soil in the vicinity of the tunnel in such soils is usually so great (unless high air pressures have been employed) that reconsolidation of the fully or partly remolded soil virtually obliterates the original state of stress. Because of the extreme difficulties in handling these problems in a theoretical manner, and because of the uncertainties of tunnel construction details, it is not likely that a more refined estimate of K_o will lead to a significant cost saving on tunnel limings or construction procedures in these types of soils.

The only soil types in which the value of the horizontal effective stress can have a significant influence on tunnel behavior and cost are soils of low permeability and of significant strength; for example, stiff or soft shales. When the undrained shear strength of such a soil is equal to or greater than the overburden pressure, and K_o is approximately equal to unity, the tunnel excavation does not lead to a development of plastic zones around the tunnel, and the effect of the stress reduction on the tunnel walls can be estimated by elastic theories. The soil will eventually reach a new moisture equilibrium, and long-term displacements and load changes may be expected. When K_o is greater than unity, the stress distribution around the tunnel is not uniform. Local overstressing can occur, resulting in plastic displacement, slabbing or other types of instability during construction, depending on, among other things, the fissuredness of the soil. Also, long term displacements and loads will depend on the original state of stress as altered by the tunnel construction and influenced by fissuredness, strength variations, consolidation characteristics, and construction details.

An accurate determination of K_o under these circumstances may assist in predicting this behavior. However, to this date no theories have been shown to generate useful and satisfactory predictions, partly because the behavior of highly overconsolidated clays under the appropriate stress conditions is poorly understood.

In general the clays that exhibit these qualities are pre-Quarternary plastic clays that have not been highly indurated. Most frequently they are tertiary clays. While these clays have caused difficulties for example in Belgium (Boom Clay) and France, they have generally been trouble-free in England (London Clay). In the United States, these clays are quite rare under metropolitan areas. Hence, the utility of a methodology development for measuring K_o is limited as far as urban rapid transit projects is concerned.

4.5.4 Hazardous Gases

The occurrence of hazardous natural gases is geologically determined. The likelihood of encountering such gases in urban areas is generally known from local construction experience. For gas to accumulate in quantity, it must be trapped beneath impervious strata: hence, a thorough knowledge of the soil stratigraphy would indicate potential gas accumulations in areas where gas may occur. A parallel may be drawn to the manner in which a petroleum engineer employs the stratigraphic knowledge to find potential gas or oil reservoirs.

While there are ways to ascertain the presence of gas in dry boreholes, this is not done during exploration for tunnels in soil. It would be prudent to employ such methods, together with stratigraphic appraisals, in areas where gas is known to occur.

Gases may emanate into the soil from breaks in gas distribution systems or from certain types of industrial plants. Breaks may occur in nearly any urban area, irrespective of geologic setting, and without any geologically indicative stratigraphy or other evident indicator. They are potentially more hazardous than natural gases. To guard against incidents associated with such gases, the entire tunnel alignment should be surveyed for the presence of gas both before and during construction. Gas lines occasionally rupture as a result of soil movements caused by tunneling. The occurrence of gas in the tunnel would be fairly sudden in such instances. Hence, exploratory tools infrequently applied would not guard against such hazards. Monitoring instrumentation in the tunnel itself would be a more refined approach.

4.5.5 Groundwater

Most severe tunnel problems are associated in one way or another with the presence of water. Groundwater is responsible for face instability in silts and sands with little or no cohesion, for migration of silts and sands into the tail void behind the shield, for causing excessive settlements, ground movements and occasional funneling to the ground surface, and for associated hazards to the personnel in the tunnel. Instability of the soil caused by water inflow sometimes determines the types of lining that can be employed, and determines how quickly grout must be applied behind the lining to minimize ground movements and lining distortions. Water pressures determine the magnitude of air pressure required in a compressed air tunnel, and delayed migration of water is responsible for long term distortions and stress changes of tunnels in clays. On the whole, groundwater is the greatest source of the variability of tunnel costs and is responsible for three of the most significant expenditures: dewatering costs or other ground improvements, compressed air costs, and contingencies on the part of the contractor.

The severity of a groundwater problem depends directly on the pressure gradients where water enters the tunnel, and the rate and the duration of flow. Hence, it depends indirectly on the hydrostatic head of water, the permeability of the soil and the quantity of water available in the particular intercepted aquifer. The permeability is a soil property, which will be discussed later in this section. The quantity of available water is strictly a function of the stratigraphy, and any possible recharge of the reservoir.

Hydrostatic conditions that determine water pressure gradients and thus the erosional force of groundwater flow, generally include the elevation of the groundwater table (or the pore water pressure if conditions are artesian), and the existence of, and pressure in, any intercepted perched water tables.

In theory, a reasonably complete knowledge of the three-dimensional stratigraphy of the tunnel vicinity, the permeabilities and porosities of the various soil strata, and the pore water pressures, would enable a calculation of:

1. The effort required to dewater the soil sufficiently for the tunnel construction.

2. The water pressure gradients for any given tunneling configuration and condition.

3. The identification of specific volumes of soil that cannot be dewatered by a reasonable effort.

4. The rate of soil erosion or piping, if any, or the general stability of the tunnel face and walls.

5. The air pressure required - if any - in a compressed air solution.

6. Whether the soil is groutable.

In practice, although the basic theories are fairly well understood, such analyses and predictions are not simple. In most instances, it would take a major computational effort to evaluate any one of these items, and unless the data are very reliable, the results would be questionable. In today's practice, extensive analyses of this nature are not performed except perhaps by the dewatering subcontractor, who takes the responsibility in most dewatering contracts. Perhaps the reason for this is the lack of sufficiently accurate data of the required types, and a general distrust among civil engineers of sophisticated groundwater flow analyses. Many civil engineers feel that for most civil engineering projects, sophisticated analyses are not warranted. Most often dewatering systems are sufficiently overdesigned or other safeguards are employed at limited expense, so that the incentive to economize by more accurate analysis does not exist. However, in soft ground tunneling, decisions must be made to determine if: (1) dewatering alone should be employed, (2) compressed air should be made available for emergency or as a contingency, (3) compressed air should be required, (4) grouting should be used to stabilize the soil, and (5) grouting can be counted on to take the place of underpinning. There are most certainly economic and safety incentives to make the best possible analysis. Through the years, millions of dollars have been spent either on contingencies such as the establishment of compressed air plants that were never used (5 million dollars alone on San Francisco BART projects), and other millions on occasions where the construction plant was not adequate for the conditions.

The theoretical tools, computational methods and professional training may not be available at this time to make the best and the most out of improved data concerning groundwater, but with the incentives established perhaps all that is needed for such predictions to be attempted and to succeed is the possibility of gathering sufficient data of high reliability.

4.5.6 Water and Soil Chemistry

Certain chemical compounds occurring with relative infrequency in soils and in the groundwater are corrosive to steel, iron, concrete, or other construction materials. Corrosion is frequently of great concern for pipelines, where corrosion protection is common practice. Corrosion has not been in the past a significant problem for tunnels because of the following: (1) cast iron tunnel segments resist corrosion well, (2) fabricated steel segments are usually painted with a protective coat and are often electrically corrosion protected, and (3) most tunnel supports involving concrete are overdesigned with respect to the permanent earth and water pressures. It is possible, however, that the future will see refinements and developments in tunnel lining design that make an accurate determination of corrosion potential economically significant. As indicated in paragraph 4.2.7, the best time to test the need for cathodic corrosion protection is after the tunnel has been placed in service. Preparation for such protection should be made in advance.

Chemicals in the groundwater may also have an effect on maintenance costs of a dewatering system. In particular, eductor well systems are prone to clogging when the water is hard or contains iron. The clogging problem may be particularly troublesome in recharging wells, where water pumped out of the ground is reinjected; here chemical treatment of the water is often required to prevent clogging. Hydrogen sulfide and free CO_2 in the water may create corrosion problems in pumps, motors, screens, or piping. Bacteria and algae also occasionally present clogging problems.

It is often less costly to construct a dewatering system incorporating a large number of eductor wells requiring small diameter borings, rather than one with few large diameter wells with submerged pumps. A prediction of the maintenance problem based on water chemistry could, therefore, have an economic benefit. Experience with the Washington Metro construction indicates that the Washington water presents a modest maintenance problem for eductor wells. This problem can usually be handled economically by adding Calgon or similar chemicals to the recirculating water, by occasional surging, and rarely by acidation. However, this problem was here learned through experience; no effort had been expended to predict this problem. In other areas of the United States, maintenance problems can be much more significant. For a recent dewatering job in southern New Jersey, one of the major dewatering contractors spent about $250,000 cleaning up his wells. Prediction of this nature requires chemical analysis of soil and water samples. While electrical well logging can indicate the approximate corrosion potential, it is not likely that the full maintenance problem can be assessed by such means.

Problems are not great in an area with a history of dewatering. Here, the contractor for his dewatering design will rely on his and others' past records and experience. In new areas, however, a prudent dewatering contractor performs his own pump test, even before bidding, and tests samples of water. Tests for dissolved gases such as carbon dioxide and hydrogen sulfide usually must be made in the field, since the gases usually vanish on the way to the laboratory. But often the tests are misleading. After extended pumping, the water in the soil has been removed and replaced by recharged water that may have an entirely different make-up. Hence, even detailed water chemistry and downhole electric testing will not tell the full story of the dynamic pumping condition.

4.6 SOIL PROPERTIES

4.6.1 Permeability

With a given stratigraphy and under given natural or improved hydrostatic conditions, the permeability determines the quantity of waterflow toward dewatering wells or toward the tunnel. A reasonably accurate knowledge of the permeability is therefore required to estimate the dewatering effort, to estimate the length of time required to dewater a volume of soil defined by stratigraphy, and to analyze recharging phenonmena. In addition, the groutability of a soil can be estimated on the basis of permeability, and a grout design prepared.

The permeability of a soil can also be used, in a secondary way, to deduce valuable information about the silt and clay content of the soil. The very highest permeabilities indicate sands and gravels with a small fines content. The very lowest permeabilities are found in clays. The behavior of either of these two extreme types of materials is relatively well predictable. On the other hand, intermediate permeabilities are difficult to assess without additional information. They are found in well-graded soils which offer only few problems, or in pure silts or varved clays which may pose severe tunneling problems.

Figure 4-1 shows in an approximate manner the general relationship between permeability and other pertinent soil characteristics, as well as some basic tunneling considerations (dewatering, grouting, and cohesive properties). The various limits indicated are influenced a great deal by factors other than permeability. However, permeability is directly useful for calculating water

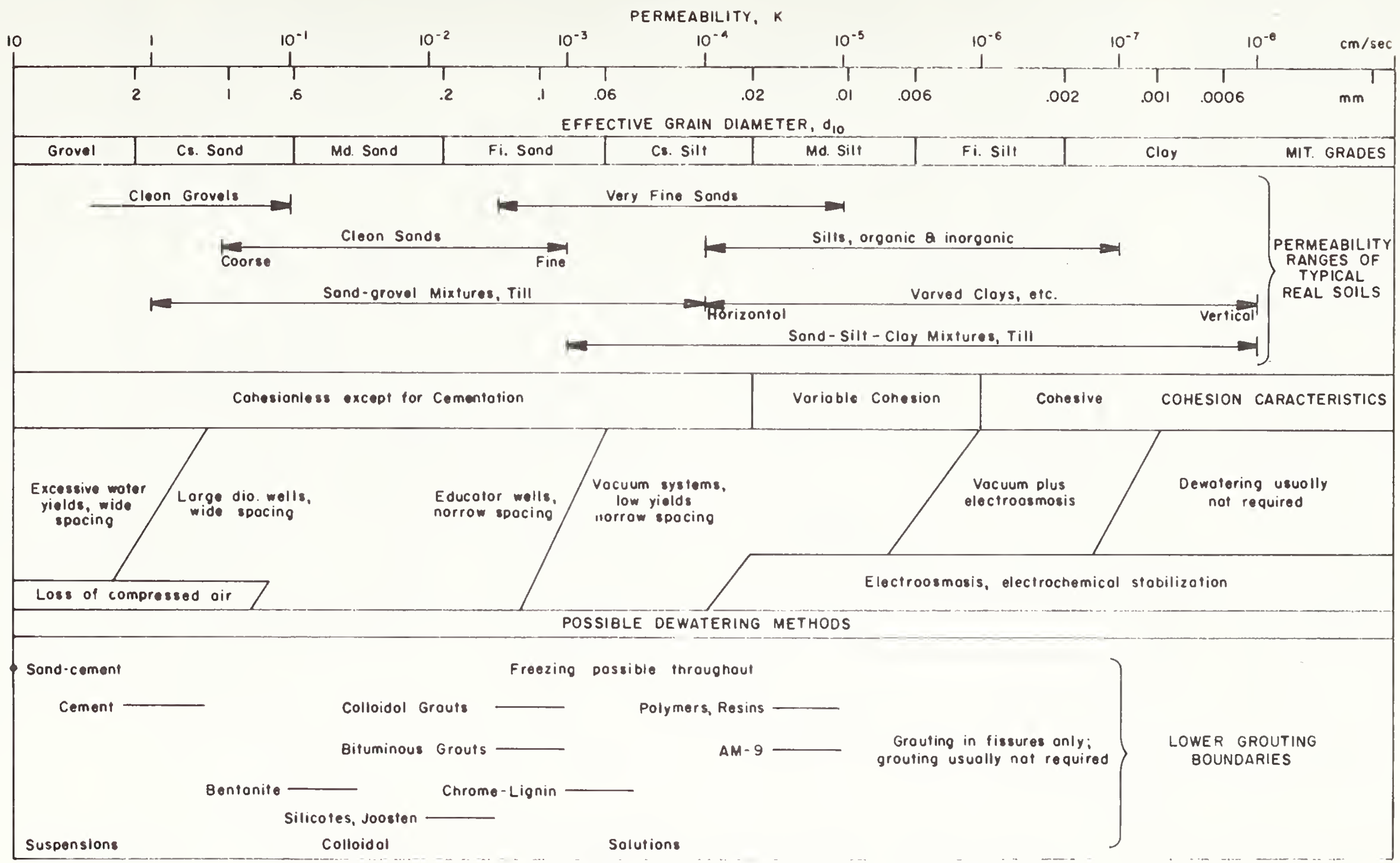


Figure 4-1. Correlation: Permeability to Soil Characteristics to Dewatering to Grouting Response.

flows and estimating gradients, and also as a tool for classifying soils and potential soil problems particularly when correlated with other parameters. The utility of permeability as such a tool will, of course, depend on whether reliable permeability measurements can be obtained in the field at a reasonable cost, and whether sufficient empirical correlations can be established to improve the interpretation of permeability logs.

Of almost as great importance as the magnitude of the permeability, is its degree of variability in a soil stratum. Water flows in uniform soils tend to be reasonably uniform and predictable. In soils with large permeability variations, flows are not uniform but tend to concentrate in more permeable strata. Hence local gradients become higher, and the risk of boiling, erosion, and instability becomes greater. In addition, dewatering becomes more difficult and unpredictable. For this reason a measure of the variability of the permeability is of considerable value, even if absolute measurements of permeability in-situ cannot be made accurately.

Given a reasonably complete and accurate description of the soil stratigraphy, and the permeability variations throughout the permeable strata, the theoretical basis is available for a reliable prediction of groundwater flows, pumping quantities and gross and local gradients. In practice, however, the data can never be perfect, and detailed hand analyses quickly become very time consuming. With the currently available solutions, a good number of simplifying assumptions must be made to tackle the time dependent flow problems. The detailed information potentially available, therefore, cannot be used to its full extent. One of the reasons detailed analytical capability is not currently available may be that detailed stratigraphic and permeability data have been out of reach. With electronic computers, however, much more detailed analyses are possible, and it can be expected that development of such analysis will be forthcoming once reliable data become available.

4.6.2 Shear Strength and Cohesion

Face stability, and roof and wall stand-up time are greatly dependent on shear strength, cohesion or soil cementation. The basic mechanisms are different in soils of low and high permeability.

For cohesive soils such as cohesive silts, sandy, silty or clean clays, soft clay shales, as well as some clayey tills and residual soils, the undrained shear strength greatly influences the stand-up time of the tunnel face, roof and walls, and the magnitudes of ground movements. The relationships are shown approximately on figure 4-2.

In cohesive soils, the moving forces are directly related to the total overburden pressure p_o. If p_o is greater than six times the shear strength ($p_o/c>6$), the tunnel face is unstable, and the encroachment of roof and walls on the tunnel is limited only by the lining, which will eventually be loaded with nearly the full overburden pressure. For p_o/c between two and six, significant plastic movements take place, and face and wall support may have to be supplied continuously if settlements can have detrimental consequences. With an air pressure in the tunnel p_a, the governing ratio is $(p_o - p_a)/c$, and ground movements increase with an increase in this ratio, figure 4-2. With the ratio between one and two, plastic movements generally are insignificant, and for $p_o/c=1$ movements are essentially elastic.

For large values of p_o (deep tunnels in stiff clay), as indicated in paragraph 4.2.4, the coefficient of lateral earth pressure at rest, K_o, assumes some importance. A K_o value much greater than unity can lead to instability even with low values of p_o/c. This problem can become particularly important if the cohesive soil is very plastic or heavily fissured.

It is clear, then, that the undrained shear strength of cohesive soils assumes an economic importance. It is the basis for compressed air or full face support requirements, and for requirements to the methods of filling the annular void. In hard clays it is the basis for specifications such as maximum unsupported span, and for the assessment of tunnel lining loads.

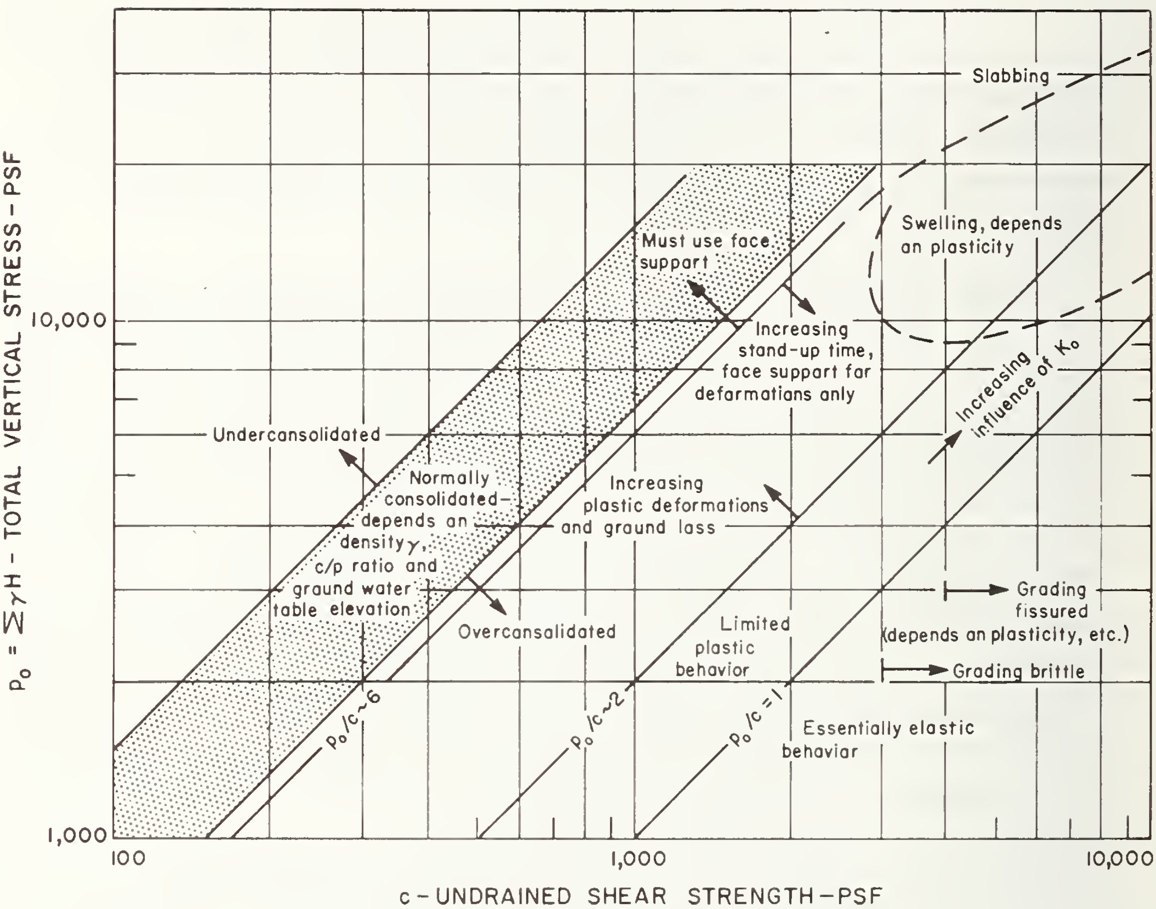


Figure 4-2. Effects of Undrained Shear Strength on Tunneling.

In soils that are basically granular, with only a small cohesion, whether due to a clay content or cementation, conditions are more complex. Above the groundwater table, a cohesionless mass will ravel to form a slope at the natural angle of repose at the face, and the annular void will tend to fill. Below the groundwater table, a cohesionless soil will offer little or no resistance to the flow of water, and running conditions prevail.

However, even a small cohesion will give the soil a capacity to stand up. In theory, a plastic zone does not develop around a circular opening when the ratio p_o/c is smaller than the quantity $\cos\phi/1-\sin\phi (= \sqrt{3}$ for $\phi = 30^o)$. However, theory also explains that even the slightest cohesion will stabilize the opening, provided a large enough plastic zone develops. The development of a large plastic zone carries with it large displacements and strains, and instability does occur as soon as strains approach failure strains, or as soon as strains have locally destroyed the cementation. Instability usually occurs by chunks or blocks of soil falling out or by slabbing. Conditions at the face are governed by the same basic laws.

Below the groundwater table, where instability occurs in conjunction with a seepage, a small cohesion of the soil increases the critical gradient and hence reduces the potential for piping and instability. The mechanism is not well understood, and such instability problems are certainly very sensitive to minor variations of strength and permeability.

Further theoretical and experimental study is required to determine quantitatively the effect of a small cohesion in the tunnel environment, but there is no doubt of its benefit. Details of shield design (hood, forepoling, etc.), requirements to dewatering or air pressure, to face support and to void filling, hinge on a proper evaluation of stability.

4.6.3 Compressibility (Modulus of Deformation)

The modulus of deformation of a soil is extremely difficult to determine by simple tests in the laboratory. Most reliable modulus determinations have been based on or verified by prototype behavior in the field. It appears at this time that field measurements are the most accurate basis for determining soil moduli.

Because of the difficulty of obtaining reliable design values for soil moduli, most design procedures for underground structures circumvent the modulus. In theory, however, it is possible to use the soil modulus for the following purposes:

1. To determine, by finite element methods or other types of analysis, the probable magnitude and extent of ground movements.

2. To evaluate the redistribution of earth stresses around and above tunnels (arching, etc.).

3. To estimate distortions and stresses in tunnel linings.

4. To calculate distribution of foundation and earth pressures on massive station structures.

5. To evaluate the interaction between neighboring tunnels and other structures.

The direct use of moduli is difficult in these instances, even if the moduli are known. For example, the behavior of these structures are greatly dependent on construction procedures, which often cannot be fully anticipated. Soil moduli vary with the imposed state of stress (compression, extension), the stress level and the magnitude of deviator stress. Considerable basic research is needed to deduce the modulus in one stress environment from modulus determinations under other stress environments, and to properly apply the modulus in design. Fortunately, practice indicates that actual tunnel behavior is fairly insensitive to variations in modulus. Empirical and semi-empirical design procedures in current use appear adequately safe. It is not known, however, to what degree underground structures are overdesigned by use of these methods. Hence, the economic benefit of an improved modulus determination cannot be fully established.

If a method is developed for rapid and inexpensive modulus determinations in the field, such determinations can have other uses. It is well-known that there is a close relationship between modulus and strength. The modulus can, therefore, be used to classify soils in terms of strength. It may also be possible to deduce the general character of the soil strength from certain types of modulus determinations; for example, whether the strength is primarily cohesive or frictional, or whether the soil strength is dependent on a cementation. The likely success of such interpretations cannot be determined accurately at this time. Field tests and actual correlations must broaden the experience base before practical use can be made of such interpretations.

Nonetheless, because of the large number of potential applications of the soil modulus, the determination of the soil modulus by field tests has a great future potential.

4.6.4 Compressibility (Consolidation Characteristics)

Compression of soft silts, clays, and organic materials due to dewatering is governed by the preconsolidation pressure and by the slope of the consolidation curve, virgin or recompression. The long term behavior of a stiff clay around a tunnel is also to some extent dependent on the preconsolidation pressure, and on the rebound behavior of the clay. While the previous section dealt with the short-term soil modulus, this section deals with the long-term modulus.

By the basic nature of the long-term modulus, it is clear that any short-term field test or any examination of the soil at its current state cannot lead directly to a determination of the long-term modulus. It must be determined by tests of some duration, most conveniently performed in the laboratory.

It is possible, however, to deduce the preconsolidation pressure from the cohesion or shear strength of the soil and possibly, after some research and accumulation of experience, from the short-term modulus. This possibility adds further significance to the determination of these parameters.

4.6.5 Classification Characteristics

These include density (void ratio, porosity), water content (per cent saturation), grain size distribution, per cent organic content, grain shapes, mineralogy of grains, and for cohesive soils also plasticity limit, shrinkage limit, and liquidity index.

Only few of these characteristics enter directly the evaluation of soil behavior in the tunnel environment, and only density and water content can be measured by in-situ tests.

The grain size distribution and grain shape are of particular importance for evaluation of the coherence of the soil and its stand-up time, especially below the water table, and for estimation of permeability. Plasticity and liquidity indices are significant for estimating the behavior of stiff clays (swelling, etc.). In this respect also the clay content is of significance.

4.7 CULTURAL FEATURES (MAN-MADE)

4.7.1 Shallow Features

Most utilities and shallow foundations do not directly interfere with tunnel construction because they are significantly above the tunnel crown. Their exact locations are of minor importance, as long as their existence and approximate locations are known. Their sensitivity to settlements must, of course, be analyzed with predictions of ground movements, but this is beyond the scope of this study. These near-surface features assume a much greater importance for cut-and-cover and shaft construction.

4.7.2 Deep Features

The only type of utility that is occasionally found at a depth where direct interference with tunneling can occur is the sewer. Except for large water tunnels, other utilities are almost always close to the surface. Sewer lines must as a rule follow gradients commensurate with gravity flow; hence, when the terrain has hills and valleys deep sewers are often required. Also, because a great effort is expended in placing these sewers underground, whether by cut-and-cover or tunneling, almost all deep sewers have a significant size, generally greater than 36-inch diameter but regularly twice as big.

In most municipalities, the location of sewers of this size is known or can be inferred from man-hole locations or similar means. Only in very few old municipalities do such sewers exist, dead or alive, full or empty, without the authorities knowing of them. Neither the San Francisco BART tunnel construction nor the Washington Metro tunnel construction have encountered such unknown facilities. Subways in Chicago encountered some old freight tunnels whose location was known in advance. Interviews with several contractors, experienced in tunnel construction in the New York area, have disclosed only few instances, where unknown sewers have been encountered directly within tunnels. It has been pointed out, however, that such sewers can also present problems when they are located a distance above the tunnel.

While the potential cost of encountering and rupturing an unknown sewer could run between $50,000 and $100,000 or even beyond $200,000 in catastrophic instances, it would appear that the occurrence is so infrequent that the cost of ascertaining their non-occurrence would not be balanced by the savings. It would also appear that any geophysical tool would only be able in the most favorable instance to give cause to a suspicion of an anomaly, provided expert interpretation is employed. Such knowledge could come about as a by-product of systematic use of geophysical tools for stratigraphic mapping from the ground surface.

Other deep manmade structures whose location and character may not be known a priori include piles supporting existing or demolished structures, soldier piles or sheet walls left in place from previous construction, or buried water front structures. For example, several rows of old sea walls exist along the west side of Manhattan.

Such structures do indeed impose severe cost penalties on tunnel construction and are generally avoided whenever possible. For example, tunneling beneath the Ferry Building in San Francisco involved the cutting of 220 timber piles at a cost (bid price) to the owner of $750 each. In addition, of course, the Ferry Building was underpinned at considerable expense.

When the cutting of piling cannot be avoided, the knowledge of their existence and their approximate number are generally sufficient. The exact location of each pile is not needed.

Only when it is possible to thread the tunnel through or below the forest of piles without interference, or where a slight shift of alignment is likely to greatly reduce the number of piles cut, does it become important to know the location and tip elevation of the individual piles with some accuracy.

The first step in determining the existence and location of such piling is a carefully executed examination of all old records, with a knowledge of the building practices of days past. Then, if problems are disclosed which do require the determination of individual pile locations, the cost of acquiring this knowledge must be balanced against potential cost savings during tunneling.

Fortunately in only rare instances is this knowledge needed. In the San Francisco BART project's 14 route miles of soft ground tunnels, piles were encountered only in one location where they were unavoidable and their exact quantity and location proved insignificant through the prior knowledge of their existence and approximate locations.

5. INVENTORY AND APPRAISAL OF EXISTING AND PROSPECTIVE METHODS OF EXPLORATION

5.1 INTRODUCTION

In section 4, the most important geotechnical parameters were defined and discussed, and a priority rating was established. Section 5 contains an inventory and appraisal of existing methods of exploration, with particular emphasis on methods suitable for exploring the high priority parameters. Many of these methods are in current use and do not warrant significant further development. Others, however, although potentially valuable, have seen little use in this country or none at all, though the state of their development is fairly well advanced. These little used methods include some that have been used extensively abroad, and others that are recent developments. Some methods have been found to be deficient either in the theory and general practice of interpretation, or in details of field application.

By matching the approximate priority ratings given in section 4 with the potential capabilities of improved methods and tools, together with an assessment of necessary development efforts, three items have been found to deserve a high development priority. These are:

a. In-situ permeability measurement methods.

b. Geophysical borehole logging tools.

c. Surface seismic instruments.

The first two items are subjects of further discussion and recommendations in Section 6. Surface seismic survey developments are not treated in detail here because they are subject to research through other Department of Transportation Research Contracts.

The various exploration methods are logically separated into those that measure soil properties or geologic conditions directly, and those that give indirect physical evidence of conditions. The latter are usually called geophysical methods and are of two types: geophysical methods employed from the ground surface, and geophysical borehole logging methods. The geophysical methods used for locating utilities and other manmade obstructions are in a separate class and are treated accordingly.

Section 5 concludes with a series of general recommendations and a look into the future of subsurface explorations for tunnels in soil.

5.2 DIRECT EXPLORATION METHODS

5.2.1 General

This section presents the inventory of in-situ direct methods of subsurface exploration. The basic principle of operation and the measured parameter(s) for each method are described. The relevance of each technique for use during investigations for urban soft ground tunnels is considered as well as its applicability for the determination of major important tunnel parameters (stratigraphy, permeability, shear strength). The limitations and need for further development of hardware, test procedures, and acquisition and analysis of raw data is assessed for each technique, with suggestions for possible innovations.

Table 5-1 lists each of the direct measurement methods considered and the soil parameters measured by each. These parameters include soil type, shear strength, deformation modulus, permeability, and piezometric level. Table 5-2 summarizes the limitations, availability, and usage of each technique. Schematic diagrams for each technique are also included as figures 5-1 through 5-10.

Though conventional boring, undisturbed sampling and laboratory testing will have an important place in soil explorations of the future, these are not inventoried and discussed here. Basically, these methods are well developed, and they are not directly within the scope of this report.

TABLE 5-1. PARAMETERS MEASURED BY VARIOUS DIRECT IN-SITU TESTING METHODS

Parameter / Type of Test	Shear Strength	In-situ State of Stress	Piezo-metric Head	Modulus of Deform-ation	Permeab-ility	Soil type
Standard Penetra-tion Test	x					x
Dynamic Cone Penetra-tion Test	x					x
Static Cone Penetration Test	x					x
Vane Shear Test	x					
Dilatometer Test	x	x		x		
Borehole Jack Test	x			x		
Iowa Bore-hole shear Test	x					
Piezometers			x		x	
Borehole Permeab-ility Test					x	
Large Scale Pumping Test			x		x	

TABLE 5-2. LIMITATIONS, AVAILABILITY AND USE OF VARIOUS DIRECT IN-SITU TESTING METHODS

Characteristics & Requirements / Type of Test	Hole Req'd	Suitable for	Analysis	Reliability & Reproducibility	Approx. Number of Different Types	Approx. Number of Manufacturers	Comments
	C-Cased O-Open S-Stabilized	C-Cohesive S-Fine granular G-Course granular	E-Empirical T-Theoretical				
Standard Penetration Test	C or O or S	C, S, G	E	Fair	--	--	Common usage with test boring. Much experience. Several useful correlations.
Dynamic Cone Penetration Test	No hole	C. S, G	E&T	Fair to Good	8	8	Little American experience. Calculations yield values of N(SPT) or undrained shear strength.
Static Cone Penetration Test	No hole	C, S	E&T	Good to Excellent	20	20	Recent developments with friction sleeves have led to ability to identify soil types. Very promising technique.
Vane Shear Test	No hole	C	E&T	Good	3	5	Recent empirical corrections have improved analytical result.
Dilatometer Test	O or S	C, S	T	Fair to Excellent	6	6	Research is currently being done on equipment. Increasing in usage in U.S.
Borehole Jack Test	O or S	C, S, G	T	Good	8	4	Applicable primarily to firm hard ground.
Iowa Borehole Shear Test	O or S	C, S	T	Fair to Excellent	1	1	Basic idea good, equipment questionable.
Piezometers	C or O or no hole	C, S, G	T	Excellent	16	26	Many variations available.
Borehole Permeability Test	C or O	C, S, G	T	Poor to Good	--	--	Results generally questionable. Need exists for standardization.
Large Scale Pumping Test	C or O	C, S, G	T	Good to Excellent	--	--	Best method for evaluating overall permeability of large zone.

5.2.2 <u>Standard Penetration Test</u> (See figure 5-1)

The Standard Penetration Test (SPT), one of the most frequently used direct methods of subsurface exploration in the United Stated, consists of driving a standard Goose Gow 2 inch O.D. split-spoon sampler by means of a 140 lb weight falling 30 inches. The standard penetration resistance, N, is the number of blows required to drive the sampler the last 12 inches of an 18-inch drive. Quite frequently the test is performed at 5-foot intervals or at stratum changes, although almost continuous profiles of SPT results may be obtained. Although a commonly used standard test for the past 30 years, several variations of the Standard Pentration Test do exist and are described by Ireland et al (1970).

The Standard Pentration Test is interpreted by means of readily available empirical correlations between the Standard Penetration Resistance N, and soil parameters such as consistency, relative density and shear strength. See Terzaghi and Peck (1967) and DeMello (1971) for detailed discussion of these correlations. Generally, these correlations should be regarded only as approximate for a number of reasons. First, most such empirical correlations are statistically derived from a broad data base. Considering the natural nonhomogeneity of soils, there is always the possibility of a fairly large deviation from the norm for the particular project at hand. At significant depth, the amount of side friction on the drill rods significantly affects results. Second, most correlations do not consider the effect of confining pressure (See Gibbs and Holtz, 1957, for an exception), which may be especially important for granular soils.

The procedure employed in performing the SPT is important. Proper seating of the sampler, connections between the drill rods, correct weight and drop, and proper washing before performing the test all have significant influence on the resulting N values. Partial obstructions such as cobbles may yield inordinately high blow counts yet remain undetected by an unqualified driller. Supervision by a qualified and experienced inspector is in fact necessary for situations where accurate blow counts are critical.

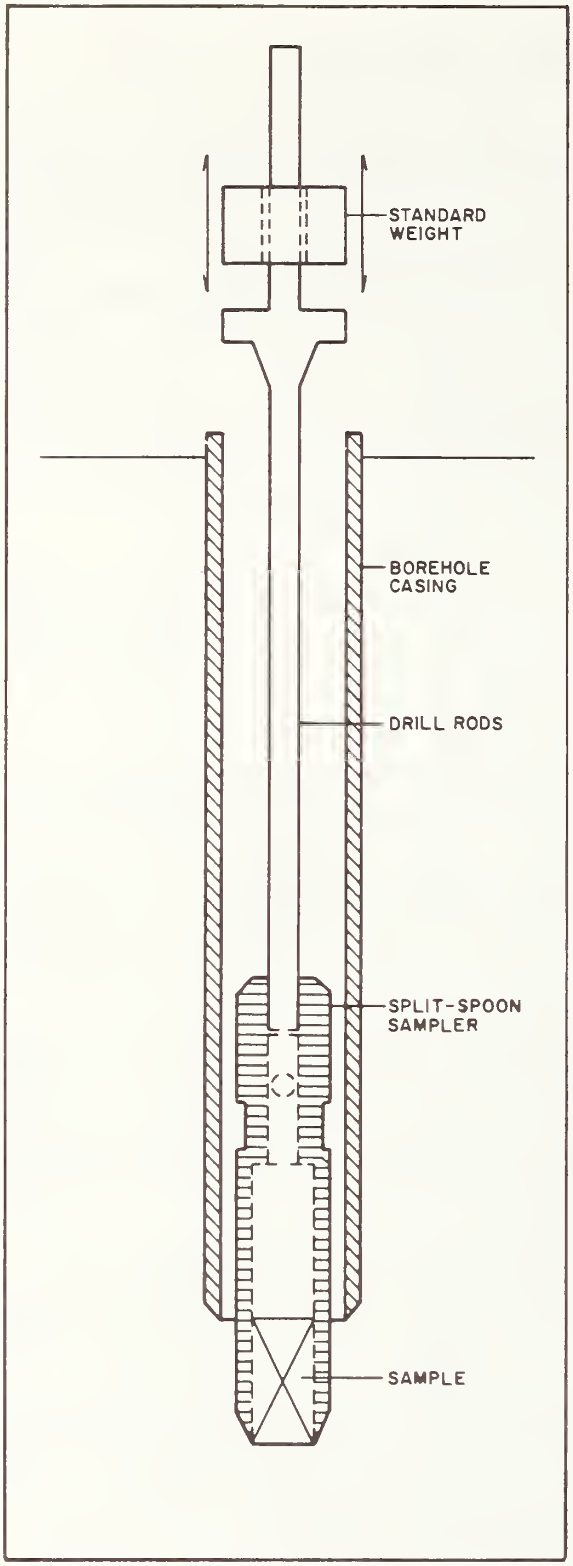


Figure 5-1. Standard Penetration Test.

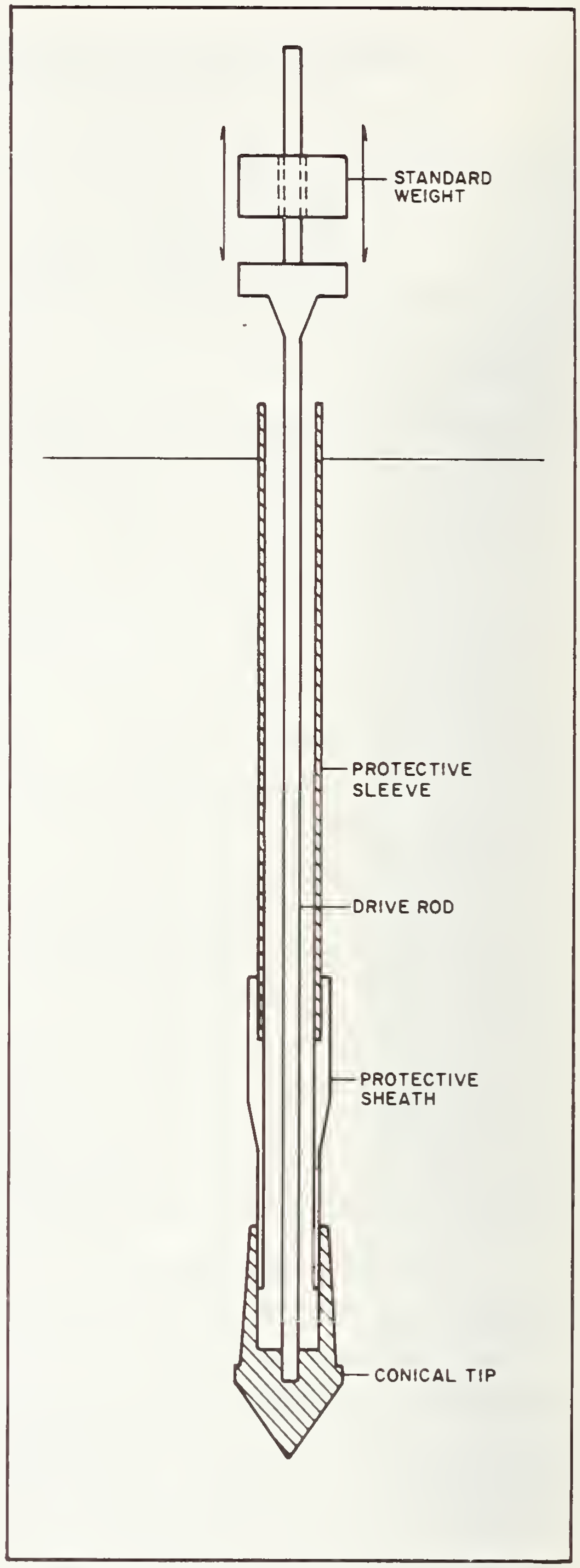


Figure 5-2. Dynamic Cone Penetrometer.

The Goose Gow sampler used for the SPT will in most soils recover a representative sample with all soil constituents retained in their proper proportions. These samples are not adequate for sophisticated laboratory tests requiring undisturbed samples but are adequate for classification of soil type and identification of stratigraphy. However, thin layers of possible significance may remain undetected.

In summary, the SPT, if properly performed, may supply valuable, albeit somewhat approximate, information regarding stratigraphy and the shear strength of soil. No significant development effort is recommended at this time since the successful interpretation of the test depends primarily on the large amount of empirical correlations and data obtained from the SPT in its present form. However, as recommended by Gibbs and Holtz (1957), the effects of confinement should be considered in correlating N to shear strength.

5.2.3 Dynamic Cone Penetration Test (See figure 5-2.)

The dynamic cone penetration test is performed by driving a conical point by means of a falling weight, and noting the amount of advancement of the cone for each blow. Unlike the SPT, dynamic cone penetrometers may be advanced without a borehole, as the cone pushes the soil in its path aside. The procedure may be used in very hard or dense materials which would refuse advancement by other tests such as the static cone.

The test may be interpreted both theoretically and empirically. Sowers and Hedges (1966) report empirical correlations between cone advancement and SPT N values which are in turn correlated with consistency, relative density and shear strength. Theoretical solutions relating the cone advancement to the friction angle of sands and the undrained shear strength of clays have been applied with moderate success in Europe (Sanglerat, 1972). With experience, the results of the dynamic cone penetration test may be correlated with stratigraphic changes to yield soil profiles, although the results are quite approximate (Sanglerat, 1972).

The primary limitation of this test is its lack of standardization. For example, Heijnen (1973) and Thomas (1965) have shown that cone advancement is very dependent upon the cone shape, yet in Europe, where the test is most frequently used, several cone configurations are quite common (Schultze and Knausenberger, 1957, Sanglerat, 1972). At significant depth, the amount of side friction on the drive rods significantly increases if the penetrometer is driven without caseing. However, present hardware does not allow for measurement of friction and there appears to be no reasonable theoretical solution to this problem.

In summary, the dynamic cone penetration test is commonly used in Europe for determining the shear strength of soils and approximate stratigraphy. Despite economic benefit from the opportunity to perform a test without a borehole, the dynamic cone is rarely used in the United States. The test yields basically the same type of information as the SPT, but it is not as well standardized, is less amenable to empirical correlation in the United States because of its lack of use, and does not yield a sample. Recommended hardware improvements would include the development of friction sleeves to permit the separation of point resistance and side resistance. However, because of the problems outlined above, there does not seem to be adequate potential for the dynamic cone penetrometer to warrant such development at the present time.

5.2.4 Static Cone Penetration Test (See figure 5-3.)

Static cone penetration tests (Dutch cone tests) are performed by advancing a conical point at a constant rate through the substrata by means of a hydraulic jack reacting against a truck or rigid frame. The total resisting force necessary to maintain this constant rate of penetration is measured. Cone penetrometers may be used in either sands or clays, above or below groundwater level, and can be advanced without a borehole. At present, there is a variety of cone configurations in use throughout Europe, although a recently proposed ASTM specification, (ASTM, 1970) calls for an apex angle of 60° and a projected

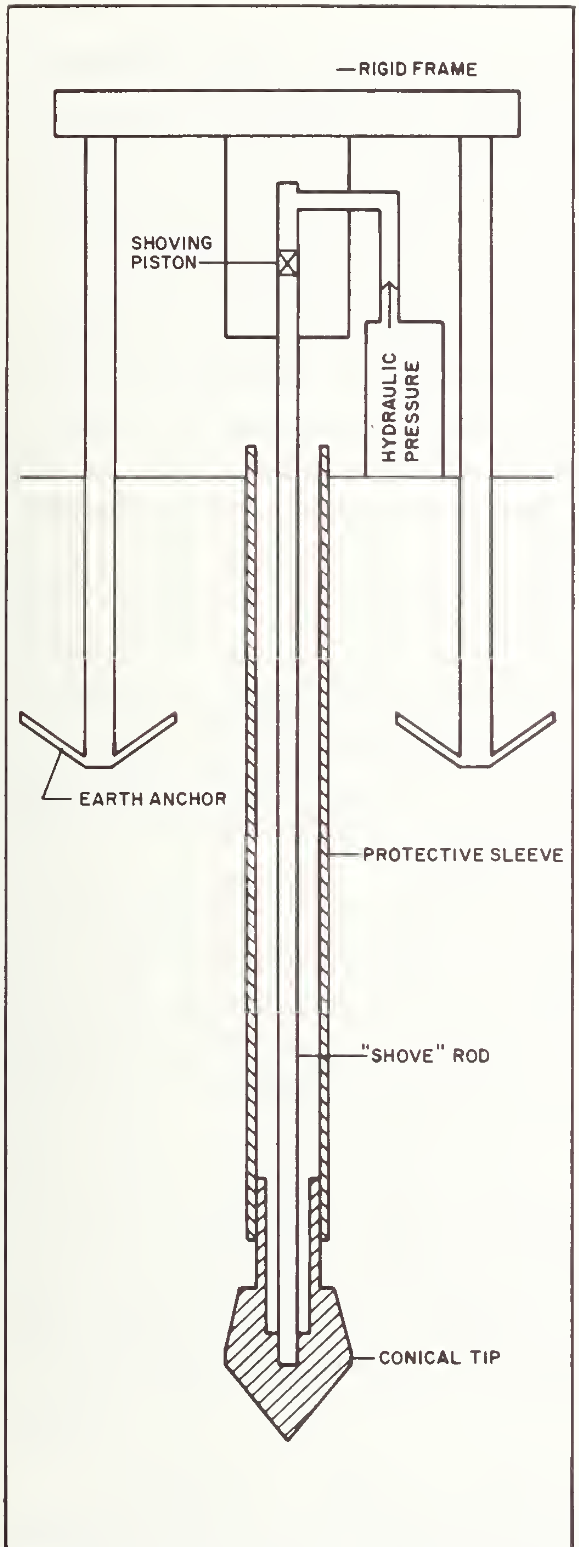


Figure 5-3. Static Cone Penetration Test.

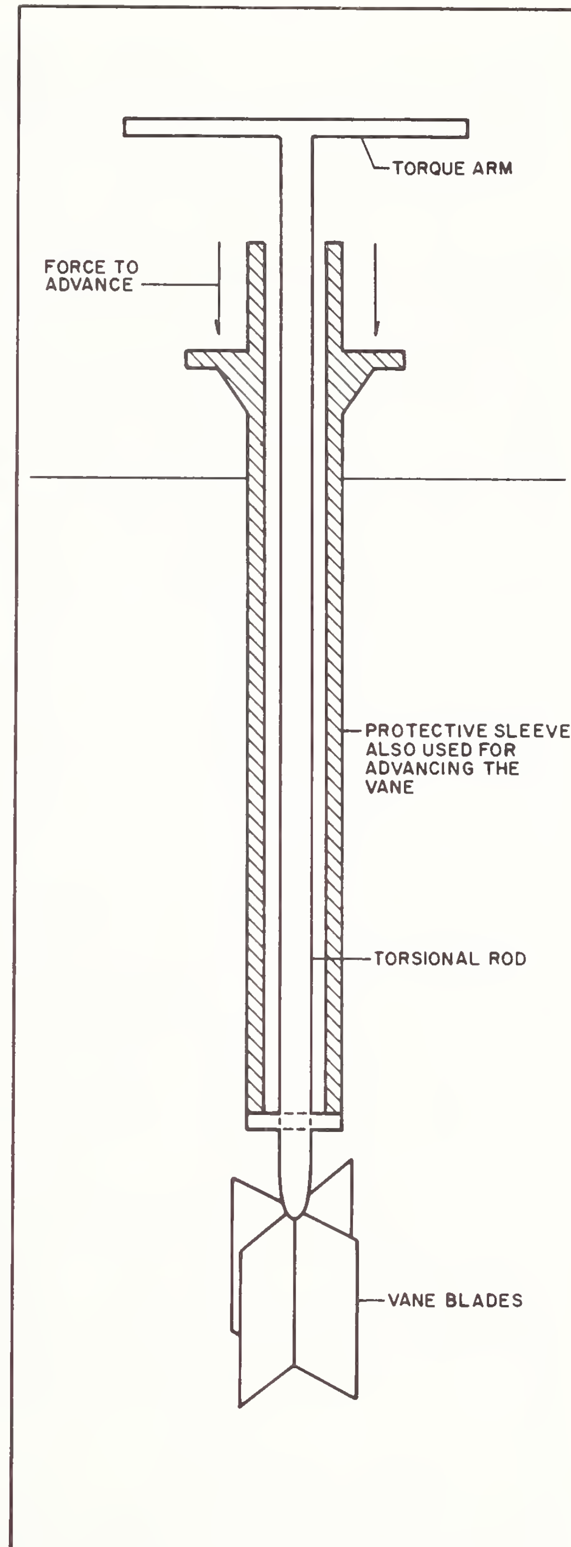


Figure 5-4. Vane Shear Test.

area of 10 sq. cm. European engineers have amassed and evaluated a large amount of static cone penetrometer data, much of which is reported in the authoritative text by Sanglerat (1972).

Significant recent improvements have focused on the development of a friction sleeve cone penetrometer which measures separately the end bearing force and the side frictional force (DeRuiter, 1971 and Joustra and Figro, 1973). A friction-sleeve cone penetrometer with all necessary peripheral equipment is currently being marketed in the United States by Structural Behavior Engineering Laboratories. This device utilizes load cells for separate measurements of end bearing and side friction forces. Readings are continuously recorded by means of a strip chart recorder, thus facilitating rapid data reduction and interpretation.

Cone resistance is used to determine cohesion and friction angle, and hence the shear strength of sands and clays, by means of semi-empirical bearing capacity factors (Mitchell and Durgunoglu, 1973, and Hansen and Christensen, 1964). Recent developments in the use of the friction sleeve also permit fairly reliable determinations of soil type and stratigraphy. Begemann's (1953) initial work in relating profiles of friction ratio (end bearing resistance/side friction resistance) to stratigraphy met with considerable success and has been enhanced by additional studies by Schmertmann (1971) and Gorman et al (1973). Because data can be continuously recorded, thin layers of material can be detected which may significantly influence tunnel construction.

One major difficulty common to many field and laboratory tests is the dependency of the measured cone resistance on rate of penetration (or strain). This problem develops either due to the lack of control over drainage conditions or the time dependent (e.g., viscous) behavior of many soils. It is most significant in evaluating the shear strength of clays. To solve this problem partially, an advancement rate of 2 cm./sec., has been semi-standardized and is most generally used. However, the basic problem still exists of applying strength data, obtained at one strain rate, to the actual tunnel problem where strains most likely occur more slowly. Consistent with the state-of-the-art in other areas of geotechnical engineering, it is suggested that data be adjusted empirically for strain rate, using the large amount of data already available on the time dependency of the behavior of soils (see Ladd, 1971, for a brief review).

In summary, the static cone penetrometer test has been successfully used for many years in Europe for determining stratigraphy and shear strength of soils. The test is suitable for many different soil types and is quite economical. The test is fairly reliable, if not on an absolute basis, certainly on a relative basis for determining changes of type and strength of soils to be encountered on any given tunnel project. Given the recent friction sleeve improvements, there seems to be great promise in encouraging the use of static cone penetrometers in the United States. At present, the most significant implementation problem will be the selection of hardware and procedures from the many that are available. Recommendations for combining a static cone penetrometer with other instruments, in one package, are made in paragraph 5.2.12 below.

5.2.5 Vane Shear Test (See figure 5-4.)

The vane shear test consists of inserting a configuration of steel vane blades into the soil, applying a torque so as to rotate the vane at a constant rate until a shear failure occurs. Angular deformation and resisting torque are measured throughout the test. The vane apparatus may be advanced to large depths in soft soils without a borehole. In this case, however, protective sheaths are commonly placed around the probe rods in order to minimize torsional friction resistance on the rods. Generally, the vane is restricted to use in clay soils and is most frequently used in locales, such as Norway, where sensitive clay is highly susceptible to disturbance associated with sampling for laboratory tests.

Hardware is fairly well developed with a variety of vane configurations. Aas (1965, 1967) has shown that, because of the inherent anisotropy of many clays, peak resisting torque is highly dependent on the height to diameter ratio of the vanes. Thus vanes with different height/diameter ratios may yield valuable information on anisotropy. However, there is a general need for more standardization. The ASTM Standard (ASTM, 1972) calls for a four blade configuration with a height/diameter ratio of 2.0, consistent with the dimensions of many commercially available vanes.

The peak torque value is related to undrained shear strength, either by means of theoretical analyses which consider the stress distribution around the vane, or by empirical correlations based on laboratory tests or backfigured strengths from failure in clay. Typical among the theoretical equations is the Cadling-Odenstad (1950) equation which assumes uniform shear stresses on all failure surfaces around the vane. Also frequently used is the Goughnour and Sallberg (1964) equation which assumes a linear variation of shear stress along the failure surfaces at the top and bottom of the vane and uniform shear stresses on lateral vertical surfaces.

Empirical correlations between vane test results and shear strength of clay, based upon studies of embankment failures, have been presented by Bjerrum (1972). Bjerrum indicates that vane shear results (as interpreted by means of theoretical equations) generally overestimate the in-situ undrained shear strength in a manner related to the plasticity index of the soil. Laboratory vane tests by Goughnour and Sallberg (1964) support Bjerrum's data.

Limitations of the vane include inordinately high measured vane strengths for thin silt or fine sand seams in a clay soil. The stress system applied by the vane is unlike any prototype stress system and therefore theoretical interpretations, as described above, should not be applied with great confidence. Finally, as for the static cone penetration test discussed above, the vane is susceptible to strain rate effects. Therefore, vane strengths depend on the rate of rotation. Commonly for soft soils, rapid rates of rotation yield high shear strengths (Parry, 1972 and Wiesel, 1973). A constant rate of rotation of 6 degrees/min. is commonly accepted as a standard, which can then be empirically adjusted for actual in-situ strain rates.

In summary, the vane shear test is a useful technique for evaluating the undrained shear strength of clays, especially sensitive clays susceptible to sample disturbance. The equipment is in a high state of development and should yield reliable and reproducible results. Because of the problems outlined above, it is recommended that theoretical interpretations be applied cautiously when estimating absolute values of shear strength, with preference given to empirical interpreations such as those presented by Bjerrum (1972). The test is especially suitable for evaluating relative changes in shear strength in a predominantly clay soil profile.

With respect to soft ground tunneling in urban environments, no additional development is recommended. There are no readily obvious improvements to be made other than continued usage to improve existing empirical correlations. The test is best used for determining undrained shear strength of clays, yields no sample and as such is limited. There appears to be more potential for development of static cone penetrometers.

5.2.6 Dilatometer Test (See figure 5-5.)

The dilatometer, or pressuremeter test consists of the application of radial stress to a cylindrical section of an uncased borehole and the measurement or calculation of the resulting deformation. An uncased borehole with a diameter between 1.5 inches and 11.7 inches (depending on type of instrument) is required (Goodman et al, 1968). Wall stabilization is usually required for granular materials, especially below the ground water level, and presents many practical difficulties. The application of the radial stress is obtained by expansion of a rubber membrane, either by air or hydraulic pressure, controlled and measured at the ground surface. Air pressure is generally preferred, due to the increased convenience and reliability of the system. Values of the maximum applied stress vary up to 2200 psi, allowing use in most soils and some soft rocks.

The test is used primarily to determine the modulus of deformation, by application of the theory of elasticity to the

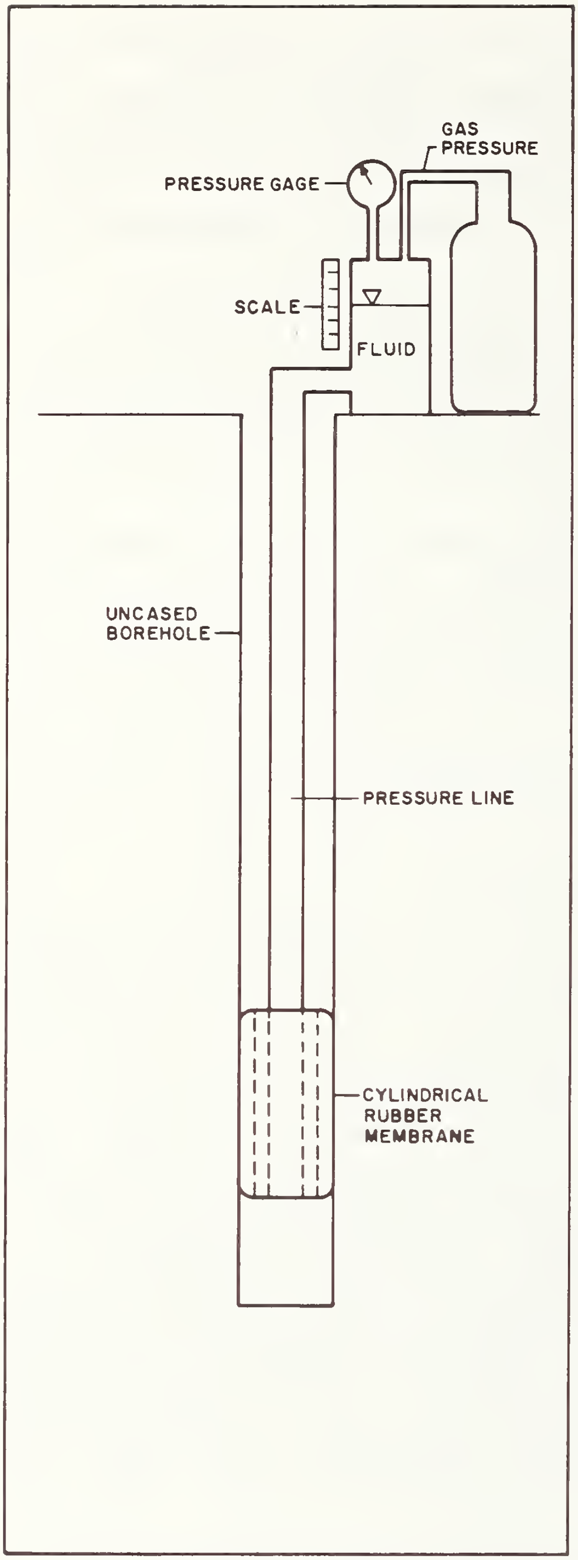


Figure 5-5. Dilatometer.

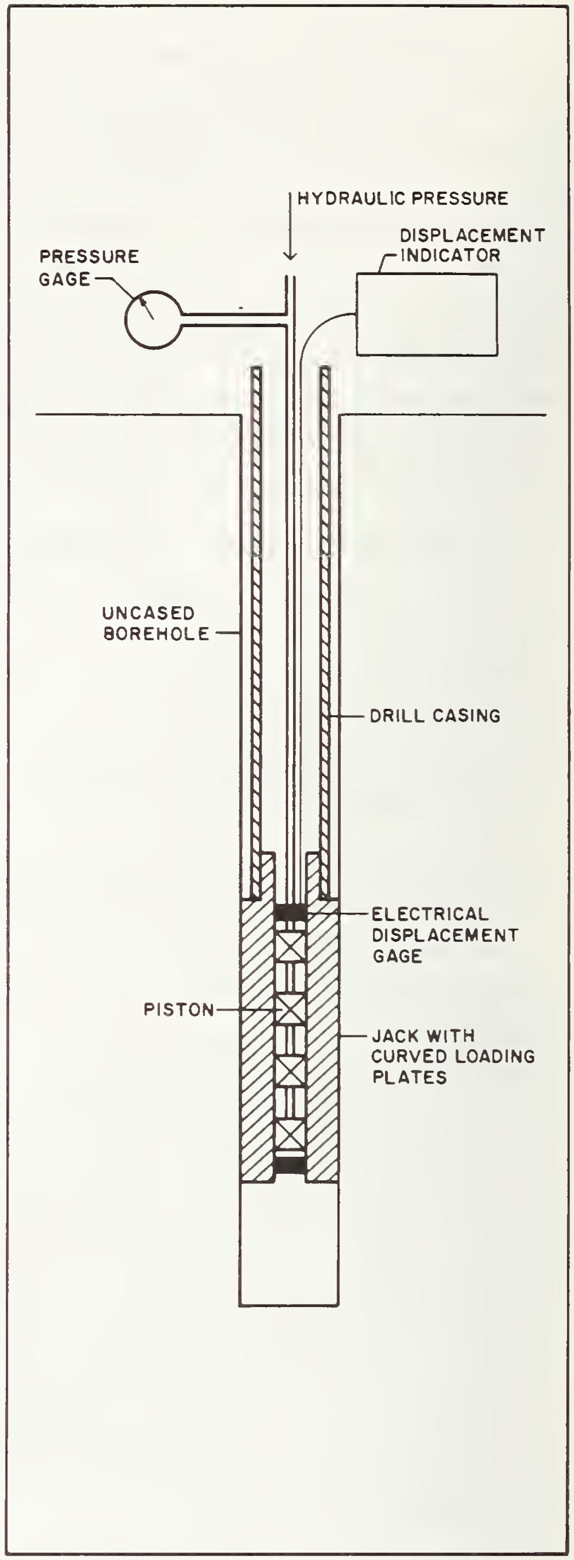


Figure 5-6. Borehole Jack.

boundary conditions imposed by the test. A few investigators (Wroth and Hughes, 1973, and Gibson and Anderson, 1961) claim moderate success in applying the test to the determination of the undrained shear strength of clays or the friction angle of sands. Most engineers refrain from using the test to measure strength properties. In-situ state of stress may also be inferred by noting the pressure required to restrain the borehole from inward deformations, although the inference is subject to gross errors due to soil disturbance.

The method used for measuring the resulting deformation is perhaps the most critical factor in dilatometer tests. In some devices, notably the Menard Pressuremeter (Dixon 1969), deformations are calculated from measurements of the volume of fluid pumped. Significant errors can develop due to leaks in the pressure system and due to the compressibility of the dilatometer itself. Other errors develop from differences in temperature or pressure between the ground surface, where pressures and volumes are measured, and the depth at which the test is conducted. Because of the limited length of the stressed area and consequent end restraints, the measured radial deformation is only the average radial deformation. Other devices (Goodman et al, 1968) circumvent this problem by utilizing electrical or mechanical techniques for measuring the radial deformation. The advantage of these techniques is that several independent radial measurements may be taken. The hardware is highly developed and reliability is good.

Improvements in the hardware have recently been made by Cambridge University (Wroth and Hughes, 1973). This new device contains, in addition to a pressuremeter, a load cell for measuring the lateral total stress and a pressure transducer for measuring pore pressure. Significantly, it is capable of augering itself into position. Although this procedure is time-consuming, it does avoid the problem of maintaining an uncased hole, and helps to minimize disturbance to the surrounding soil.

The dilatometer test appears especially attractive because the hardware is readily available and at a moderate state of development (with recent innovations currently under investigation). It is one of the few devices suited for the in-situ determination of modulus. It has received little usage in the United States but holds great promise for tunneling in soft ground. A recommendation for increased usage is made in paragraph 5.2.12.

5.2.7 Borehole Jack Test (See figure 5-6.)

The borehole jack test consists of the application of a unidirectional load to opposite sides of an uncased borehole via curved loading plates. The load is applied by means of a hydraulic pressure system and changes in borehole diameter are commonly measured by means of downhole displacement transducers. Alternatively, the change in borehole diameter may be determined from the volume of fluid applied to the jack. Applied load capacity is high, with the Goodman jack (Goodman et al, 1968) capable of applying pressures up to 8800 psi. Hardware is in a fairly high state of development and is gaining increased usage in the United States. Detailed descriptions of the various available hardware are presented by Hall and Hoskins (1972) and Cording et al (1974).

The raw data, in the form of applied load and change in dimension of the borehole, may be used to determine deformation modulus and shear strength. Generally, application of the theory of elasticity to the boundary conditions applied by the test is necessary for the interpretation of the test.

The major limitation of the borehole jack test for tunnel explorations in soft ground is the condition of the borehole required by most of the available hardware. These systems generally require an uncased or stabilized borehole, often of large diameter. The effect of this constraint is to limit use of the test primarily to very dense or hard soils, or rock. One significant exception is the Goodman jack which has been successfully applied for explorations in soft soils. However, more reliance is generally placed on the dilatometer test for soft soil investigations, and further development of the borehole jack test for these purposes is not warranted at this time.

5.2.8 Iowa Borehole Shear Test (See figure 5-7.)

The Iowa borehole shear test is performed by lowering an expandable shear head to the desired depth in an uncased borehole. Two opposing plates on the shear head are expanded until seated on opposite sides of the borehole, and consolidation of the soil is allowed to occur under equal unidirectional forces applied to the plates. When consolidation is complete, the shear head is pulled vertically upward and the maximum resisting force developed by the soil is measured. The shear head may then be contracted and rotated 90 degrees for another test along an orthogonal diameter.

The shear strength of the soil may be obtained by computing the maximum shear stress on the plates necessary to develop the measured resisting force. By performing a number of Iowa borehole shear tests at different normal plate loadings, it is also possible to determine the Mohr-Coulomb envelope parameters, cohesion and friction angle. The test may also be used to determine the in-situ state of stress by measurement of the horizontal force exerted on shear plates which have been in place for a period of time, although this measurement is not generally accepted as very reliable.

Although the technique appears promising, several limitations, over and above the requirement for an uncased or stabilized borehole, have prevented full acceptance of the test. It is not possible to control drainage conditions fully, so that it is not known whether the measured strength is the fully drained, fully undrained, or partially drained strength. The applied stress is not similar to the prototype stress system. Finally, the shear strength of unconsolidated portions of the borehole wall, not overlain by the shear head plates, may contribute to the measured resisting force but are not accounted for in the interpretation of test results. No innovations to overcome these limitations are foreseeable in the near future. Therefore application of the Iowa Borehole shear device to explorations for tunnels in soft ground does not appear to be immediately promising.

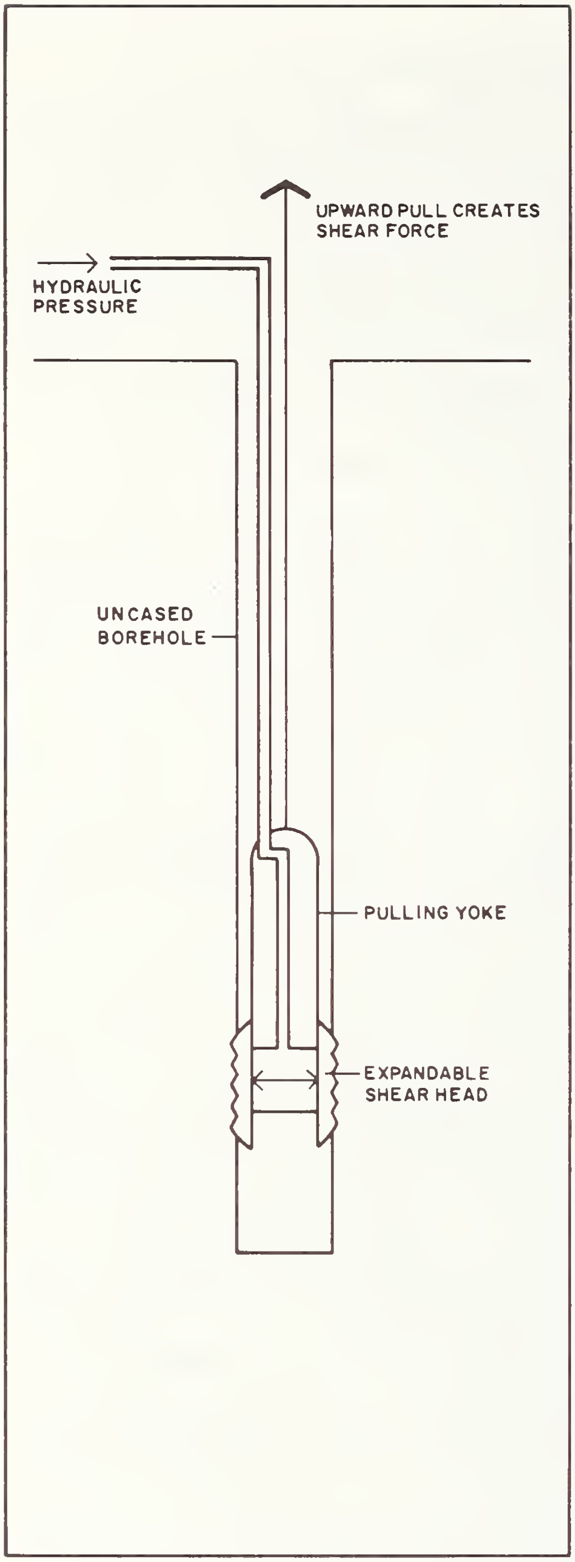


Figure 5-7. Iowa Borehole Shear Test.

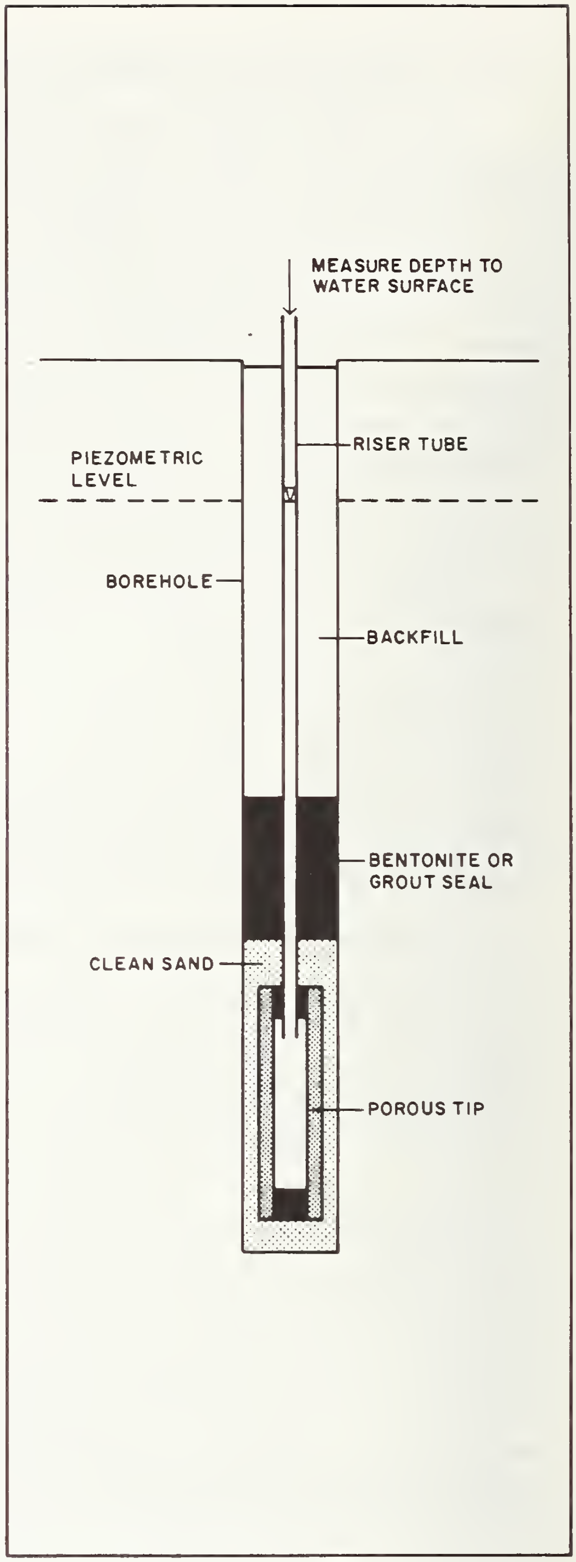
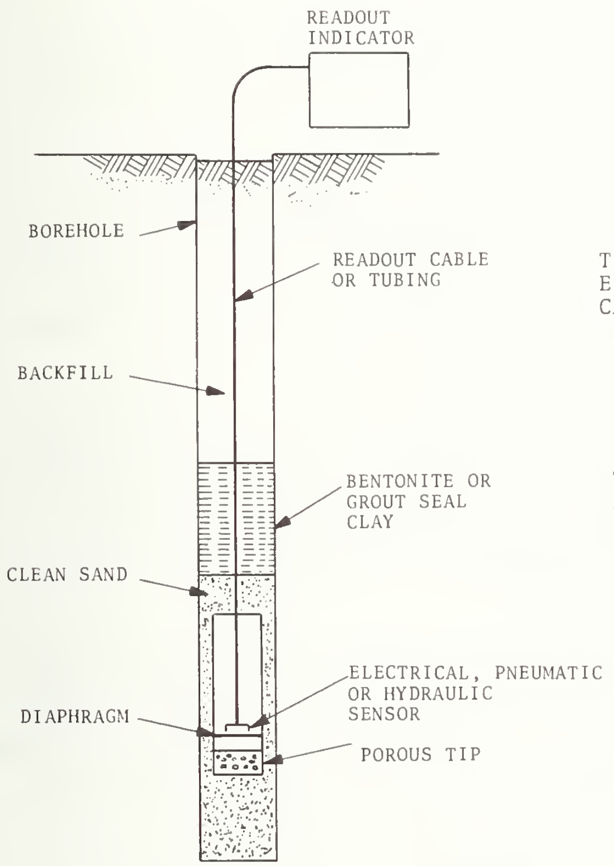


Figure 5-8. Open Standpipe Piezometer.



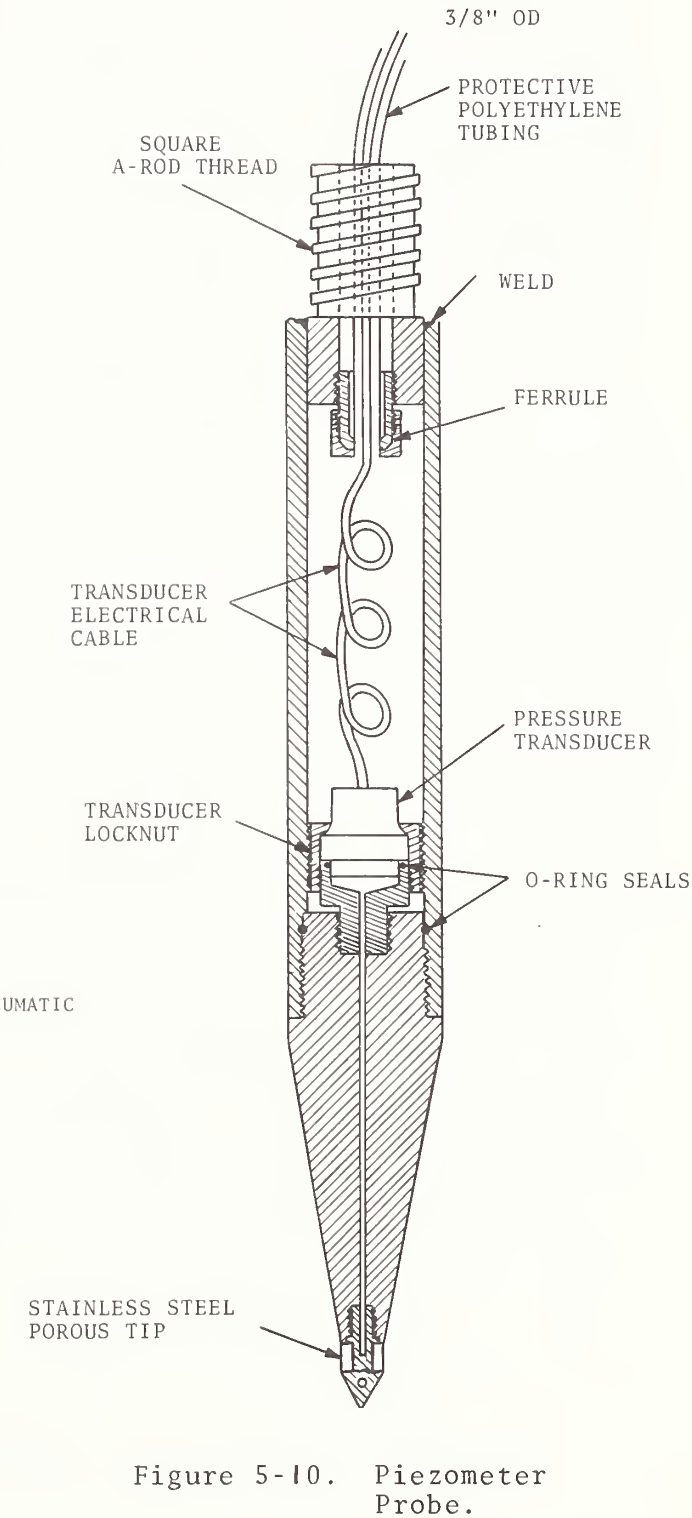


Figure 5-9. Diaphragm Piezometer.

Figure 5-10. Piezometer Probe.

5.2.9 Piezometers (See figures 5-8, 5-9, and 5-10.)

The use of piezometers for the determination of static groundwater levels or excess pore water pressures is described in this section. Use of piezometers for other purposes is discussed in the following section. The state-of-the-art of available hardware is largely satisfactory and proven methods are available. Piezometer types are described and discussed by Dunnicliff (1972) and Schmidt and Dunnicliff (1974). In general, piezometers are categorized either as flow piezometers or diaphragm piezometers.

1. Open-system flow piezometers (figure 5-8) consist of a porous tip connected to a riser tube or standpipe. The porous tip, usually sintered bronze or ceramic stone, is embedded in the ground at the desired location with the riser tube protruding to atmospheric conditions at the ground surface. Water is free to flow through the porous tip and up the riser tube. The level obtained by the water in the riser tube represents the piezometric level at the porous tip.

2. Closed system flow piezometers may be used in situations where the piezometric level is above the ground surface. In these systems the piezometric level is measured by means of a Bourdon gage mounted directly on the riser tube.

3. Another version of the basic flow piezometer is the purge bubble piezometer. With this system two concentric tubes are attached to the porous tip, the inner tube terminating within the tip. When readings are to be taken, air pressure is applied down the inner tube and the air pressure measured as air flow and bubbling occurs. The measured pressure is equal to the water head above the tip. Other dual-tube piezometers are available which allow for saturating the porous tip and de-airing the tubes.

4. Diaphragm piezometers (figure 5-9) differ from flow piezometers in that a diaphragm separates the pore water from the pressure sensing arrangements. When under pressure,

the diaphragm deflects slightly. The deflection may be sensed electrically, using a resistance or vibrating wire strain gage, and the output may be calibrated to pore pressure. Alternatively the pore pressure may be counter-balanced by application of pneumatic or hydraulic pressure to the opposite side of the diaphragm. With any of these sensing systems it is possible to obtain rapid readings of the existing piezometric head since the quantity of fluid flow required to activate the device is very low.

Recommended improvements to piezometer hardware and installation methods are discussed by Schmidt and Dunnicliff (1974).

A recent innovation by Wissa et al (1974) enables a diaphragm piezometer to be used as an indicator of both pore pressure and permeability, and possibly also of consistency and relative density. The probe consists essentially of an electrical pressure transducer contained within a cone shaped housing (figure 5-10). The probe is pushed into the ground at a constant rate. Hydrodynamic response is rapid, and pore pressures generated during pushing can be measured. Changes in the measured pressure can be used to identify qualitatively the consistency or relative density of the soil strata being penetrated. The time rate at which the excess pore pressure generated by the probe dissipates, when pushing of the probe is stopped, can be used to differentiate the boundaries between soils of different permeabilities. The pore water pressure in the soil mass at the tip of the probe is the equilibrium pore pressure recorded by the probe when the excess pore pressure generated by the probe has dissipated. The probe has been used on several projects and is believed to hold great promise for the future. At present permeability, consistency and relative density are indicated qualitatively. An analytical solution for the rate of excess pore pressure dissipation with time would perhaps make it possible to obtain quantitative in-situ permeability measurement. A recommendation for development of an analytical solution, together with a recommendation for combining a piezometer probe with other instruments, in one package, is made in paragraph 5.2.12 below.

5.2.10 Borehole Permeability Test

Borehole permeability tests are performed by pumping water either out of a borehole (drawdown test) or into a borehole (infiltration test). The test may be performed as a constant head test, in which the rate of pumping necessary to maintain a constant piezometric level in the borehole is measured. Alternatively, variable head conditions may be obtained by observing the change in piezometric level in the borehole after pumping is stopped. The permeability of a localized zone of soil surrounding the borehole is computed by application of well established theoretically derived equations, which account for the type of test and imposed boundary conditions (e.g., fully cased or uncased, partially cased borehole). See Hvorslev (1951) for a presentation of these theoretical equations.

The infiltration test is used more often than the drawdown test, in part because many of the commercially available pumps limit the drawdown to a maximum of 15 to 20 feet. The drawdown test is therefore limited to situations in which drawdown of less than 15 to 20 feet is adequate. Constant head tests are preferred to variable head tests because they are easier to perform properly, and generally provide more reliable and consistent data.

Because of a number of limitations the results of borehole permeability tests often indicate a great deal of scatter. They are generally considered to provide only crude estimates of permeability, only slightly more accurate than the admittedly crude estimates based upon grain size correlations. One major problem results from the possibility that the limited zone of tested soil may not be representative of overall soil conditions. The effects of very thin, but important, non-representative layers of soil (e.g. silt layers within a primarily clay soil) may be masked. Other serious problems include leakage either in the pumping system, at connections between sections of casing, or along the outside of casing. If performed at sufficiently high gradients to initiate a quick condition in the test zone, the drawdown test may indicate permeabilities for granular soil that are too high.

The infiltration test is especially susceptible to filter skin effects caused by the accumulation of fines on the areas where the pumped water enters the surrounding soil. The infiltration test may also be influenced by the wetting of non-representative soils located above the static phreatic surface.

Thus, there are a large number of problems associated with borehole permeability tests which generally reduce the accuracy of such tests. The severity of these problems depends to a large degree on the skill and experience of the driller making the boring and performing the test. Since this is difficult to control, it would be desirable to develop hardware and procedures that would minimize the effect of the driller's possible lack of skill.

Some recent innovations aimed at reducing the effects of the problems outlined above have focused on the use of flow piezometers for downhole permeability tests (see Schmid, 1967 or Lang, 1967). Flow piezometers have been used for drawdown and infiltration tests, both constant and variable head. The advantage of using piezometers is positive control over the dimensions of the wetted surface, and hence improved definition of best geometry, permitting more precise and reliable application of the theoretical techniques used to interpret the test results. Other advantages of using piezometers include a reduced dependency on leakage at casing connections and along the casing. However, head loss through any tubing and the porous tip must be known and accounted for. Installation procedures, especially sealing of the piezometer tip within the test zone, must be stringently controlled.

In summary, the use of piezometer tips, either of the flow or diaphragm type, appears highly promising for borehol permeability determinations. At present however, the test procedures and interpretation techniques for borehole permeability tests are in the developmental stages and will require considerably more development before accurate and reliable estimates of permeability can be made. As discussed in the previous section "Piezometers" a recent innovation by Wissa et al (1974) enables indirect measurements of permeability to be made by pushing a diaphragm piezometer probe into the ground. Recommendations for further developments are made in paragraph 5.2.12 and in section 6.

5.2.11 Large Scale Pumping Test

Large scale pumping tests are performed by pumping water into or out of a screened well embedded below the static groundwater level. As pumping proceeds the piezometric water level is observed in surrounding observation wells and recorded. Generally four or more of these observation wells are used for monitoring pumping test results.

Pumping tests are generally categorized as equilibrium (steady state flow) tests or non-equilibrium (transient flow) tests.

Equilibrium pumping tests are characterized by the ultimate realization of constant piezometric levels within each of the observation wells. The time required for this to occur may be very large, especially if the test is performed in fine-grained soils. Data from this type of test may be analyzed using the Thiem Formula (Lang 1967) to determine the overall permeability of the aquifer. Although these tests yield excellent results their usage in urban environments may be severely limited, due to potential problems caused by large scale lowering of the groundwater level.

The non-equilibrium test relates the rate of pumping and rate of drawdown in the observation wells to the overall average permeability of the aquifer. Because it is not necessary to achieve equilibrium conditions, test duration may be greatly reduced and groundwater level lowering may be controlled and halted. Among the theoretical techniques used for interpreting the non-equilibrium tests are those described by Theis (1934), Cooper and Jacob (1946) and Chow (1952).

There is a large number of recommended techniques both for the performance of pumping tests and their interpretation. Among the items that can be varied are the number and placement of observation wells, and the pumping procedure. For example, alternating intervals of pumping with intervals of recharge, combined with a sustained test, may provide important information with respect to permeability. Refer to Universal Oil Products (1972) and Departments of the Army, Navy and Air Force (1971) for more detailed discussion of the many possible variations.

Large scale pumping tests are currently the preferred method of determining in-situ permeability for major construction projects. They yield reliable results, partly because the zone tested is very large and hence local anomalies are masked over. The hardware, procedures, and analytical techniques, although multitudinous and non-standardized, are quite highly developed.

However, there are a number of limitations that should be considered. Full scale pumping tests are very expensive even at shallow depths, and increase in cost as the well depth is increased. Specific test procedures should be selected on the basis of stratigraphy and required information. Hence there are many variations to the procedures. Therefore, considerable engineering analyses must be performed in order to select the best procedure for the particular problem at hand. Finally, considerations especially pertinent to large scale pumping tests in urban areas include the effects of water table lowering on existing structures, and the difficulties in installing observation wells in desired locations. Recommendations for further developments are made in paragraph 5.2.12 and in section 6.

5.2.12 Recommendations for Emphasis and Development

Several of the techniques discussed in paragraph 5.2 merit additional consideration for use in subsurface investigations for tunnels in urban environments. The techniques which are recommended for future study have been selected on the basis of applicability in measuring parameters of importance, as documented in section 4, as well as ease and feasibility of development in a relatively short period of time (approximately three years).

On this basis, the following four techniques have been selected for emphasis:

Static cone penetrometer
Dilatometer
Borehole permeability tests
Large scale pumping tests

In addition, emphasis is given to the development of a combined instrument, consisting of the following components:

Static one penetrometer
Diaphragm piezometer
Moisture sensor

The recommended emphasis for each of these methods is discussed in the following paragraphs:

1. Static cone penetrometer. The method is available and at moderate state of development, but has not been used to a significant extent in the United States. Before funding further development, it is recommended that use of the method be encouraged and increased on this continent. A summary of existing techniques is given by Sanglerat (1972). However, little guidance is given in recommending specific hardware and analytical techniques for each specific application. There is a need for a short evaluated summary to serve as a source of information and as a user's guide. In that way, it is believed use and acceptance of static cone penetrometer methods will be enhanced. No effort has been made to pursue the topic under this Contract.

2. Dilatometer. As with the static cone penetrometer, the method is available and at a moderate state of development. Summaries of existing techniques are given by Hall and Hoskins (1972) and Cording et al (1974). A major development concerning installation procedures has recently been made by Wroth and Hughes, (1973). This development is currently under study at the Massachusetts

Institute of Technology (M.I.T.) and initial findings indicate that the improvements have greatly reduced installation problems. M.I.T. has received no funding for the study, and little emphasis is being placed on its pursuit.

Although limitations exist in the surface peripheral equipment, it is believed the new device has substantial future potential, and that its use should be encouraged in order to build up a bank of information and confidence in the data. The instrument is being manufactured by Wykeham Farrance Engineering Ltd. of Slough, England, is available in the U.S.A. through their agents, Troxler Electronic Laboratories, Inc. of Raleigh, North Carolina, but has not been used to a significant degree in practice.

It is recommended that use of dilatometers in their present form be encouraged on federally funded urban soft ground tunnel projects before further hardware developments are initiated.

3. Borehole permeability tests. The determination of in-situ permeability is an area sorely lacking in proper instrumentation and interpretation. Excluding the full scale pumping test, which is extremely expensive, none of the currently available methods can be relied upon to yield consistently accurate results. Since permeability is of major importance for tunneling, a concentrated effort should be undertaken to improve this situation. Two hardware improvements which show promise in improving the current state-of-the-art are briefly discussed in the following paragraphs.

   One such device is a borehole permeability probe, utilizing a flow piezometer tip for controlling the "wetted" area, and a packer system for isolating the zone to be tested. Packer systems have been fabricated (Hatcher, 1973) and have met with some success, but have not been well suited for use by most drillers. Any device which is to have a chance of surviving on the market must be readily compatible with existing methods of test boring. Hardware modifications to accomplish this should commence as soon as possible.

The other recommended improvement is the development of a perforated casing which would couple directly with conventional casing. The casing would permit isolation, in-situ, of a large zone of material for testing, yet maintain simple boundary conditions. Thus the test would be amenable to theoretical interpretation. It is felt that this casing will substantially improve reliability and accuracy of borehole permeability tests. Permeability tests could be performed at a number of locations in a single borehole as the permeable casing section is driven to a greater depth after each test.

Detailed recommendations for development of a borehole permeability probe and a perforated casing test are made in section 6, and specifications for hardware development are presented in appendix D1.

4. Large scale pumping tests. Currently the full scale pumping test is considered the most reliable method for measuring the overall permeability of a soil stratum. A great deal of information concerning full scale pumping tests is available in the literature but no standardized procedures are available. In addition, full scale pumping tests have been developed for purposes of assessing the water supply potential of an aquifer. The factors affecting water supply, although similar, are not necessarily the same as the factors affecting the design and implementation of a dewatering system for tunnel construction. Thus it would be desirable to modify the methods of performing full scale pumping tests, to better suit the problems of tunnel design and construction, and to standardize hardware and procedures.

   A logical extension of a modified full scale pumping test would be a full scale field test of the anticipated dewatering system. The consensus among many dewatering contractors is that more information is obtained in the first few days of actual construction than can be learned by extensive research of borings and permeability test results. The cost of a limited number of ejector wells, well points and/or deep wells installed in conjunction with observation wells in critical areas of the tunnel route could be more than offset by a lower dewatering bid price and fewer construction problems and delays. Therefore it is recommended that consideration be given to full scale field testing of dewatering systems, to be paid for by the owner and analyzed by the design engineers.

Detailed recommendations for development of a modified full scale pumping test and a full scale field test of the anticipated dewatering system are made in section 6. Specifications for development and testing are presented in appendix D2.

5. Combined static cone penetrometer, diaphragm piezometer and moisture sensor. The static cone penetrometer has been described in paragraph 5.2.4, and a case has been made for encouragement of use prior to funding further development. Diaphragm piezometers have been described in paragraph 5.2.9, and it is recommended that funding be made available for development of analytical solutions for use in determination of permeability using a piezometer probe. It is believed that these two devices, the static cone penetrometer and the piezometer probe would, if combined in one instrument, facilitate economical and rapid measurement of shear strength, pore pressure, permeability, consistency and relative density.

   Selig et al (1973) have developed an electronic in-situ moisture sensor based on the relationship between the amount of water in a soil and the dielectric constant. When fully developed the device will be operational in any soil type, and will be rugged, durable and accurate. However, there is still a considerable need for research and usage aimed at a full evaluation of the device, and the developers have received additional funding from the National Cooperative Highway Research Program for this purpose. This effort is being pursued during an 18 to 24 month period which began on July 1, 1974. Emphasis will be on field evaluation, design improvements of sensor and electronics, evaluation of dependence on chemical composition of soil, and installation effects on accuracy. A moisture sensor of this type could be included with a combined static cone penetrometer and piezometer probe package, to provide measurement of a further significant parameter.

Development of such a combined instrument appears attractive and is recommended. However, it is believed funding to achieve the combined package should not be made at this time, but rather should be withheld until the three separate components have been further advanced. No further effort has therefore been made to pursue the topic under this Contract.

5.3 INDIRECT METHODS

5.3.1 General

Indirect methods of exploring the character of the subsurface have been developed and used mainly by the petroleum and mining industries as tools for natural resource surveying. Their use in these industries has many parallels to the needs of the engineering community, and some methods may have unique applications to the soft ground tunneling environment. A systematic review of available indirect methods is necessary to assess the full potential of these techniques for providing subsurface information that can improve the safety and efficiency of tunneling in soft ground. General references for these techniques include Heiland (1946), Dobrin (1960), Grant and West (1965), and Griffiths and King (1965).

Indirect methods, or geophysical methods as they are commonly known, have followed the general technological explosions of the past 20 years in finding new applications and refining the meaning of the data derived from using the methods as exploratory tools. In spite of this, they are not widely used by civil engineers, primarily because civil engineers are generally unaware of the existence or the potential of most of these methods. Evaluations and recommendations are given in this section to demonstrate the applicability of geophysical techniques to specific geotechnical parameters, and to identify the most useful tools and those that have only minor and secondary utility.

A single geophysical method rarely provides enough information about subsurface conditions to be used alone. Each method typically responds to several different physical characteristics of earth materials, and cross-correlation among methods has been found to provide the most meaningful results. Certain methods may be useful in specific ground conditions and offer no information whatsoever in others. Qualified personnel are ordinarily required to select the appropriate methods for a particular exploratory situation.

The following paragraphs describe the various geophysical techniques, their physical basis of operation, their advantages and disadvantages. But first a few general observations must be made.

1. Geophysical surveys utilize both active and passive measurement techniques. In an active mode, some form of energy is introduced into the subsurface and the effect on the energy or the response of subsurface materials to energization is measured. Active measurement techniques usually provide the greatest accuracy. Passive measurements simply record the strengths of various fields or changes in field strength which are always present. Analytical assumptions are necessary for interpretation that introduce ambiguity in the results.

2. Precision of measurements is high in all methods, but accuracy in the interpretation and inferences drawn from the measurements depends very much on the experience of the interpreter. All methods are inherently subject

to lower accuracy due to interpretation as distance increases between the energy or field source of interest and the detecting sensors, especially in those methods based on field strength measurements (passive mode).

3. Resolution capability of subsurface characteristics varies widely among geophysical methods when surveys are conducted conventionally. The parameter to be measured or inferred must be understood before a resolution dimension can be defined. Almost total resolution of any soil or strata parameter is possible if the survey is appropriately designed and time/cost requirements are not considered. One reasonable approximation is selection of measurement point separation on the order of the dimension of objects or strata changes to be resolved.

4. Very few geophysical methods measure parameters directly used by the engineer (seismic and electrical methods may be exceptions), and all methods present the "averaged" effects of materials between and around sources and points of observation. Most results are based on interpretations that infer what kind of subsurface conditions would cause the measured parameter to have a certain value or to change in a certain way.

Geophysical methods for subsurface explorations are discussed in the following sections, beginning with those conducted on or very near the ground surface and followed by those conducted in or from boreholes. Surface methods have analogues in the borehole techniques (and vice-versa), but the scale and effectiveness of each depends strongly upon where and why the survey is conducted. Comments regarding the basis of the method and utility for soft ground exploration are given for each. A tabulation and abstract of the discussions is presented in appendix C.

5.3.2 Indirect Methods Employed from the Ground Surface

1. Seismic methods. The basis of all seismic exploration techniques is an interpretation of the time required for particular types of elastic waves to travel known distances through the subsurface. In certain instances, the change in amplitude of the motion with distance, or a comparison of two different elastic waves traversing essentially the same path may be analyzed (see Whitman, 1966). A wide variety of methods are available to introduce elastic energy into the ground, record what happens to that energy, and interpret the recordings to infer subsurface conditions.

   Typical earth materials encountered in soft ground tunneling are more or less horizontally stratified deposits of material with different elastic properties. The properties of interest to seismic methods are density, compressibility or bulk modulus, and rigidity or shear modulus of the materials, and contrasts of these between soil strata. Engineering parameters may be derived from these three, and the three properties also determine seismic wave velocities in the subsurface. The attitude of the soil strata, lateral changes in soil characteristics, structural conditions (such as faults) or other discontinuities (buried channels, solution cavities) are inferred from the seismic data.

   Limitations and requirements of seismic techniques for use in the soft-ground tunneling environment are given following discussion of the methods.

2. Seismic refraction surveys. Refraction surveys are conducted by introducing energy into the ground at one point near the ground surface and observing what happens to the energy as it travels to a series of detectors placed on the ground at increasing distance from the point of energy introduction. Energy introduced near the surface travels away from the start point as seismic waves, and

these are refracted and reflected at subsurface boundaries between different materials. Interpretation of the travel time patterns of waves refracted along the boundaries forms the basis for refraction surveying.

Explosives are commonly used as a source of energy, and detection of the resulting ground motions (seismic waves) is accomplished by recording the amplified electric outputs of small coil-magnet generators (geophones), which respond to relative motion between the soil and the magnet. The pattern of seismic wave travel times for known distances to the geophones depends upon subsurface layer thicknesses and layer velocities. The time-distance pattern obtained from a survey is interpreted to derive those two factors.

3. Seismic reflection survey. Essentially the same equipment used in refraction is also used for reflection surveys. The seismic waves of interest in this case are those reflected from subsurface boundaries rather than refracted along them. Interpretation of reflection data is based upon the length of time required for a seismic wave to travel from the start point to the reflecting boundaries and return to the surface geophones.

   Reflection surveys are most useful for rapidly mapping the lateral changes of multiple subsurface boundaries once the boundaries are known at one place from other observations, or if the layer velocities are known so that depths may be calculated.

4. "Vibroseis". The Vibroseis technique of seismic surveying (Geyer, 1969) is a sophistication of the basic refraction/reflection methods, with important differences in the type of energy input and analytical treatment of the data recorded. The technique has been used for tunneling explorations (Mossman and Heim, 1972, Mossman et al, 1972, 1973), but not specifically in soft ground. In Vibroseis surveying, the energy put into the ground is a preformed signal that is changing in frequency with time. The

resulting seismic wave has similar characteristics when refracted or reflected, and computerized correlation of the input signal with the recorded signal (after certain adjustments) is used to indicate the signal arrival from subsurface layer boundaries.

The non-destructive nature of the Vibroseis signal generator (a hydraulically-driven vibrating pad pressed against the ground surface) and the low level of signal detectable in a noisy environment are very positive aspects of the technique for soft-ground tunneling explorations. Resolution and accuracy of the interpretations requires improvement for use in shallow soft-ground tunneling explorations.

5. Seismic holography. Seismic holography, which is more akin to continuous profiling methods used in ocean bottom surveys than to laser holographics at its current status of development, is primarily a multiple application of standard reflection seismology with improved signal processing and correlation techniques. Recent developments have strong potential contributions to subsurface explorations for geotechnical parameters (Dunkin and Levine, 1971; Fitzpatrick et al, 1972; Steinberg, 1972; Soland et al, 1972). A dense array of surface geophones and energy input positions is required (explosions have been tried, and a Vibroseis signal generator is currently being evaluated). The resulting signal recordings are filtered, cross-correlated, and otherwise processed among detector and source positions to determine the three-dimensional location of reflecting discontinuities in the subsurface.

6. Seismic limitations and requirements. Seismic techniques have certain limitations when evaluated in terms of exploratory surveys in soft-ground and in urban areas. Certain ground conditions prevent accuracy for some techniques, and the physics of subsurface elastic wave propagation have a basic effect upon all methods. Theoretical considerations are given by Ewing et al, (1957), Cagnaird (1962), White (1965), and many others.

In seismic refraction, the presence of a low velocity layer beneath higher velocity materials has the effect of causing the seismic waves to refract energy downward with the net result that the layer is not represented in the typical data interpretation. Very significant errors in calculation of the depth of deeper layers may result, and the character of the layer itself is not determined. A common soft-ground example of this condition would be a layer of loose river gravels beneath dense clay strata, or a layer of organic silt beneath sands and gravels.

Survey of shallow reflection horizons in the subsurface by reflection techniques is complicated by direct and refracted waves reaching the geophones before the reflections: the early high amplitudes commonly mask shallow reflection signal arrivals, severely limiting the "shallowness" of effective surveying.

All of the seismic techniques depend upon ability to detect and accurately time seismic wave arrivals at the detectors. Effects on signal detectability by natural and man-made earth noise, geometrical energy spreading, wave reflection coefficients, mode conversions, and energy dissipation must be considered. Current theory is adequate for most survey needs but a specific program of development and evaluation is needed. As a practical matter, high energy sources with high frequency content are needed to produce useful signals for soft ground explorations. The sources must be acceptable environmentally.

Resolution of subsurface discontinuities by seismic methods requires sufficient energy to overcome any factors which reduce signal amplitudes. Similarly, enough detectors or source positions are required so that signals representing discontinuities are recorded. Overlap and redundancy of signal recordings is usually required for confidence in results. High signal frequencies are required to produce short wave lengths so that adequate refraction or reflection of the energy from small discontinuities occurs. High energy is required to achieve depth penetration. As a rule of thumb a discontinuity must have physical dimensions on the order of one-quarter of a seismic wave length to refract or reflect "significant" energy. The full effect possible occurs where the discontinuity is dimensioned as large as one wave length. Figure 5-11 shows some typical frequency wave length effects in soft ground materials. Figure 5-12 demonstrates geometrical spreading and energy dissipation effects on signal amplitudes for typical materials.

Signal processing techniques are often applied to recorded seismic data both to reduce the effects of the ambient noise field and to enhance particular wave types. Band-pass filtering (to record only waves in a selected frequency band), time delay and summation of multiple signals, straight summations of repeated signals, signal spectral analyses, and many others which operate on multiple detector arrays are common. A summary and brief explanation of most techniques is given by Soland et al (1972).

General characteristics of the seismic system most useful to soft ground explorations should include the following:

a. High energy, high frequency (1000 cps or greater) source and recording capability for resolution of subsurface conditions.

b. Magnetic tape recording of signals and on-site computerized signal processing for versatility and maximum potential use from each survey.

These two items, particularly the first, are the keys to optimum application of surface seismic surveys for deriving soft ground geotechnical parameters in the urban environment.

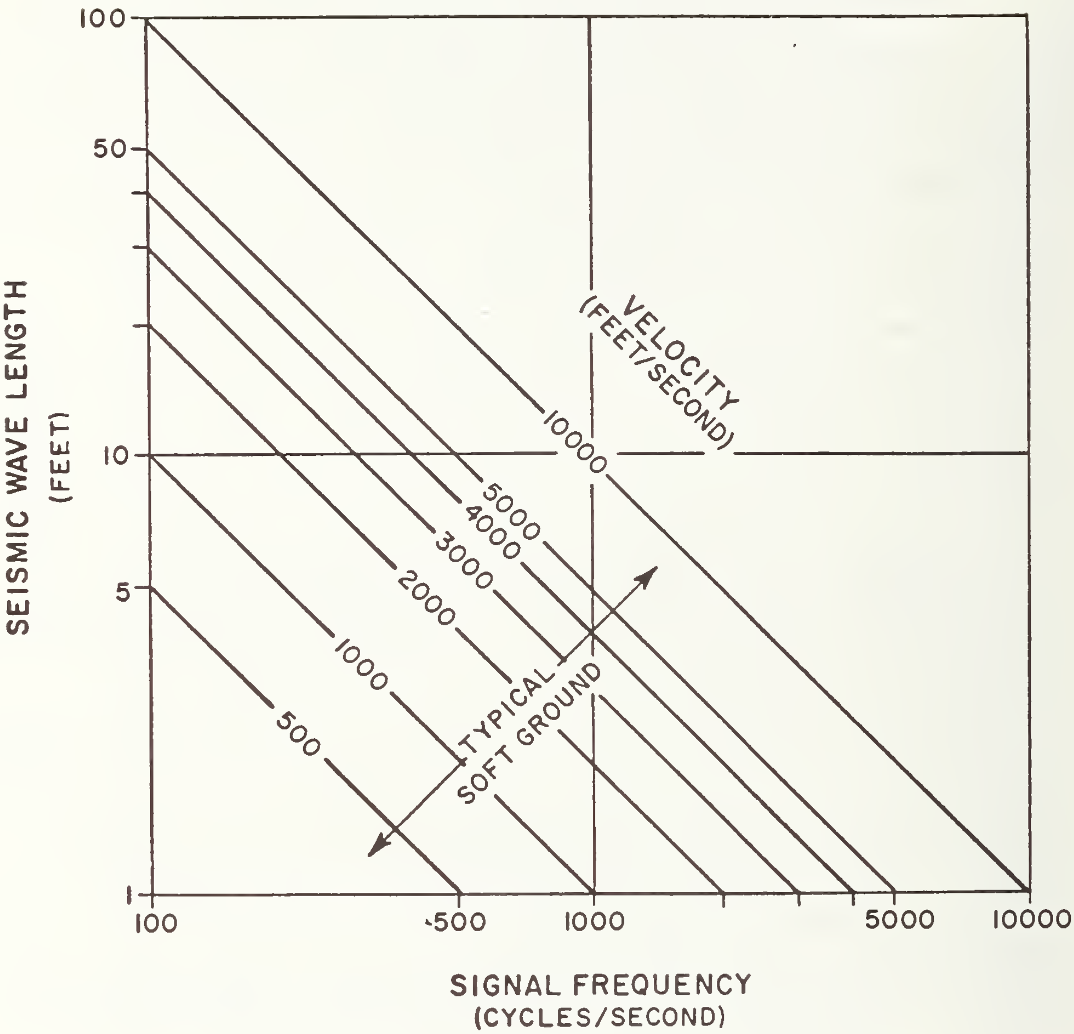


Figure 5-11. Typical Frequency/Wavelength Effects in Soft Ground.

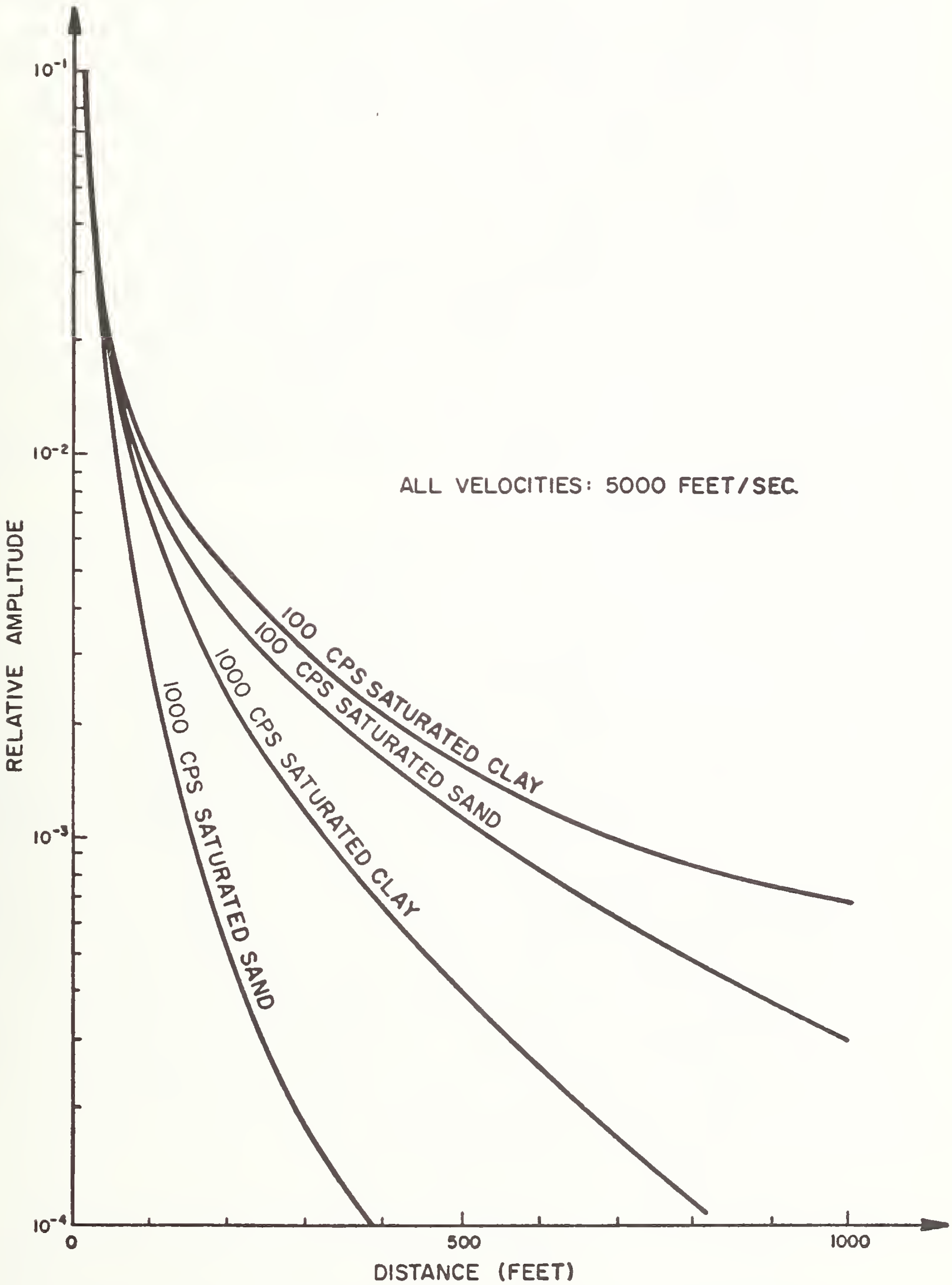


Figure 5-12. Energy Dissipation of Seismic Waves with Distance.

7. Seismic/sonic. One unique approach to seismic methods for subsurface explorations involves a combination of a seismic wave path and a sonic energy source (Cook and Wormser, 1973). For this method, acoustic energy is directed toward the ground by an ordinary loudspeaker. The acoustic energy striking the ground surface generates elastic waves that propagate along the surface (Rayleigh waves). The speed of propagation depends upon subsurface seismic velocities, and when differences in velocity are encountered, the shape of the wave also changes. The seismic waves are detected by geophones on the surface. Basic theories involved are given by Rayleigh (1885), Press and Ewing (1951), Press and Jardetsky (1952), and Horton (1953).

   The method is used primarily to detect lateral rather than vertical changes, and relatively large areas may be surveyed rapidly by simply traversing the loudspeaker system across the surface and correlating wave shapes with the particular loudspeaker-geophone path to identify anomalies. Penetration depth is limited (on the order of 10 feet) at its present state of development, and ambiguity in interpretation from depth changes rather than lateral changes may result from inexperienced analytical use of the data.

8. Geoelectric methods. There are three primary subsurface exploration techniques that utilize electric or electromagnetic concepts as a basis for investigation. Variations from each basic approach have been developed to accommodate the methods to the different terrains or subsurface conditions. All are directly influenced by the gross electrical resistance and electrical capacitance of materials in the subsurface.

   Particular types of deposits (soil, lithified sediments, bedrock, etc.) tend to have characteristic electrical properties in localized areas, which can often be mapped by geoelectric methods. The presence and electrical characteristics of subsurface water are also inferred by the direct electrical techniques. Profiles of the thicknesses of subsurface units with contrasting electrical properties, depths to ground water tables interfaces between fresh and saline waters, and lateral changes in elevation of the different subsurface units are typical results of such surveys.

There are numerous technical papers on the subject of geoelectric method applications. A basic reference for geoelectric methods is provided by Keller and Frischkneet (1966). Penetration depths and accuracies are discussed by Roy and Appora (1971), and Mallick and Roy (1968).

9. Electrical resistivity surveys. Resistivity surveys are conducted by inserting electrodes into the ground a foot or so, applying electrical power to the electrodes, and measuring the potential in the ground at positions away from the powered electrode positions. A number of different arrangements of electrodes and power levels are used, with electrode arrangement selection and power level based upon the degree of detail required and ground characteristics in the area surveyed. Either direct current or alternating current may be applied to the electrodes; analytical techniques are available for either kind of current application.

   Analysis of the measurements taken is based upon the assumption that the voltage at the measurement points is influenced by deeper materials as distance from the powered electrodes increases. A trend of drop-off in electrical power with distance from the powered electrodes results from resistance to current flow in the subsurface materials: changes in the trend with increasing distance infer the depth where the change occurs, and the amount of changes in the trend indicates the change in resistance characteristic.

Resistivity methods are essentially non-destructive, but are subject to a wide variety of interferences. Among the sources of interference are the variable electrical coupling of the contact between electrodes and the soil as positions are changed, variable near-surface soil moisture, stray current fields from electrical utility grounding, variable static electric charge fields, thunderstorms, etc. Gradational changes in electric properties in subsurface units are also common: laterial changes in calculated resistance are often interpreted as changes in depth, and unless other techniques are also used, large errors of interpretation can result.

Typical engineering applications of resistivity surveys are given by Foster (1951), Flathe (1958), Norris and Spicer (1958), McGinnis and Kempton (1961), Griffiths and King (1965). Basic interpretation techniques are given by Mooney and Wetzel (1956), Van Nostrand and Cook (1966), and Kunetz (1966).

10. Electromagnetic surveys (non-specialized). Typical electromagnetic surveys are based upon the principles of electrical currents induced in a conductor by a changing magnetic field. The conductor in this case is the subsurface; the inducing field may be generated by an alternating electrical current in a portable coil (Amos, 1970), long wires stretched out on the ground surface, (Moffattant Peters, 1972), or even very low frequency radio broadcast stations, (Wait, 1962), Schlak and Wait (1967), Bahar (1970, 1971, 1972, 1973). Metal detectors are typical small versions of this geophysical technique.

The electromagnetic field radiating from the source induces currents in subsurface materials which, in turn, generate secondary fields that have the effect of modifying the power and phase of the inducing field. That difference is measured and interpreted in terms of the amount (thickness, depth) of conducting earth materials in the subsurface, and the relative conductivity of different materials.

The main features of interest to urban environment explorations using electromagnetic techniques lies in the ease and efficiency of conducting a survey without environmental disturbance. The presence of stray fields from other sources, however, is a significant interference, and resolution problems are very similar to those of the seismic and resistivity techniques. Seismic is commonly more accurate and resistivity less accurate than electromagnetic results. Relatively high power and high frequencies are required to resolve thin layers or small objects. Lower frequencies have greater penetration depth. If a strong contrast in electrical properties is present, a lower inducing power may be satisfactory in producing a detectable anomalous field.

11. Electromagnetic pulse sounding. A technique of directing sharp pulses of electromagnetic energy directly into the ground and observing pulses returned to the surface as "vertical reflections" from subsurface materials with contrasting electrical properties has been developed for subsurface explorations (Geophysical Survey Systems, 1972a; 1972b, Morey and Harrington, 1972). The method provides essentially a continuous profile of the subsurface reflections, which represent contrasts at soil interfaces, bedrock boundaries, pipes, stones, cavities, etc.

    Electromagnetic pulses are broadcast from either a small parabolic antennae or along long lines (Moffatt and Peters, 1972; Bahar, 1973) which also serve as receiving antennae. The resulting data from each pulse emitted (or from a systematic sampling of pulse) may be recorded visually on a cathode ray tube or chart recorder and on magnetic tape. The tape can also be processed further by computer techniques. The ability to computer process the recorded data directly enhances the versatility of the method since sophisticated signal processing techniques can be applied Resolution of subsurface objects and discontinuities can be controlled to some extent after the survey is made in the field.

The pulse technique is limited when subsurface materials become strongly conductive to electrical currents. When the medium is conductive, electromagnetic energy is rapidly dissipated and return signals to the surface are very weak. Wet clays, saline water (but not fresh water), and some organic materials represent common soft ground materials that may interfere. In general, the depth of useful penetration for the continuous profiling at present is on the order of 50 feet under favorable conditions: larger antennae with greater pulse power may improve the method for soft ground use where highly conductive materials are absent.

12. Magnetic surveys. Techniques for determining the presence and location of magnetic materials in the subsurface are highly developed, and are useful in terrains where the deposits contain even minute amounts of magnetic particles (primarily magnetite in sediments, maybe pipes, conduits, or cables in urban areas). If no magnetic materials are present, however, the technique has no use in subsurface explorations.

The basic principle of magnetic surveys involves the measurement of variations of the earth's magnetic field, caused by magnetification of susceptible materials. The variations may be very small, but they can be resolved by today's measuring techniques. Interpretation of the measurements is based on potential theory, and the results are highly ambiguous unless local calibration by factual subsurface observations is available.

State-of-the-art instrumentation may be of interest, however, since the basis of at least one method may be particularly useful for other allocation (see Pickett and Lemcoe, 1959). Certain mobile ions, hydrogen in particular, have spin axes that tend to align either parallel or normal to a magnetic field. If another field is applied, the ions will precess about their axis to align with the resulting field. When the applied field is released they will precess back, generating an electromagnetic field proportional in strength to the number of ions precessing and in return time to the strength of the applied field. If the strength of the inducing field is known, the earth's field can be calculated. If the ion generated field is known, the proportion of mobile ions (inferring mobile water) can be estimated. Mobility of water in the strata is proportional to strata permeability.

13. Gravimetric method. The general gravity field of the earth is modified by the presence of near surface materials of differing densities and differing depths from the surface. Very minor changes in the elevation of known materials or the presence of materials different from the typical stratigraphy in a local area may be indicated by changes in the observed gravity field. Parasnis (1962) discusses the basic gravity techniques: a typical engineering survey for bedrock mapping is described by Sumner and Burnett (1974). Point-by-point gridwork measurement positions on the ground surface is the most common survey approach: continuous profiling, vehicle carried system is under development.

    Strength of the gravity field depends upon the density and volume of the material causing the field, and distance of the material from the point of observation. If either can be determined directly, the other can be calculated. The primary difficulty in interpretation of surveys pertinent to soft ground tunneling is that all material (including buildings, automobiles, subsurface facilities, etc.) contribute to changes in the gravity field since they have mass, and separation into components of mass and distance which might provide suitable accuracy is difficult.

14. Thermometric methods. Thermal radiation from the ground surface depends upon the temperature of the ground and thermal characteristics of the ground materials (See Cook, 1962, Cook and Wormser, 1973, Van Orstrand, 1934). The

presence of buried objects or the ground disturbance resulting from burial may cause the radiative field to differ over the object compared to the normal radiation levels because of the differing thermal characteristics. In order for the object to influence radiation leaving the ground surface, sufficient heat must be applied for a long enough period of time to change the temperature of the object. A lag between application of heat at the surface and an increase in subsurface temperatures is one of the limitations of the method.

This method is not considered especially favorable for future use in soft ground tunneling surveys because of the very shallow depth of effective investigations, and because of the wide range of potential sources of interference. Soil color, vegetation, soil density, moisture, microtopography, and many other factors may cause flux anomalies larger than those required for effective surveying, even at very shallow depths.

15. Nuclear methods. Two methods utilizing radiometric earth material characteristics are available for engineering surveys. None of the methods have effective penetration depth to be useful in an exploratory sense when used from the ground surface. The principles do have application in the subsurface, and these will be discussed later. Numerous reports of the surface techniques are available, standard techniques and interpretations are given in ASTM STP 293 (1960) and STP 412 (1968).

16. Passive radioactivity surveys. Natural radioactivity is most commonly related to emissions from naturally occurring uranium, thorium and potassium (isotope 40) contained in both hard and soft ground materials. These elements have some preferential placement in terms of geologic structure and soil types, but the geologic distribution is not considered unique enough to be of significance to soft ground tunneling explorations from the ground surface.

17. Active radioactivity surveys. A variety of radioactive tools for measuring the effect/response of soils to radioactive emissions are used to measure soil moisture and soil density at very shallow depths (1 foot or less). Measurement of soil moisture is based upon the principle that hydrogen has a large "nuclear cross section": and so is a primary interference with the transmission of neutrons through the soil. A neutron flux is applied at the surface by exposing the soil to an appropriate radioactive source, and the amount of neutron flux remaining after a predetermined time is a measure of the relative hydrogen (and moisture) content. Essentially the same approach is used for density determinations, but a gamma-ray flux is applied, and the relative electron density (which is proportional to the total density) in the soil is inferred from the resulting gamma radiation.

    Neither of these approaches has penetration capability from the surface adequate for exploratory work except for special cases where reconnaissance is needed. The fundamental limitations are such that developments are not likely to be productive in view of depth requirements for investigations related to soft ground tunnels.

5.3.3 Indirect Methods Employed in Boreholes

All geophysical surveys conducted at the surface have analogs in surveys conducted in boreholes. The surveys ordinarily provide continuous vertical profiles of information from the subsurface materials penetrated, with varying degrees of information from beyond the borehole wall. Typical survey procedures involve lowering an instrument package into the borehole, which both energizes the materials in and around the borehole and senses the response to the applied energy. Control of the package output and recorders for the various reactions are operated on the ground surface. Guyod (1969) discusses borehole techniques for soils engineering and Pokhanov (1962) describes basic theory and applications: over 40 companies in the free world offer borehole logging as a service.

1. Sonic/acoustic methods. The 3-D Velocity Logging method is a full acoustic wave logging method. The log displays photographically the amplitude of elastic waves as a function of time and of the depth of the logging tool in a fluid-filled borehole. Elastic waves are generated by a piezoelectric transducer and detected by a receiving transducer at a fixed distance from the source. The output of the receiver is displayed by transmitting the image of a scope beam through a fibre optics system onto photographic film. Computer analysis of the data may be employed to determine elastic properties of the materials surrounding the borehole.

   A full complement of elastic waves, including compressional, shear and boundary waves, is recorded in intensity modulated form on magnetic tape to be analyzed by a computer program. The primary input into the computer program is digitized from three borehole logs; namely, the 3-D velocity log, Gamma-Gamma Density log, and Caliper log. The program determines corrections that are applied to the raw data and computes the corrected compressional and shear velocities, Poisson's Ratio, Young's, shear and bulk moduli and porosity of the rocks. The Young's modulus derived from the 3-D velocity log has been related to the pore and rock pressure. For the unconsolidated low velocity medium (lower than 10,000 ft/sec.) it is difficult to measure the shear velocities due to the fluid signals. An attempt has been made to measure the compressional and shear velocities by the hole-to-hole techniques with some success.

2. Seismic methods. Engineering use of seismic methods in boreholes has two particular uses: to obtain a measurement of velocity changes with depth for calibrating other seismic surveys, and to obtain the compressional and shear wave velocities to be used in calculation of elastic parameters. The survey differs from the acoustic wave method above in that small explosive charges are usually exploded in the borehole and the resulting seismic waves

are sensed by geophones either on the surface or in nearby boreholes (uphole and cross-hole surveys, respectively). Standard geophysical texts describe the techniques thoroughly, some reports of particular engineering interest include Carlson, et al (1968) for uphole surveys and Cherry and Waters (1968) for shear wave studies.

Compressional waves (p-waves) are relatively easy to identify in both surface and borehole seismic surveys. Identification of the shear wave is more difficult because of interference by refractions, reflections, and mode conversions of the p-wave which arrive at and before the s-wave arrival. Efforts in development of in-borehole generators which produce high energy s-waves with little p-wave generation are, and have been, of major interest to engineering use of this technique. Analytical techniques which might insure that the s-wave is clearly identified have also been investigated without full success. Vibratory sources similar to the Vibroseis technique described in paragraph 5.3.2 have also been examined for sweep frequencies of 10-70 hertz for borehole surveys (Cherry and Waters).

3. Normal resistivity. Normal resistivity surveys, usually performed by lowering two or more electrodes into the borehole, are the most commonly performed borehole electrical surveys. Voltage is applied to one of the borehole electrodes (grounded at the surface) and the resulting voltage at various distances from the powered electrode is measured. Electrical fields in the borehole vary according to the sidewall resistivities, and the net change is measured at short and long electrode spacing. The short electrode is intended to measure the part of the sidewall, while the longer spaced electrode measures the effects of the same factors plus the additional influence of materials unaffected by the borehole.

Theoretical penetration beyond the borehole for the conventional electrical surveys is on the order of one-quarter to one-half of the spacing between the powered and sensing electrodes. Depth of penetration of the electrical field into the sidewall is also strongly influenced by the actual resistivity (and implied permeability) of the materials: least resistant beds are penetrated most as a rule, but high resistance in adjacent beds may limit effective penetration in a low resistance bed. Resistance contrasts also have strong effects upon the resolution of bed contacts, with the greatest contrasts providing the sharpest contact resolution. Thickness of bedding influences the ability to resolve individual beds, with "thickness" defined in terms of the electrode spacing (thickness = 10 x spacing).

Beds of resistivity contrast of 4:1 or 5:1 may be resolved if thicknesses are on the order of one-tenth of the electrode spacing, but analytical experience and training are needed to provide such detail. Resolution of beds with such contrasts at one-half electrode spacing is much more common. Accuracy of location of such contrasts in the borehole using conventional electrical methods is subject to the usual cable length considerations, with the additional consideration for contrasts and bed thickness. Estimated accuracies in actual depth are ±2 feet and ±1 foot for relative depth. Tables of correction for borehole diameter, mud resistivity, invaded zone resistivity, and bedding thicknesses are available to allow estimates of formation and formation fluid resistivities.

Short electrode spacings are most sensitive to porosity (resistivity) changes in highly porous materials (up to 45% porosity, void ratio 0.8), long spacings are most sensitive to porosity (resistivity) changes at low porosities (0-10% porosity, void ratio 0 to 0.11), and the very long spacing is most useful for the location of thin, high resistance beds in thick low resistance beds in thick low resistance formations (Lynch, 1962). Formation bulk density estimates on the basis of resistivity measurements and related logging are typically accurate to within about 10% of the true value on the basis of petroleum logging experience.

4. Dipmeter/caliper. The borehole dipmeter is conventionally an extension of a borehole caliper tool which uses the extended caliper arms as support for microlog electrodes. Doll (1943) described a spontaneous potential model, de Chambrier (1953) the use of micrologs for dipmeter applications, and Moran, et al (1962) the application of digital computing techniques for dipmeter surveys.

   Use of the log for subsurface explorations lies in the physical characteristics of the borehole itself from which may be inferred standup times (from caving in of the borehole), permeable zones (from the electric logs), and identification of strata attitudes for correlation and structural considerations. A minimum of three arms is commonly used, and the number may range to over twenty (not all with electrodes). Microlog electrodes are mounted on the caliper arms in a small pad which is pressed firmly against the borehole wall and standard micrologs are taken as the tool moves up the borehole. An oriented magnetic survey accompanies the dipmeter. Microfocussed induction logs (see below) may also be used rather than resistivity techniques.

   Strata attitudes are calculated from a correlation of the individual microlog outputs according to the difference in elevation of similar resistivity or conductivity readings at contrasts in the borehole wall and the diameter of borehole from caliper readings. Accuracy of the relative location of resistance contrasts in the strata are reported to be 0.2 inches at 60 foot/minute logging rates (Allaud and Ringot, 1969); no statements of dip accuracy were found in the literature search. Direction of dip is taken from the accompanying magnetic compass output. Resistivity of the borehole fluids and a spontaneous potential log may be measured while lowering the tool in the borehole for the dipmeter survey (conducted uphole ordinarily).

5. Electromagnetic logging. The principles of measuring electrical fields resulting from induced currents in the subsurface are common to both surface and borehole techniques. Operations in a borehole allow some modifications in equipment to provide a great deal more detail. The need for and limitations of electrical resistivity logs are essentially eliminated by some induction techniques, unique data may be obtained if recommended developments are successful. Most descriptions of the techniques are confined to petroleum explorations, but Doll (1949) Moran and Kunz (1962) provide a clear description of the basis for induction logging. Borehole service company brochures also describe the best uses of the induction technique.

6. Focussed induction logging. The surface technique of traversing a survey area with a field inducing coil and separate field detecting coil is modified into a compact instrument for borehole use. Best results are usually obtained in moderate to high void ratio materials. An arrangement of electrodes (which serve as the field incuding coil) is used to focus the inducing fields into an intense narrow disc of magnetic field that penetrates the borehole wall and induces electrical current in the surrounding materials. The width of the disc is on the order of a few inches, which allows the data to be interpreted at least to that order of accuracy for locating changes in the electrical characteristics and inferring the location of the changes. The strength of the resulting field is measured at a pair of electrodes in the borehole instrument, but separated from the others.

The importance of Focussed Induction Logging for soft ground explorations lies in the accuracy of location of subsurface changes (1 foot), depth of penetration beyond the borehole wall (1-20 feet) and capability to operate in wet, dry or mixed wet/dry boreholes. Results are commonly presented in terms of material bulk conductivities (the reciprocal of resistivity). Conductivities are used to infer the presence of conductive fluids (mineralized ground water), relative volumes of interconnected pore spaces in saturated materials, grain size and amounts of clay, and changes of these characteristics in the strata penetrated by the borehole.

7. Electromagnetic nuclear response. Application of an electromagnetic field to the strata around a borehole not only induces electrical currents, but it also has an effect upon unbound ions in the strata. These free ions typically have electromagnetic spin axes, and the axes tend to align either parallel or perpendicular to the earth's magnetic field. When an electromagnetic field is added to the earth's field, the free ions rotate to align with the resulting field. Basic theory for the method is given by Block (1946) and Pake (1958); Schlumberger (1972) offers the method as a service survey.

   Usually the greatest amount of free ions in the subsurface, especially in typical saturation zones of soft ground, are hydrogen ions of water not chemically bound or otherwise limited in mobility. Identifying the unbound ionic hydrogen component of the strata immediately removes some of the limitations of conductivity (resistivity) logging, and particularly permits more accurate interpretation of nuclear logging methods (below) that respond to total hydrogen content.

   Further, when the electromagnetic field is applied, the ions rotate to new positions, and when the field is removed, the ions precess back to their alignments with the earth's magnetic field at a constant precession rate for each particular element. As the precession occurs, a secondary electromagnetic field is generated that is proportional in strength to the total number of precessing ions and in decay rate to the amount of original rotation. Since the strength of the field represents the total mobile ions and most mobile ions are hydrogen, a measurement of the field generated essentially represents the total amount of free and mobile water in the strata. Empirical data from tests of the technique show that the mobile ion content is directly related to the permeability of the strata.

Permeability is the second most critical soft ground tunneling parameter, and the possibility of providing a measurement of this parameter from undisturbed materials beyond the borehole wall offers a unique contribution to subsurface exploration results. The identification of mobile hydrogen ions also removes ambiguity from other borehole log interpretations, and development of this technique is highly recommended.

8. Gravimetric surveys. Gravimetric surveys in open or fluid-filled boreholes are used to provide density profiles of subsurface materials. Because of the corrections required for data of this type and relative unimportance of density to the minerals industry, however, borehole gravity surveys are not widely used or highly developed. Smith (1950) describes the potential of borehole gravimeter surveys, and Howell et al (1966) describe some early developments and applications.

   One of the most common methods of borehole gravity surveying is to observe the changes in frequency of a vibrating wire caused by changes in the gravitational field as the gravimeter is lowered into the borehole (Thyssen-Bornemisza, 1974). The changes in gravitational field are related to changes in density of the materials traversed in the borehole. Corrections for variations in borehole size, terrain, temperature, etc., are required. Based upon measurements of core samples or direct observation of subsurface materials in shafts near surveyed boreholes (McCulloh, 1965), accuracies are reported to be within $\pm$0.004 to $\pm$0.01 milligals, or an equivalent density accuracy of $\pm$0.01 to 0.050 grams/cm^3 (about 0.01 to 3 pounds/ft^3).

The borehole gravimeter method of subsurface investigation is not considered an especially favorable technique for further development in this evaluation. The problems of obtaining appropriate correction factors, making continuous logging without data errors related to motions of the instrument (which are reflected as gravitational accelerations), and making use of the results for more than a very limited range of engineering parameters place the method in a lower category than other borehole techniques.

9. Borehole thermometry methods. Temperature profiles in a borehole reflect the position of the water table in materials penetrated, may identify the location of zones where inflow or outflow occur, and have been widely used in the minerals industry to identify grouting (cementing) levels outside of casing in a borehole. Primary interests of the temperature profiles in soft ground tunneling are related to subsurface water features. Typical thermometric survey methods are discussed by Gasham and Macune (1958) and Gaskell and Threadgold (1960).

Two types of surveys are normally provided by this type of borehole logging: a) a vertical absolute temperature profile vs. depth; b) a differential temperature profile vs. depth. The differential profile is the more accurate and most used of the two types of surveys.

Either method may be used in cased or uncased boreholes. Time is required for the borehole temperature to stabilize after drilling operations (usually about 1 day is adequate), and measurements after this time may be considered essentially accurate since only very small temperature inversion cells exist in small diameter boreholes. Accuracy of the survey is based upon the usual consideration of knowledge of the probe position from cable length entering the hole, measurements of logging rates (response time of temperature sensors) and the borehole size (temperature inversion cell size). Reported accuracies (Lynch, 1962; Raskell, 1962) using standard thermistor bridges are

Vertical position ± 1 foot
Temperature
Direct $\pm 1.0^{\circ}C$
Differential $\pm 0.1^{\circ}C/ft.$

Logging rates (typically 5000 ft/hr) within the accuracies above are adequate for surveys to provide information concerning both water levels and cementing as mentioned above.

Temperature surveys are not considered especially critical within the typical problems of subsurface investigations for soft ground tunneling. Other methods with additional versatility which provide the information inferred from temperature surveys are available, unless very high ($150^{\circ}C$) temperatures are encountered which could affect the resistivity or nuclear surveys.

10. Visual and visual imagery methods. Borehole techniques that permit direct active viewing of the borehole wall, photographing of the wall or otherwise obtaining a visual image of the physical appearance of the wall may be considered as borehole geophysical methods. The appearance of the borehole wall and features caused by various boring activities may be related to engineering or construction characteristics encountered by actually opening the ground in tunneling operations. Inferences regarding the location of soil boundaries, "standup time" (from presence and degree of washouts), permeability (from amounts of mudcake buildup on permeable zones penetrated by the borehole), and some information about the size

and distribution of grain sizes (pebbles, etc.) or fractures are provided by these methods. Ultrasonic imaging may also be used to examine materials beyond the borehole wall (see acoustic wave methods). A complete image around the borehole depth is available from most methods. Kelly (1939), John (1958), as well as Gaskell and Threadgold also discuss this technique briefly.

Direct photography or televiewing methods usually require that the boreholes be dry or contain clear fluids. Investigations of using near visible light (both infrared and ultraviolet) to bypass the effect of "muddy fluids" show only limited improvement over the visible spectrum recordings (Sherbakova, 1962). Ultrasonic techniques, which provide an image of the amplitude of sonic waves reflected from the borehole wall as a transmitting/receiving probe is lowered in the borehole, bypass the fluid problems as long as the fluids are well mixed by borehole conditioning (Brenden et al, 1970). The depth of penetration and resolution power of ultrasonic methods may be varied by changing power outputs, frequencies of reflected waves recorded, and output wave frequencies, making this technique very versatile in subsurface investigations (Holosonics, 1971).

Accuracy of the imaging techniques is essentially dependent upon accuracy of the probe location and resolving powers of the receiving equipment. Vertical accuracy for shallow surveys is estimated to be well within one-half (± 0.5) foot, and objects as small as 1/32nd of an inch (fractures) have been located accurately.

Imaging methods are not considered here to have particularly high development requirements for increased use to soft ground tunneling problems. Requirements for either dry or extensively conditioned boreholes may limit the utility or time in which surveys can be conducted even if developments were undertaken. Ability of the methods to provide information which is not expressed in anything but the visual appearance of a very small subsurface area of a borehole wall is strictly limited, and, therefore, not very likely to be generally useful for all borehole surveys which might be encountered. For specific cases, tools are available that are suitable at their current development status.

11. Nuclear logs. Borehole logging by nuclear methods results in a continuous profile of either the effects of materials around the borehole on an applied radiation flux or of the reaction of the materials to the applied radiation, with one exception. The exception is a passive logging technique which records a profile of natural radiation. Since the techniques respond to physical characteristics of the strata, they are of particular importance to definition of subsurface physical parameters required for design and planning. The advanced techniques also offer the only indirect methods for examining the chemistry of both the strata and any saturating fluids or gases: these can be uniquely important in some soft ground conditions. A comprehensive summary of these techniques is reported by the International Atomic Energy Agency (1971). Nuclear logs typically provide a measure of the effect or response of the geologic materials surrounding the borehole resulting from exposure to radioactive sources. A generalized nuclear log response diagram for materials typically encountered in soft ground is shown in figure 5-13.

12. Natural gamma logging. Natural gamma ray logging tools are simple Geiger-Muller tubes or scintillation crystals with an adequate amplifying stages to transmit radiation count rates to a surface recorder. Basic instrumentation is described by Jones and Skibitzke (1956). Minor modification to include a pulse-height analyzer can be incorporated into the system for that purpose (Brannon and Osaba, 1955).

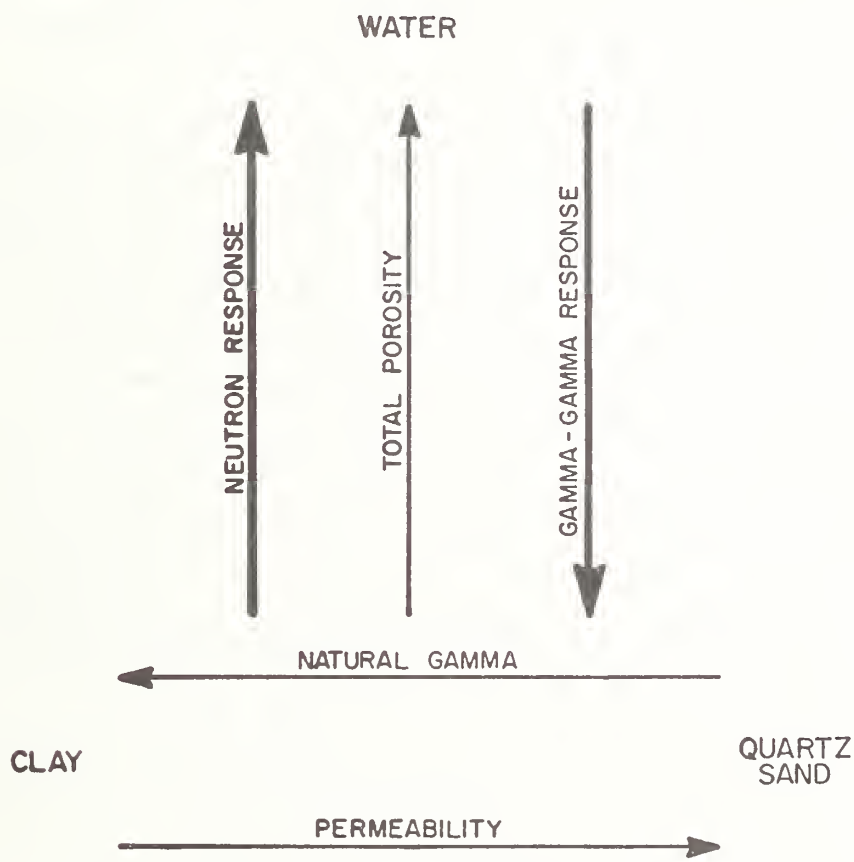


Figure 5-13. Generalized Nuclear Response Diagram.

13. Gamma-gamma logging. Two principal kinds of gamma-gamma logging are used for subsurface explorations. The difference between the two is mainly a difference in the gamma-ray energy levels recorded, and selection of which to use is based on the exploration interest. For engineering explorations, interests are in the high energy gamma rays (>200,000 electron volts) for bulk density measurements. Low energy gamma ray logging is used mostly in mineralogical explorations.

Gamma-gamma density logging is simple in principle (see Tittmann and Wahl, 1962; 1965). Photons (gamma rays) emitted from a radioactive source interact with electrons of the surrounding strata, producing scattered photons with an intensity proportional to the electron density in the starta. Electron density is directly proportional to bulk density, and with appropriate corrections for source power, borehole conditions, source-detector spacing, and chemical compositions, a recording of the intensity results in a continuous profile of bulk density penetrated by the borehole. If solid and fluid densities are known, porosity (or void ratio) can also be calculated. Successful logging results in bulk density measurements with 2-3% accuracy (Danes, 1960; Keys, 1967).

Borehole gamma-gamma tools satisfactory for soft ground explorations are already available, but modifications to provide more accurate and reliable logs can be made. The primary modifications needed are to provide a small diameter eccentrically compensated tool to reduce the influence of borehole materials (muds, other fluids, gases) between the tool and the strata of interest, and to compensate for variation in borehole diamter.

14. Neutron logging. Neutron logs express the effects of strata on a flux of neutrons applied to the borehole wall or reactions of materials in the strata to the neutron flux (See Tittle, 1961; Alger, et al, 1963; Allen, et al. 1964; Tittman and Sherman, 1966; Tittle and Allen, 1966;

Allen, et al, 1967). Both passive (continuously emitting radioactive sources) or active (pulsed neutron) sources of neutrons are available. Neutrons are classed according to energies:

Fast Neutrons	=	10 million to 10 thousand electron volts
Epithermal Neutrons	=	10 thousand to 1 electron volts
Thermal Neutrons	=	1 to 0.01 electron volts

Results of exposure to the neutron flux can be measured by tools that have gamma, epithermal, or thermal detectors. Several techniques are used to identify specific elements making up minerals in the strata around the borehole.

Spectrometric neutron-gamma (Hoyer and Rumble, 1964)
Neutron activation (Senftle and Hoyt, 1966)
Fast neutron activation (Senftle and Hoyt, 1966)

These operate on the principle that the applied neutron flux results in radioactive isotopes of elements in the strata which have spectral peaks and half-lives characteristic of the elements. The spectral techniques have specific soft ground use in indicating cementation, fluid, and gas compositions in the subsurface, and as methods of identifying strata and strata boundaries. Other neutron logging techniques respond mainly to hydrogen content of the strata (primarily water):

Neutron-Gamma	(Keys and Boulgne, 1969)
Neutron-Epithermal Neutron	(Tittman and Sherman, 1966)
Neutron-Thermal Neutron	(Youmans, et al, 1964)
Neutron-"Lifetime"	(Youmans, et al, 1964)

Degree of saturation, type of saturating fluid (saline or fresh water), and porosity/inferred permeability are the primary parameters of interest provided by these techniques. The Neutron-Epithermal Neutron log is of special interest because it is not affected by formation of saturating fluid chemistry as much as the others (Tittman, et al, 1966).

15. Pulsed neutron logs. The pulsed neutron source is the most attractive type of neutron tool for soft ground tunneling exploration because it is radioactively inert unless in use. It also provides the highest energy, can be used for either gamma or neutron type of detection, and borehole effects are minimized in comparison to the isotope sources (Allen, et al, 1965). Almost all of the neutron logs can be obtained using pulsed generator sources by selection of the proper detectors and post-pulse observation times. Modification of currently available borehole tools is necessary for use in small diameter boreholes.

5.4 EVALUATION OF GEOPHYSICAL TOOLS FOR SOFT GROUND TUNNELING

The approach taken here to evaluate the geophysical techniques in terms of soft ground tunneling exploration requirements is somewhat different from typical system evaluations. Since the methods are indirect and commonly do not measure first order engineering parameters directly, inferences from the parameters that are measured have to be qualitatively judged with as little bias as possible in order to provide a fair evaluation. The method described below is the base for evaluation in this report.

The three categories of evaluation take measure of present state-of-the-art conditions, pass judgment on the techniques in terms of soft ground tunneling problems, and estimate the investments required to make the techniques more useful. The specific categories are:

I. Current use of the technique for providing information about a particular engineering parameter.

II. Potential for developing the technique toward specific use in soft-ground tunneling problems.

III. Development effort required to bring the technique to a status where specific soft-ground engineering parameters are provided by its use.

Rating levels within each category ranging from one (1) to four (4) were used to assess each technique. High numbers rate the technique favorably, low numbers imply the technique is viewed unfavorably within the soft ground tunneling problem environment. A rating of zero (0) is not applied to any technique; indirect methods are notably versatile if new correlations or inferences are found.

Rating levels within each major category are defined as follows:

I. Current use of the technique for providing information about a particular engineering parameter.

1. Limited use, or no use at present.
2. Some use at present, but not currently used in soft-ground tunneling.
3. Some use at present, not widely used.
4. Widely used.

II. Potential for developing the technique toward specific use in soft-ground tunneling problems.

1. No obvious potential for development to improve use.
2. Some potential, but relationship is not clear.
3. Technique offers additional or more accurate information if developed further.
4. Technique has strong potential to provide new or unique information if developed.

III. Development effort required to bring the technique to a status where specific soft-ground engineering parameters are provided by its use.

1. Major research and development effort would be necessary to find an application of the technique to soft-ground tunneling.

2. Significant development effort is necessary: Theory, prototype equipment, and basic analytical methods are available, but not extensively tested (est. $10M plus, 3-5 years plus).

3. Moderate development effort required: Theory, equipment, and analytical methods well tested, but specific soft-ground tunneling development is necessary ($1M - $10M, 2-3 years).

4. Normal development for some acceleration of actual use required: Theory, equipment, and analytical techniques have been used in situations closely related to soft-ground tunneling, or have been directly used (approx. $1M, 2-3 years).

Significant engineering parameters in terms of cost, safety, and environmental impact were summarized in section 4. On the basis of the subsurface engineering parameter evaluation, the following rating sequence is considered for evaluation of geophysical tools, starting with the most important parameters:

Soil Boundaries (Stratigraphy)
Permeability
Groundwater
Natural Obstructions
Cohesion of Granular Soils
Undrained Shear Strength
Modulus
Consolidation Characteristics
Man-made Obstructions
Chemistry of Subsurface Gases
In-Situ State of Stress
Drained Strength Parameters
Grain Size Distribution
Density

Each indirect method has been rated against each of these parameters for the overall evaluation, forming a matrix of <u>Method</u> vs. <u>Parameter</u>. Within that matrix, the four rating levels within each category are expressed by a three number sequence. The first number is from category I (current use), the second is from category II (development potential), and the third is from category III (development effort). Results of the rating are shown in table 5-3 for the surface geophysical methods and in table 5-4 for techniques used in boreholes.

If the engineering parameters are given a simple weighting based upon order of importance to soft-ground tunneling, the evaluation should reveal the most useful method with greatest overall potential for development requiring the least developmental time, costs and effort. However, it should be noted that several important facts may be obscured by the weighting and by the evaluation itself:

1. The importance of any particular parameter in a single tunnel depends entirely upon whether or not it contributes to a problem in that tunnel. The rating scheme attempts to provide an overview of a generalized tunneling environment, but cannot account for the specific of importance to a single tunnel.
2. A simple summation of the numbers given in the rating matrix in tables 5-3 and 5-4 provides the guidelines for a "best" development approach. Distinctly useful techniques for one particular problem which have little use in resolving others may be lost in the overall summary.
3. For the borehole instrumentation, actual application of the techniques may have severe limitations dependent upon borehole conditions which are not directly reflected in the rating. These must be accounted for in the final evaluation of the indirect subsurface techniques. Multiple method borehole instrumentation packaging and interpretation is a rule rather than exception, and versatility for surveying a variety of subsurface conditions must be accounted for.

TABLE 5-3. EVALUATION OF SURFACE GEOPHYSICAL METHODS

ENGINEERING PARAMETERS → / SURFACE Geophysical Method ↓	Density	Grain Size Distribution	Drained Strength Parameters	In-situ State of Stress	Chemistry of Subsurface Gasses	Man-made Obstructions	Consolidation Characteristics	Modulus	Undrained Shear Strength	Cohesion of Granular Soils	Natural Obstructions	Groundwater	Permeability	Soil Boundaries stratigraphy
Seismic Refraction	333	212	223	232	111	233	233	333	333	233	233	434	223	444
Seismic Reflection	233	212	223	222	111	233	233	233	233	233	233	334	121	444
Seismic Vibroseis	233	212	223	222	111	233	233	233	233	233	233	234	121	444
Seismic Holography	233	212	223	232	111	343	233	233	233	233	343	234	121	244
Sonic (Acoustic)	121	121	122	122	111	322	211	211	121	211	121	121	121	121
Resistivity (Conventional)	121	121	122	122	121	333	223	223	223	223	333	434	223	434
Electromagnetic (Conventional)	121	121	122	122	121	333	223	223	223	223	333	334	223	333
Electromagnetic (Subsur. Prof.)	121	121	122	122	121	434	223	223	223	223	344	334	223	434
Electromagnetic (Pulse Sound.)	121	121	122	122	121	332	223	223	223	223	233	233	123	233
Electromagnetic (Surf. Waves)	121	121	122	122	121	232	122	222	123	123	223	333	122	233
Nuclear Density - Moisture	411	212	122	121	121	111	211	121	121	121	121	121	121	121
Radioactivity Survey	211	121	111	111	121	111	111	111	111	111	111	111	122	121
Gravimetric Survey	233	111	121	121	111	232	221	121	222	121	232	121	111	222
Magnetic Survey	121	111	111	111	111	334	111	111	111	111	223	121	111	222
Thermometric Survey	121	121	111	121	121	233	111	111	111	111	121	211	121	121

TABLE 5-4. EVALUATION OF BOREHOLE GEOPHYSICAL METHODS

ENGINEERING PARAMETER → / BOREHOLE Geophysical Method ↓	Density	Grain Size Distribution	Drained Strength Parameters	In-situ State of Stress	Chemistry of Subsurface Gasses	Man-made Obstructions	Consolidation Characteristics	Modulus	Undrained Shear Strength	Cohesion of Granular Soils	Natural Obstructions	Groundwater	Permeability	Soil Boundaries stratigraphy
Sonic Acoustic	333	223	223	222	121	333	333	333	233	233	232	334	323	434
Seismic Uphole/Crosshole	333	222	223	222	121	333	333	333	233	233	333	334	323	434
Electric Normal Logs	122	122	222	121	121	233	222	223	222	232	233	334	333	334
Electric Microlog Dipmeters	223	122	222	121	121	222	222	223	222	232	222	334	333	344
Electromagnetic Conventional	223	122	222	121	121	234	222	223	222	232	234	223	223	333
Electromagnetic Dual Induction	223	122	222	121	121	243	222	223	222	232	234	223	223	333
Electromagnetic Nuclear Response	333	222	223	122	233	222	233	223	222	232	222	243	344	344
Gravimetric Survey	333	121	223	121	121	333	223	223	233	121	333	223	223	232
Visual or Visual Imagery	221	222	.223	121	121	121	223	223	223	344	121	121	333	344
Thermometric Survey	111	121	121	121	121	121	121	121	121	121	121	334	323	334
Nuclear Natural Gamma	333	121	121	121	233	121	121	223	222	121	222	233	223	234
Nuclear Gamma/Gamma Density	333	233	223	122	121	121	233	233	233	223	222	233	333	334
Nuclear Neutron Porosity	333	233	223	122	121	121	233	233	233	223	222	233	333	334
Nuclear Thermal Decay	333	233	223	122	223	121	233	233	233	223	222	233	333	334
Nuclear Spectrometric	233	222	223	122	243	121	233	233	2,33	223	222	233	333	333

In view of the facts above, no specific weighting has been applied to the values in the tables. A simple summation of the numbers for the techniques orders them in overall capability for the required geotechnical explorations as follows:

SURFACE

Seismic (refraction, reflection, Vibroseis, holography)
Electromagnetic
  Subsurface Profiling
Resistivity
Electromagnetic
  Conventional
Electromagnetic
  Pulse Sounding
Sonic/Acoustic
Electromagnetic
  Surface Waves
Magnetic-Gravimetric
Nuclear
  Density-Moisture
Thermometric
Nuclear
  Natural Gamma

BOREHOLE

Seismic
Uphole/crosshole
Sonic/Acoustic
Electromagnetic
  Nuclear Responses
Nuclear
  Thermal Decay
Nuclear
  Spectrometric
Nuclear
  Density-Porosity
Electric
  Normal, Micro, Dip
Electromagnetic
  Conventional and Focussed
Gravimetric
Visual/Imagery
Natural Gamma
Thermometric

Those techniques with highest potential and lower development costs are outlined in the tables. Parameters which are most likely to be obtained are also suggested by the number of outlined high ratings in each parameter's column.

On the basis of these evaluations a number of borehole techniques have been selected for recommended development as a package. A description of the selection and the development program is described and performance specifications are presented in appendix E.

5.5 METHODS OF LOCATING UTILITIES AND OTHER MAN-MADE OBSTRUCTIONS

5.5.1 General

It has been pointed out that utilities and other man-made obstructions can have considerable economical and safety impact on tunnel construction. For bored tunnels, the most common problems are with deep sewers, piles or building rubble. For cut-and-cover, shallow utilities and obstructions hinder the installation of retaining walls. Shallow utilities also present hazards to exploratory borings.

Because of the different character of different types of utilities and obstructions, exploratory techniques to discover these obstructions must be selected according to the types of obstructions; no single methodology will discover obstructions of all kinds.

For this purpose, utilities may be classified as nonmetallic (most sewers and drains), metallic (e.g., water or gas lines) and live (i.e., carrying an electric current). Other obstructions may be metallic or nonmetallic and are generally characterized by a greater density and rigidity than the surrounding soil. Such traits form the basis for the remote discovery of these obstructions. Nonmetallic sewers or drains exhibit a water or air filled void space that may sometimes be discovered by special techniques. Another aid to discovery lies in the loosening or disturbance of the backfill soil over and around the obstruction, contrasting with the natural soil.

The first step to locate utilities and other obstructions is to examine existing inventories and records available at local authorities and public and private utility organizations, and old building plans. In many cases, such information is not available or it is inaccurate or incomplete. Exploratory test pits may be employed in certain cases, but test pits at close intervals in the areas of dense network of pipes and cables are inconvenient, expensive and time consuming; they may cause damage, and may even be dangerous. Test pits are useful when they can be executed as an initial part of, for example, deep excavations, prior to constructing retaining walls, but as a rule, other means of prospecting for subsurface utilities and other man-made obstructions are required.

Many different remote techniques are available that may locate different obstructions at greater or lesser accuracy. The methodologies are of several basic types:

1. Detection of existing electromagnetic fields, for example, as generated by power cables.

2. Detection of electromagnetic fields deliberately generated by inducing electric current directly through utilities.

3. Transmitting probes pulled through utilities, in combination with a surface detector.

4. Mapping of electromagnetic field induced in the ground, either through AC generators placed on the ground surface, or through a transmitter held in a constant geometrical relationship with the antenna and receiver.

5. Measuring reflections of downward directed radar pulses.

6. Mapping of potential fields (DC) induced in the ground through electrodes in various configurations (conventional resistivity surveys).

7. Seismic techniques, reflection or refraction.

These various methods utilize contrasts of resistivity (conductivity), dielectric constant, or seismic velocity, between different soil types and between soils and obstructions. Where no contrasts of these natures exist, features cannot be mapped. Where contrasts make mapping possible, utilities or obstructions generally appear as anomalies of more or less recognizable form.

Conventional resistivity surveys (type 6 above) are quite well known and have been used with success under appropriate circumstances. Their resolution with depth is poor, and the urban environment is not favorable for thier use. In theory, the effect of conducting utilities on the potential field could be utilized to locate them. However, stray currents and other irrelevant anomalies make interpretation difficult, and some of the methods further discussed below are more suited.

For surveys of the types 1 to 4 above, equipment is available, well developed, and used by service companies and utility companies, and a few other types of users. Surveys of type 5 are still in experimental stages and only available through the companies that have developed these tools. Simple seismic techniques (type 7) are available in general use, but improvements are needed.

The following paragraphs discuss the basic principles, application and utility of most of the various types of instruments, and their potential for development. The discussion is based on manufacturers' and service firms' literature, interviews with users (utility companies around the New York Metropolitan Area) and a brief review of the rather meager relevant literature.

From the simpler electromagnetic instruments, the output may be a tone signal whose pitch indicates a signal strength, or a simple gage. Changes in the signal indicate anomalies in the subsurface. Many instruments may be adapted to a recording device that will store the analog signal on a chart, greatly facilitating accurate interpretations. Recording on magnetic tape allows computerized data analysis and office plotting of the data.

5.5.2 Electromagnetic Techniques

1. Metal locators. One of the simplest tools for locating buried metallic items is the metal locator. As most electromagnetic tools, it employs a low frequency radio transmitter and a receiver (coils in a roughly circular housing). The transmitter generates an electromagnetic field which is captured and modified through induction by conducting elements, and the response is measured through the receiver.

   Metal locators may be used to locate manhole covers, valves, lost tools, etc. The depth of effective penetration is typically shallow and depends on the conductive properties of the object and the surrounding soil, and the size and shape of the object. Nearby highly conductive large objects will give the strongest signal. If the surrounding soil is more conductive that the target object, detection becomes difficult. Under average field conditions a metal surface 1/2 inch x 1/2 inch at a depth of about 4 inches, a metal surface 1 foot x 1 foot at a depth of about 2.5 feet, and a metal surface 5 feet x 5 feet at a depth of about 5 feet can be detected in soils.

Metal locators are useful for specific purposes but have limited general utility for a major earth moving activity such as tunneling. The tool is well developed, and further refinements are not likely to enhance its utility for the present purposes.

2. Pipe and cable locators. Pipe and cable locators also employ a low frequency (between 80 and 120 kHz) radio transmitter and a receiver, in this instance at a fixed distance a few feet apart, or with a fixed transmitter and moving receiver. The receiver detects and traces the electromagnetic field. By this means, the location and orientation of the target object can be determined. There are generally two modes of operation: 1) Inductive and 2) Conductive. In the inductive mode there is no physical contact between the transmitter and the metallic object whereas in the conductive mode a direct wire connection between the transmitter and a buried metallic object such as a pipe is made.

   Pipe and cable locators are used to locate pipes, cables, conduits, mains, manholes, junction boxes, etc. The depth of penetration depends on conductive properties of the surrounding soil and transmitted signal strength. Signal strength detected will increase with the size of the object. Depending on the type of instrument, the depth of penetration under ideal conditions may be 15 to 20 feet. Average depth of penetration is about 10 feet or less. Current carrying cables may be detected to a depth of about 7 feet.

   Using these instruments in the ordinary fashion allows only a poor indication of the depth of a utility. If depth is an important parameter (e.g., when earth anchors have to be installed), a hole may be drilled adjacent to the utility and a specially designed probe lowered to find the depth. An estimate of depth may also be obtained by using directional antennas; two measurements taken with different angles of the instrument will define the depth. Tools are available that will perform these functions.

Pipe and cable locators are useful but may fail in areas of complex networks of pipes and cables. Any improvements such as greater penetration depths under average field conditions, print-out maps of subsurface features by using automatic plotters, computer analyses of data, etc. may contribute considerably to their use.

3. Receiver and probe. This technique consists of attaching a specially designed radio transmitter (probe) to a wire, cable, plumber's snake, or sewer tape which is inserted into the sewer line. The operator on the surface then traces the radio signals from the transmitter with a receiver. Nonmetallic sewers, ducts, culverts, drains, etc, can be detected to depths up to 40 feet, if no interference from other features is present. Although the depth can be estimated in some cases, other means will often be required to establish the depth of the target object.

   Receiver and probe techniques are useful where the subsurface network of pipes, ducts, etc. is relatively simple and there is an access to the target line to introduce the probe. In metropolitan areas where the network of utilities is very dense, receiver and probe techniques may become impractical.

   The techniques would be more sueful for the location of subsurface utilities if depth determinations could be made automatically. Basically, the tool is well developed and available in many versions, but methods of use and interpretations can be refined.

4. Receiver and induced current. The basic principle is to inject a low voltage alternating current into the ground by means of two electrodes. This current concentrates according to the conductivity of the ground and the

features in it and generates an electromagnetic field. The current flow pattern or the orientation of the magnetic field can be measured with a receiver. If the current can be fed to both ends of the target pipe, tracing to depths up to 30 feet may be possible; otherwise it would be considerably less.

Receiver and induced current techniques do not allow accurate depth determinations. Trial test-pits or borehole probes are required to determine the depths of metallic subsurface utilities and other metallic obstructions. In addition, a complex network of metal pipes can make the investigation impractical. Therefore, these techniques are frequently not suited for the location of subsurface utilities and man-made obstructions for tunneling. The state-of-the-art is such that any improvements will not contribute a great deal to their use in tunneling.

5. Electromagnetic subsurface profiling (ESP). Electromagnetic subsurface profiling produces a continuous profile of subsurface conditions, under ideal conditions showing depth and location of geologic formations, buried utilities and cavities. Information is obtained by sending broad-band radar pulses containing radio waves at low frequencies into the earth and recording the reflected pulses from interfaces and objects. The depth can be determined from the reflected pulses. Depth of penetration of the signal is governed primarily by the conductivity of the medium and reflection is governed primarily by contrasts of dielectric constant. As the conductivity increases, attenuation of the signal increases, and penetration by the pulse decreases. Water content and chemistry influence the depth of penetration; an increase in water content decreases penetration, especially where the water is highly mineralized. Salt water completely blocks penetration. Depth of penetration is up to about 25 feet in sand and 10 feet in clay. More details regarding the possibilities and prospects of ESP are found in paragraph 5.3.2.

Underground utility mapping may be done by, for example, taking an ESP survey along lines spaced on a 10-foot grid. The equipment is pulled behind a truck and the unit travels at about 3 mph. The reflections are recorded on magnetic tape and also displayed on a cathode ray tube in the truck.

An interpretation of subsurface features can be made in the field, but computerized interpretation in the office allows accentuation of desirable features through filters and selective amplification, etc. ESP seems to be the most sophisticated of the techniques available at this time, and it can be very helpful in location of subsurface utilities and other obstructions in tunneling. Developments in the system may improve its applications considerably in tunneling. These developments will include such things as increased power, modifications of pulse band width, etc. Computer processing of data must be refined to eliminate uncertainties and to reduce the need for highly trained interpreters.

5.5.3 Seismic Reflection Techniques

Seismic reflection techniques for subsurface prospecting have a considerable application in oil and mineral exploration. The techniques available for location of man-made subsurface obstructions are relatively simpler. In these techniques, hammer impulses, (instead of explosive charges) may be used with today's technology. Arrivals are received by one or several geophones and may be recorded on a magnetic tape. This tape is then processed to make it suitable to give a printout of all reflected arrivals through a digital plotter. The charts then can be examined for patterns to show such features as cavities, filled shafts, culverts, large pipes, old foundations, large boulders, etc.

Considerable experience is required to interpret the patterns produced and determine the depths of man-made obstructions. The system can be useful provided it is used with calibration boreholes to determine the character of subsurface features and their seismic velocity properties.

Seismic reflection techniques have long been known and used particularly for deep subsurface prospecting in the oil and mineral industry, and it is often not accurate at shallow depths with current practice. Possible improvements to seismic techniques are described elsewhere in this report.

5.5.4 Conclusions

With the present state-of-the-art of subsurface prospecting, the location of shallow metallic utilities may be determined with reasonable accuracy under relatively simple circumstances. The exact elevation of such utilities is more difficult to define, and where a dense network of utilities traverses the area, most of the methods will often fail to perform.

The key to success for all of the electromagnetic techniques discussed lies in the interpretation of data more than in further hardware developments. With electromagnetic subsurface profiling, an attempt has been made to ease the interpretation by the presentation of vast amounts of data in meaningful fashion, and the interpretation is improved by computer enhancement and filtering. The success of pipe locators and similar tools will be improved through similar improved means of display interpretation. Such developments are underway (Amos, 1970).

For utilities deeper than about 20 feet, especially nonmetallic utilities, and for detection of other types of obstructions, refinements of seismic techniques appear to bear some promise. Such possible refinements are treated in paragraph 5.3.2. The cost/benefit ratio of such developments, if made solely for the purpose of detection of deep sewers and similar facilities, is not favorable because of the relatively rare occurrences of unknown deep utilities, because of the uncertainties of interpreting indirect data to obtain precise information, and because of the relatively high cost of seismic profiling. But when obstruction detection is considered as an important fringe benefit of geologic profiling, this benefit adds to the utility of development of such profiling.

The various techniques in locating obstructions all require a good deal of skill both in handling the equipment and in the interpretation. Proper data handling and display allow easier and safer interpreations, but there is no doubt that even very sophisticated methods will have to rely on the success or the interpretative skills of the operator.

5.6 GENERAL CONCLUSIONS - A SET OF TOOLS FOR THE FUTURE

5.6.1 The Direction of Technique Development

Based on the definitions of the parameters significant to soft ground tunneling, the cost impact of these parameters, and the analysis of currently used and potentially useful techniques, it is possible to define the most promising avenues of development:

1. Methods of direct permeability measurement.
2. Borehole geophysical tools, a package for multiple use, developed for soft ground explorations.
3. Development of seismic methods with high frequency, high energy sources and interpretation of redundant data using computerized correlation techniques.

These developments have about equal merit. The first requires the least outlay of effort and money for development, but concentrates on one parameter. Permeability is a very important parameter, but more sophisticated methods of analysis and empirical correlations must be developed to make full use of the permeability parameter.

Developments of borehole geophysical tools show great promise. Already such tools have been used for years in other endeavors and have shown their potential. Some tools may be used for soft ground explorations with little modification; others need significant alteration, or new methods of interpretation must be developed; yet other tools showing great promise (pulsed neutron tools in particular) are in developing stages.

To cover the unexplored areas between boreholes and other spot measurements it is necessary to employ the third high priority development item, seismic explorations. A discussion of suitable seismic developments was given in paragraph 5.3.2 (Seismic Limitations and Requirements). Though detailed development plans are not presented here for reasons already given, it is emphasized that seismic developments may be expected to bear fruit with an effort estimated to be less than $2 million, less than 3 years.

The emphasis on these three items does not mean that no other developments warrant attention. In particular, electromagnetic subsurface profiling (see paragraph 5.3.2) deserves attention. This method is at present under development.

As regards the direct methods of exploration, it must be noted that the availability of excellent geotechnical exploration tools and methods of interpretation is no guarantee that they will be used. Present day practices of assigning budgets for tunneling explorations and practices of exploration and testing are limited and conservative, and many excellent tools are hardly every used. In particular, the various penetrometers and dilatometers should be properly employed in American practice before great efforts are expended on developing new tools for exploring strengths, compressibilities and densities.

A tool that shows considerable future potential is a combination of the static cone penetrometer, the piezometer probe and the moisture sensor. In soils where penetration is possible, this combined tool will provide information about relative density and consistency of the soils, shear strength, moisture content and permeability. While the penetrometer is well developed today, the piezometer probe and the moisture sensor parts of this future tool are under development, and development of the combined tool should be undertaken when these parts are completed and checked out.

5.6.2 The Direction of Exploration Programs

The make-up of exploration programs of the future - not only for soft ground tunnels but for other structures as well - will include a number of items not often used today:

1. For overall coverage between borings, the exploration specialist will choose between seismic or electromagnetic explorations, or both. In some instances he may select electric methods.

2. To determine strength, density and consistency of soils, the specialist will choose between conventional borings (with undisturbed sampling and testing), dilatometers, vane shear devices or other direct borehole tools. Static cone penetrometers or combination penetrometer tools may be used without a borehole. Most likely, several of these devices will be used on a project. Correlation and extrapolation will be possible through the use of borehole geophysical tools, which will also be important to define stratigraphic boundaries, mineral content, water content and other physical parameters.

3. To determine the soil permeability, its distribution and variation, and evaluate effects of groundwater on construction, several methods would usually be used. The most direct method would involve the use of a piezometer probe or borehole permeability method. Indirectly, continuous profiles of permeability may be obtained by borehole geophysical tools, correlated with some direct measurements. In critical cases, full scale dewatering tests may still be needed.

4. Utilities and certain other man-made obstructions will be located by electromagnetic subsurface profiling, or in simple cases by pipe locators. Valuable information of this nature will also be available from seismic profiles.

5. Computers will be used extensively, not only to provide interpretations of surface and borehole geophysical data, but for overall correlation purposes, storage of data and display.

The exploration engineer of the future will have to be more specialized than now. He must know not only about soil mechanics, boring, sampling and testing, but also about in-situ testing as preferred alternatives to many types of laboratory testing, about indirect borehole logging methods, their uses and interpretations, and about geophysical ground surface explorations such as seismic and electromagnetic developments. He must be able to select the appropriate package of exploratory tools, suitable for a given environment, and to perform the explorations and interpret the data into meaningful engineering terms. Engineers with this set of capacities are rare now, but it may well be necessary for the profession to develop such specialists.

6. RECOMMENDED DEVELOPMENTS - INSTRUMENTATION

6.1 INTRODUCTION

As discussed in depth earlier in this report, groundwater has a very great impact on tunnel costs, and is associated in one way or another with most tunnel design and construction problems. In addition to stratigraphy and hydrostatic conditions, soil permeability is a major factor in determining the tunnel construction procedure and the required dewatering effort, and in estimating length of time required to dewater and analyze the recharge phenomena. Soil permeability is also a significant parameter affecting grouting, freezing techniques, and other phases of tunnel design and construction. Currently very limited data relating to soil permeability are obtained for either the design or construction phase. This is believed inconsistent with the importance of permeability and inconsistent with the sophisticated technology which could readily be developed for analyzing the data. The need for improving direct measurement of permeability and the technology of utilizing this data has been established as a priority and is the subject of this section.

Of all soil parameters, permeability is the most variable and erratic. Subtle changes in grain size, stratification, density, etc. can make enormous differences in permeability. It is felt that no single device or method can reliable be used to measure soil permeability accurately. Meaningful permeability data is gained only from a combination of laboratory tests, various direct in-situ tests, correlations with similar conditions on previous projects, and needs analytical technology to interpret and utilize the data. The extent of permeability data currently collected for tunneling projects normally consists of numerous standard test borings, and a limited number of laboratory grain size tests. On rare occasions, a large scale pumping test may be performed. Several other methods of direct permeability measurement are available, but these methods have numerous limitations and disadvantages. Problems with current technology include hardware limitations, analytical limitations, lack of standardization, general distruct among engineers and contractors of sophisticated ground water flow analyses, and lack of any technology developed specifically for tunneling problems.

The recommendations of this chapter consist of:

a. A number of specific hardware innovations.

b. Recommended development of improved theoretical methodology.

c. Creation of a data acquisition and processing system to predict the impact of groundwater conditions prior to construction, and to evaluate the effectiveness of the chosen ground water control techniques.

The format of this chapter includes conceptual explanation of the recommendations and a proposed research, development, and testing program for implementation of the recommendations. Table 6-1 summarizes the recommendations and includes development and testing costs and suggested time schedules.

In an effort to respond most effectively to the needs of practicing engineers and contractors, the preliminary manuscript of this chapter has been reviewed by expert consultants with experience in all phases of tunneling design and construction. Critical comments, opinions and recommendations have been obtained from experts in the field of tunnel design, tunnel construction, tunnel dewatering, ground water hydrology and exploratory test boring. Their comments have been incorporated into the present text.

6.2 DIRECT PERMEABILITY MEASUREMENT SYSTEM

6.2.1 General

The recommended hardware and methodology are intended to satisfy the following criteria:

1. Development of standardized hardware and procedures.

TABLE 6-1. SUMMARY OF RECOMMENDATIONS FOR IMPROVED DIRECT MEASUREMENT OF PERMEABILITY

RECOMMENDATION	CONCEPT	JUSTIFICATION	IMPLEMENTATION
1. Borehole Permeability Probe	A simple, inexpensive borehole permeability test which minimizes testing errors and standardizes testing procedures.	Present borehole permeability tests often yield inconsistent and misleading information. A simple, accurate and standardized borehole permeability test is clearly needed.	Implementation of the Borehole Permeability Probe and Perforated Casing Permeability Test requires a development and testing program costing about $95,000 and requiring about 18 months to complete.
2. Perforated Casing Permeability Test	Consists of incorporating a section of special perforated casing into the casing string of a standard cased test boring. By sealing the bottom of the casing, infiltration and/or drawdown permeability tests could be performed.	Existing borehole permeability tests as well as the proposed Borehole Permeability Probe tests only a small zone of soil. The Perforated Casing Permeability Test, which could be conducted quickly using present boring methods and tests a relatively large zone of soil, offers considerable promise.	
3. Large Scale Pumping Tests	Consists of modifying and standardizing present methods of large scale pumping tests to serve the specific needs of tunnel design and construction.	A large scale pumping test is considered the most reliable method for measuring overall permeability. However present methods have been developed specifically for assessing the water supply potential of an aquifer. There is a need to modify these methods to suit the problems of tunnel design and construction.	Implementation of the Large Scale Pumping Test and the Full Scale Dewatering Field Test will require a research and development program costing about $58,000 and requiring about 12 months to complete.
4. Full Scale Dewatering Field Test	Consists of a full scale field test of the anticipated dewatering system.	The cost of a limited number of ejector wells, well points and/or deep wells installed in conjunction with observation wells in critical areas of the tunnel could be more than offset by fewer construction problems and delays.	

TABLE 6-1. SUMMARY OF RECOMMENDATIONS FOR IMPROVED DIRECT MEASUREMENT OF PERMEABILITY - Continued

RECOMMENDATION	CONCEPT	JUSTIFICATION	IMPLEMENTATION
5. Improved Theoretical Methodology	Consists of the development of computer techniques to analyze geohydrologic data assess the impact of groundwater on tunnel design and construction, and predict dewatering requirements.	There is a definite need to develop more sophisticated analytical technology in order to make optimum use of the improved geohydrologic data.	Implementation of Improved Theoretical Methodology and Data Bank will require a research and development program costing about $154,000 and requiring about 24 months to complete.
6. Data Bank	Consists of the creation of a data bank to store and analyze the predicted and actual performance of ground water related design and construction on completed projects.	Field performance data are essential to validate new technology. Without this substantiation, new technology would be too academic for the practitioner.	

2. Elimination of the various limitations and disadvantages of the currently used hardware.

3. Hardware and techniques for measurement of the permeability of small zones of soil (less than 3 feet in vertical extent), measurement of moderate size zones (5 to 15 feet in vertical extent), and measurement of the overall permeability of the entire aquifer system.

4. Hardware which utilizes, as far as possible, current drilling techniques and proven technology in order to minimize the expense and difficulty of implementation.

5. Development of necessary analytical technology in order to make optimum use of the resulting permeability data.

6. Development of confidence in both the permeability data and the analytical technology, through a systematic documentation of predicted and actual field performance of groundwater related problems on tunneling projects.

7. Development specifically for design and construction problems associated with tunneling.

The recommendations include six specific areas for improved hardware and methodology as discussed below. Although beyond the scope of this study, laboratory testing must be included in any subsurface investigation program. The data from laboratory testing of representative boring samples provides the engineer and contractor with invaluable information to supplement direct in-situ measurements.

6.2.2 Borehole Permeability Probe

Current practice in subsurface explorations for urban tunnels includes taking of numerous test borings along the proposed tunnel route. A standardized borehole permeability test could be developed and implemented in a short period of time without requiring significant changes in current subsurface exploration practices.

There are numerous borehole permeability test methods presently available, but no standardized hardware or procedures have been developed. Due to inherent problems in the hardware, procedures, and theoretical analysis of test results, the available borehole techniques often yield inconsistent and misleading information. A simple borehole device, developed especially for use in cased boreholes, along with more convenient testing procedures, is clearly needed.

A conceptual sketch of the proposed hardware, is shown in figure 6-1. In essence, the device consists of a porous tipped probe coupled with a packer assembly. The probe would connect to standard drill rods and could be driven and/or jetted into the soil at the bottom of a standard cased test boring. By injecting water into the probe, a falling and/or constant head infiltration test could be performed. The packer allows for sealing off the casing against upward flow during infiltration testing. The primary advantages of this test are testing below the zone affected by wash water siltation and testing a zone of known geometry. Specific features of the test system will include:

1. The system will be compatible with existing boring techniques and equipment.
2. The test will be performed quickly at minimal cost.
3. The porous filter can be easily interchanged in the field as soil conditions dictate.
4. Flow boundaries will essentially be known and not affected by drilling operation.
5. The packer assembly and porous filter will be one unit and will connect directly to standard drill rods. The pressure line to the packer will be in the annular space between the drill rods and the casing.
6. Field trials will be conducted to evaluate the proper method of installation and to develop a standard testing procedure.

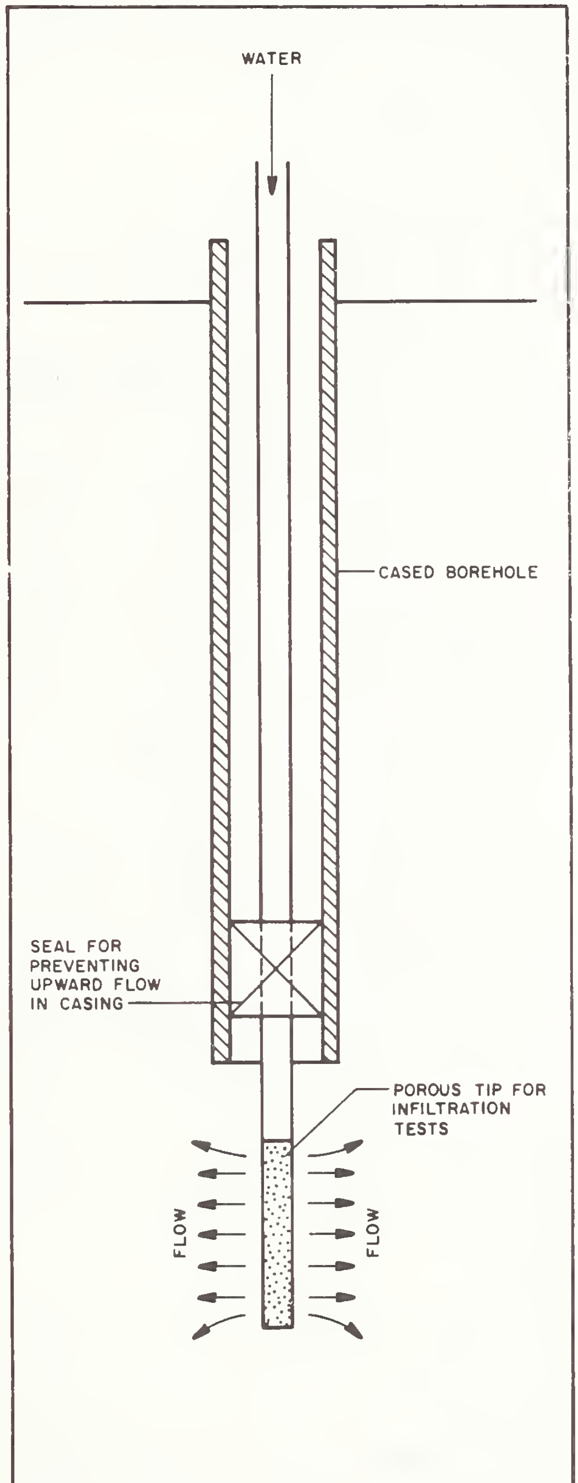


Figure 6-1. Conceptual Sketch of Borehole Permeability Probe.

7. Laboratory model tests will be conducted to study the imposed flow pattern and develop solutions for calculating permeability values.

6.2.3 Perforated Casing Permeability Test

Existing borehole permeability tests, as well as the proposed borehole permeability probe, test a relatively small zone of soil. A perforated casing permeability test, which can be conducted quickly using present boring methods and which will test a relatively large section of the soil stratum, is proposed. As with the borehole permeability probe, development and refinement of this concept offers considerable promise for upgrading in-situ soil permeability measurement. A sketch of the proposed hardware is shown in figure 6-2. In essence, the hardware consists of a section of special perforated casing which can be sealed at the bottom. This casing would be incorporated into the casing string of a standard cased boring and driven down as the hole is advanced. Specific features of the test will include:

1. Special casing will mate with currently used casing and become part of a standard cased borehole. By using more than one section, the length of the perforated casing could vary as conditions dictate.
2. The test will be performed quickly at minimum cost, though at greater cost than the borehole permeability test.
3. The casing will allow for a seal at the bottom; this would not have to be a packer type seal, but rather could be a simple gravity seal, either within or below the casing.
4. The size of perforations will be selected in the field as soil conditions dictate.
5. Flow boundaries will essentially be known and not affected by drilling operation.

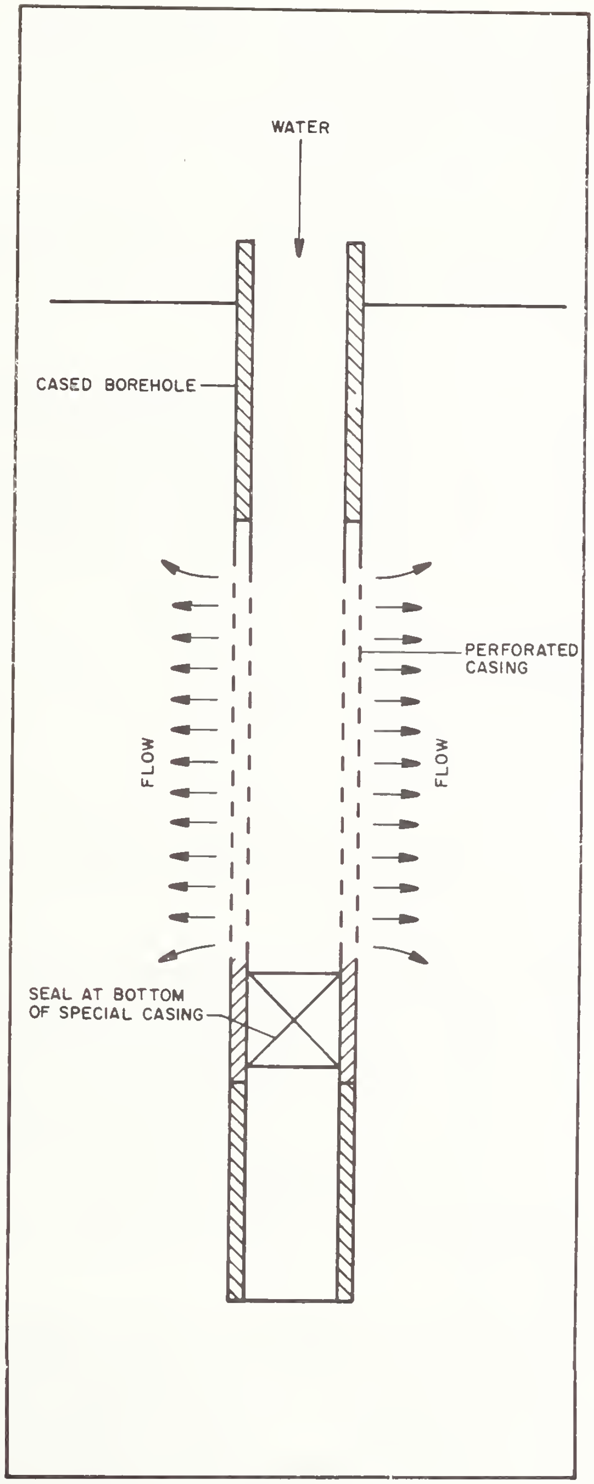


Figure 6-2. Conceptual Sketch of Perforated Casing Permeability Test.

6. Infiltration tests, either constant head or falling head, could be conducted through the perforated section. A drawdown test could also be conducted in lieu of or in conjunction with infiltration tests.

7. Since the special casing will be behind the lead section, strata boundaries and material types will be known beforehand and the test locations chosen with this knowledge in hand.

8. The test could be used to measure the overall permeability within the specific zone of the proposed tunnel. This information would be of value particularly when complete dewatering is not contemplated. The data could be utilized to predict inflow into the tunnel, and feasibility of grouting.

9. Field trials will be conducted to evaluate the proper method of installation and to develop a standard testing procedure.

10. Laboratory model tests will be conducted to study the imposed flow pattern and develop solutions for calculating permeability values.

11. The perforated casing permeability test could be utilized in conjunction with the borehole premeability probe to give a complete log of permeability. Tests with the borehole permeability probe would be made at the bottom of the casing and would measure the permeability of small zones, while the perforated casing test would measure the overall permeability of larger zones between the probe test locations.

12. By incorporating flow meters which measure the flow at specific sections within the perforated casing, it may be possible to determine both the permeability of individual strata and overall permeability with one test. Thus the perforated casing test could eventually replace the borehole permeability test.

6.2.4 Large Scale Pumping Test

Currently the large scale pumping test is considered the most reliable method for measuring the overall permeability of a soil stratum. A great deal of information concerning large scale pumping tests is available in the literature. However, large scale pumping tests have been developed for purposes of assessing the water supply potential of an aquifer. The factors affecting water supply, although similar, are not necessarily the same as the factors affecting the design and implementation of a dewatering system for tunnel construction. Thus, it would be desirable to modify the methods of performing large scale pumping tests to better suit the problems of tunnel design and construction.

It is recommended that a modified large scale pumping test be developed to better serve the specific needs of tunnel design and construction. Modifications should give consideration to the following criteria:

1. Standardized equipment and procedures.
2. Better assessment of drawdown and recharge rates.
3. Better assessment of the cone of influence and effects of overlapping cones of influence.
4. Assessment of permeability at various levels within the well in addition to the overall permeability.
5. Assessment of the changes in required pumping rate as an aquifer is dewatered.
6. Better assessment of drawdown effects on local structures.
7. Better assessment of recharge schemes.

Details of modifications in hardware and procedures are beyond the scope of this study. A research, development, and testing program, as outlined in paragraph 6.3 and detailed in appendix D2 would be required to make specific recommendations and finalize the modified hardware and testing procedures. Preliminary suggested modification might include:

1. Changes in number and placement of observation wells.
2. Instrumentation of the well to measure flow at various levels within the well. This has been attempted and has met with some success, but further studies are warranted. The information could be used to improve assessments of variations in permeability with depth.
3. Placement of a cluster of two or more closely spaced small diameter wells to improve assessment of the influence of overlapping cones of influence.
4. Changes in pumping procedures to improve assessment of drawdown and recharge periods. This might include a sustained test in conjunction with alternate intervals of pumping with intervals of recharge.
5. Improved non-equilibrium test procedures to limit adverse affects of drawdown.

6.2.5 Full Scale Dewatering Field Test

A logical extension of a modified large scale pumping test would be a full scale field test of the anticipated dewatering system. The consensus among many dewatering contractors is that more information is obtained in the first few days of actual construction than can be learned by extensive use of borings and permeability test results. The cost of a limited number of ejector wells, well points and/or deep wells installed in conjunction with observation wells in critical areas of the tunnel route could be more than offset by a lower dewatering bid price and fewer construction problems and delays. Therefore, it is recommended that consideration be given to full scale field testing of dewatering systems to be paid for by the owner and analyzed by the design engineers. The information would then be supplied, in detail, to bidders. Due to the relatively high cost of full scale field tests, the tests would only be performed in very critical areas and/or in areas where dewatering predictions are likely to be unrealistic.

The details of a full scale field test are beyond the scope of this report. A research and development program as outlined in paragraph 6.3 and detailed in appendix D2 would be required to make specific recommendations concerning the design and installation of dewatering test sections, when such a test section would be warranted, what data should be recorded, and how best to present the results.

6.2.6 Improved Theoretical Methodology

A basic finding of this study has been that little use is currently made of sophisticated methods of analyses. This may be due to lack of adequate geotechnical data commensurate with the complexities of such analyses. The recommendations in paragraphs 6.2.2 through 6.2.5 have been developed to provide adequate geotechnical data. There is a need to develop analytical technology in order to make optimum use of such geotechnical data.

It is believed that the use of computer techniques offer promise for analysis of geohydrologic data, assessment of the impact of groundwater on tunnel construction, and prediction of dewatering requirements. Currently such work is being performed in the area of groundwater supply, thereby enabling groundwater hydrologists to predict well yields, drawdown and recharge characteristics, and overall effects on the groundwater regime. Computer techniques offer the great advantage of considering the complexities and anomalies in groundwater conditions and stratigraphy which exist in nature. Closed form analytical solutions are restricted by their assumptions, and usually can only solve problems involving simple uniform subsurface conditions.

It is recommended that computer techniques be developed to analyze dewatering schemes. These techniques should have the capability of treating:

1. Soil stratigraphy, groundwater conditions, and soil permeabilities as inferred from subsurface explorations.
2. Various dewatering methods including well points, deep wells and ejector systems with various spacing, sizing, depth and pumping rates.

3. Dewatering schemes involving limited regional drawdown through the use of recharge wells.

4. Predictions of the rate of drawdown, changes in required pumping rates as water is lowered, and steady state condition.

5. Prediction of shape and extent of drawdown.

6. Effects of rainfall infiltration, bodies of water, possible "leaky" utilities, or other man-made impacts.

7. Rate of recharge after dewatering is terminated.

The application of computer technology would enable design engineers and/or contractors to compare various schemes readily, to improve assessments of effects of construction, and plan construction procedures more accurately. Detailed development of such technology is beyond the scope of this study, and requires a research and development program as outlined in paragraphs 6.3 and detailed in appendix D3.

6.2.7 Data Bank

As with any new hardware device or theoretical methodology, field performance data is essential to validate new technology. This is particularly significant when technology is available for utilization by contractors to estimate costs and construction procedures. Without a high confidence level, new technology would be too academic for the practitioner. Therefore, it is recommended that a data bank be established to store and analyze predicted and actual performance of groundwater control efforts on completed projects, in conjunction with related geotechnical data. The information would be stored and analyzed using computer techniques in conjunction with technology to be developed as discussed in paragraph 6.2.6 above.

It is recommended that collection of all pertinent data would be a requirement on federally funded projects. A standardized report would be completed and filed with an appropriate agency by the engineers responsible for design and construction supervision of the tunnel. The standardized report would include:

1. Subsurface information obtained prior to and during construction.
2. Details of the design related to groundwater and permeability.
3. Documentation of the construction of the tunnel pertinent to groundwater and permeability.
4. Other pertinent data which may have affected the construction such as rainfall records, river levels, tide records, etc.
5. General comments on the overall dewatering effort.
6. Estimated and actual costs of dewatering including claims for changed conditions sought by the contractor.

The information would be utilized to compare theoretical predictions with actual performance, to assess the validity of the subsurface exploration program, and to determine causes and possible predictions of "unforseen" conditions. Details of the data bank are beyond the scope of this study. A research and development program as outlined in paragraph 6.3 and detailed in appendix D3, is required.

6.3 PROPOSED RESEARCH, DEVELOPMENT AND TESTING PROGRAM

6.3.1 General

Paragraph 6.2 includes conceptual recommendations for improved direct measurement of permeability and development of techniques for expanded use of such data. The implementation of these concepts will require a phased development and testing program. The intent would not be to make major technical advances in the fields of groundwater hydrology and soil mechanics, but rather to develop a program that could be implemented on actual projects within a three to five year period and be of practical significance to the tunneling industry. Due to similarities between required areas of expertise and field testing requirements, the six specific areas for improved hardware and methodology have been combined into three recommended programs. These programs are outlined below and specified in detail in appendix D.

6.3.2 Hardware Development and Testing of a Borehole Permeability Probe and Perforated Casing Permeability Test

The requirements of the borehole permeability probe and the perforated casing permeability test have been developed in sufficient detail for the immediate initiation of a fabrication and field testing program. The specific purposes of the program will be to:

1. Design and fabricate the necessary hardware.
2. Conduct detailed field testing of both devices.
3. Conduct laboratory model testing and analytical evaluation of the devices aimed at studying the imposed flow patterns and developing solutions for calculating permeability values.
4. Develop a manual specifying standardized installation procedures, testing techniques and data analysis, develop guidelines for appropriate implementation of the tests on tunnel projects, including estimated user costs.

Appendix D1 outlines the specific task requirements for the proposed program. It is estimated that the program will cost approximately $95,000 and require about 18 months to complete, as detailed in appendix D1.

6.3.3 Research and Development of Large Scale Pumping Test and Full Scale Dewatering Field Test

Development of a modified large scale pumping test and full scale dewatering field test will make use of current hardware and testing techniques. Thus, extensive hardware fabrication and field testing will not be required. Rather the development of these tests and their implementation will require a detailed research and development program. The specific purposes of this program will be to:

1. Assess present large scale pumping test methods and currently used tunnel dewatering techniques.

2. Develop a modified large scale pumping test to better serve the needs of the tunnel industry.

3. Determine the need, justification, and requirements for performing full scale field testing of the anticipated dewatering system.

4. Develop a manual for each test, specifying standardized installation procedures, testing techniques, and data analysis. Develop guidelines for appropriate usage of these tests on tunnel projects, including estimated user costs.

Appendix D2 outlines the specific task requirements for the proposed program. It is estimated that the required program will cost approximately $58,000, and require about 12 months to complete, as detailed in appendix D2.

6.3.4 Research and Development of Improved Theoretical Methodology and Data Bank for Groundwater Related Design and Construction of Soft Ground Tunnels

The implementation of improved theoretical methodology and data bank will require a research and development program. The specific purposes of this program will be to:

1. Review and evaluate present computer technology relating to groundwater hydrology.

2. Develop computer technology to analyze geohydrologic data, to assess the impact of groundwater on tunnel construction and to assess various dewatering schemes.

3. Develop the technology for collection, analysis, and presentation of actual field performance data relating to the improvement of predictions of groundwater related tunnel design and construction.

4. Develop computer software, procedures for data collection, and specific detailed recommendations for continual updating of information, data retrieval, and data presentation.

Appendix D3 outlines the task requirements for the proposed program. It is estimated the required program will cost approximately $154,000 and require about 24 months to complete, as detailed in appendix D3.

6.4 RECOMMENDED DEVELOPMENTS - BOREHOLE GEOPHYSICAL LOGGING TOOLS

6.4.1 General Discussion of Indirect Methods

Surface Surveys Evaluation of geophysical surveys of interest to soft ground tunneling problems shows that the seismic methods are most used, offer the greatest development potential, and require lowest time-effort costs to develop. The electromagnetic techniques offer the next rank of feasibility if ground conditions are suitable and if the limitations of the resistivity approach are taken into account. There appears to be no particularly strong developmental potential in resistivity and the method offers very limited information unless accompanied by other survey techniques. All other methods have unique application to one soft ground parameter, or are not generally useful.

The primary development effort in the seismic methods should be in the area of increasing the frequency and input power of the seismic source for shallow, soft-ground surveys. The detecting/recording/analyzing/display techniques have been highly developed by the minerals industry, but energy sources which provide sufficient high frequency energy compatible with urban environmental requirements are lacking. Increased energy is required for greater penetration of high frequency signals, higher frequencies are required to improved resolution of subsurface conditions.

Subsurface Surveys Seismic surveys in the subsurface again rate high in this evaluation, but a bias in the evaluation of the methods decreases the attractiveness for improvement and innovation.

Direct borehole (uphole or crosshole) survey techniques have been used by the minerals industry extensively and by the engineering community as well. Developments which offer significant potential gains in cost, usefulness, or uniqueness of results are not evident. High rating in the seismic method as evaluated here is also related to the category I (use by engineering community) as opposed to development potential.

Sonic or acoustic methods also rate high, but borehole requirements and some physical conditions in the subsurface materials can limit the utility of the method considerably. Optional use of the sonic method requires an uncased, fluid-filled borehole in relatively non-porous materials (porosity no greater than about 25% or void ratio no greater than about 0.3). These considerations lead to placing the sonic method low on a priority list of development for soft ground use, but high in terms of usefulness for specific tunneling conditions where the ground is more compact then inferred by "soft-ground" terminology.

In general, the nuclear methods of borehole geophysics offer the greatest potential for development to a more useful tool. Major reasons include the range of borehole conditions which can be tolerated, and familiarity in the engineering community in their current status. Careful development will not only provide information about the most important engineering parameters, but may also lead directly toward unique determination of some of the lower ranked parameters as well. With the exception of the pulsed neutron borehole tool, most of the nuclear devices are already efficiently packaged in small diameter tools and several types of logs may be obtained simultaneously in a single borehole logging run. Development of the pulsed neutron tool and some innovation in analytical techniques should be the development goals.

Along with the nuclear methods, borehole surveys based upon inducing electromagnetic fields in the subsurface materials are next in line of versatility and development potential. The standard "focused" induction logs offer relatively deep penetration beyond the borehole wall, and either dry, non-conductive fluid, or mud-filled boreholes may be logged by the induction method.

A special use of induced reaction in the material around the borehole is provided by the "nuclear magnetism" induction log. The principles are the same as a proton precession magnetrometer, but the "mobility" of hydrogen ions in the subsurface materials may be inferred and the amount of free water estimated by use of this method. This is the most valuable of all borehole tools in having potential for measuring critical factors related to in-situ permeability in the subsurface. Again, tool development and analytical technique improvements have strong potential for providing accurate information for soft-ground needs.

Following nuclear and electro-magnetic techniques in a borehole, the various borehole resistivity methods are next in the line of importance according to this evaluation. These are the oldest of indirect borehole techniques and their efficiency is well established. Developments in analytical techniques have only moderate potential for improving use of such logs, but the results from their use may be essential to interpretation of other surveys. Most critical among the electrical tool developments is the need for an accurate, versatile, small-diameter dipmeter/caliper tool with a capability to expand to large dimensions for continuing measurement in washouts without losing contact with the borehole wall.

The other borehole surveys listed, excepting visual, gravimetric, and thermometric logs may be obtained from the tools described above. These three exceptions are not considered especially useful nor do they show much potential for development toward the soft-ground tunneling problems.

6.4.2 Recommended System

A count of the outlined elements in tables 5-3 and 5-4 strongly suggests that borehole geophysics is the appropriate direction to follow for improvement in subsurface investigations for this program: Twice as many method-parameter pairs with high potential and low-cost rankings in borehole methods are shown in the tables compared to surface methods. Further, the borehole methods have potential use in explorations for all five of the most important soft-ground parameters and show some rating for ten of the fourteen geotechnical parameters listed. Only seven of the fourteen are indicated in the surface technique evaluation.

A system comprised of several borehole tool packages with surface data processing is therefore recommended as the highest-return, lowest-cost geophysical approach for subsurface geotechnical explorations. Many of the tools are already available and could be tested now in soft ground: some require modification mainly in tool dimensions or logging configuration.

The package of tools recommended for general use in explorations includes:

A1. Pulsed neutron
A2. EM Nuclear Response
A3. Focused Induction
A4. Microlog Dipmeter/Caliper
A5. Neutron-epithermal neutron

Tools for all of the above are currently available, but none meet the requirements of capability in small diameter boreholes. Additional tools to complete the package are already of a size satisfying the dimensions required, but require some modifications for optimum logging results (compensated tools):

B1. Gamma-gamma

Other tools belonging to a comprehensive package, but with no particular development requirements are:

C1. Sonic/Acoustic
C2. Visual/visual Imagery
C3. Natural gamma, Spontaneous Potential
C4. Neutron-thermal neutron/gamma

The "A" group of tools can be tested in large diameter boreholes at present (6-1/2 inches), while the "B" and "C" groups can be utilized in small diameter boreholes (3 inches), to provide basic data for full evaluation.

Combination of Logs for Geotechnical Parameters Since the different types of borehole logs represent the response of different physical parameters in the surrounding soil strata, the combination of measurements at a particular location in the borehole provides a method for placing bounds on interpretation of what each measurement represents. The interpretation is usually based on "logical" geotechnical possibilities in the subsurface to narrow ambiguity in any one logging technique. Secondary parameter values inferred from the combination log interpretation are the basis of the resulting geotechnical profile.

Logging results are essentially precise, but unless careful calibrations are made, the results may be inaccurate. The common method to alleviate this problem is to use standard test boreholes available at various institutions so that each particular logging tool output can be set at an output voltage level representing a known physical parameter value (void ratio, bulk density, borehole diameter, etc.). Each logging system must be calibrated periodically for this purpose to insure that the "logical" possibilities of subsurface conditions from the log are not strongly biased away from real physical conditions. Carry-along calibration standards are also often available for tools which have been in use beyond the developmental state.

Virtually all of the borehole logs may be used alone to provide geometrical strata maps of soil boundaries and stratigraphic units by correlations from borehole to borehole. A combination of logs adds a confidence factor to such correlations, especially if the logs respond to different physical characteristics. Similarity of each log response from borehole to borehole also makes a continuation of strata type from borehole to borehole possible, and subtle changes in the level of strata response to logging operations can be utilized to determine changes in the characteristics of a particular stratum.

A few simple combinations of different logs can also provide accurate measurements of the subsurface parameters. Actual bulk density of the strata (in lbs/ft^3) may be determined from the gamma-gamma log, providing that the system response is previously calibrated by measurement on samples of known density. Given the bulk density from the log and a value of the density of the particles forming the strata (most commonly dominated by quartz grains in the soft-ground case), the void volume in the strata can be calculated. Similarily, for most materials, sonic velocities and attenuation rates can be related to relative dry porosities. Use of the sonic logs can be applied for porosity estimates if signal attenuation rates are not too extreme.

A log indicating hydrogen content (neutron logs) to infer water volume can be calibrated for response to water by simply obtaining a response while the downhole tool is in a tank of water (equaling 100% saturation). The amount of volume indicated as containing water is usually water in the void space, and percent saturation is indicated. If the volume of voids is essentially the same as the volume of water indicated, total saturation exists.

With the two logs above, then, a continuous vertical profile of bulk density, porosity, the presence and degree of saturation by ground water, and some inferences regarding stratigraphy (clays, clean sands) are available. Lateral continuation by correlation with similar logs from nearby boreholes can be used both to indicate the presence of the same strata (from consistent profile patterns) and changes in numerical value of these parameters from borehole to borehole.

Following these logs, permeability of the saturated strata can be indicated by either induction or electromagnetic nuclear response logs. Electrical conductivity in the subsurface is dominated by the presence and degree of mineralization of saturating fluids. If the saturation is present and a high conductivity is measured, the inference is that saturation exists in the void spaces and that interconnected saturated voids are present to conduct the electrical currents. Interconnected voids are directly related to permeability, and the absolute bulk conductivity values are controlled by the amount of saturated interconnections in the strata. Interference in the accuracy of these measurements by clays with adsorbed ions may be bypassed by using the slower logging rate electromagnetic nuclear response technique that does not respond to adsorbed ions. In fact, the difference between these two logs can serve as a measure of the amount of adsorbed ions.

Gross permeability is also indicated by the thickness of mud filtrate buildup on the borehole wall, or absence of the filtrate. The thickness is a factor measurable with the microlog dipmeter/caliper tool. Permeability of a stratum is sometimes a function of clay content: in those cases where naturally-occurring radiogenic minerals are present, the ratio between amount of clay and radioactivity level is constant enough to measure the clay content from radioactivity levels measured by the natural gamma logging technique. General stratigraphic components are also indicated by natural gamma logging, since radiogenics are relatively rare in clean sands and gravels.

For parameters more directly related to actual subsurface excavation/construction activities, those logs providing chemical and physically tangible measurements extend the usefulness of the borehole observations. Chemistry of components of the subsurface strata contribute both to knowledge of the reasons for permeability conditions if the mineralogy of cementing agents is identified: ability to demonstrate degree and type of cementation is an important factor in judging both difficulty of excavation, and resistance to collapse in an unsupported face. Neutron activation and spectrometric logging offer this possibility, and the possibility of identifying the chemistry of the strata, gases, and fluids as well.

The microlog dipmeter/caliper log and the visual or visual imagery logs are more direct in providing some information about the problems above. Profiles of the degree of washout in the borehole, collapse zones, fractures, large voids, and even gross grain size distributions are measured or even visually displayed to indicate those situations which will be encountered in a tunnel.

Combinations of the logs are required to describe subsurface parameters in as much detail as feasible: feedback corrections among the logs to refine the logging results for more accuracy is a general rule in most logging situations. Specific ground conditions indicate which set of logging techniques will satisfy minimum requirements, and these may also clearly show methods that offer no information at a particular site. The tools recommended are intended to encompass as much of typical soft ground as possible, and to offer as many redundancies as reasonable for a versatile and realizable system.

Data Display and Processing Each logging tool output, with some hard-wired signal conditioning, needs to be monitored during a logging run to insure that it is operational and to provide a log for preliminary analysis and guidance for subsequent runs. On-site visual logs must be considered a minimum requirement in the final system. Hard-wired processing consists of simple electrical circuits to modify the voltages or counts for analog strip chart recordings.

The raw or partially processed tool outputs also need to be recorded on magnetic tape for further processing, combination log analysis, and eventual permanent storage. In the interest of space and versatility, digital data recording is strongly recommended. Digital computer processing of the multiple log outputs provides the degree of adjustment, cross-correlation, and displays most useful in the interpretation of the borehole logging data anticipated.

At present, processing of the digitized data at an off-site computer center appears the most feasible approach for multiple log analysis. Development of analytical computer programs, correlation and calibration techniques, and conversions to meaningful engineering parameters are most easily accomplished at a centralized location. The eventual goal of the development program should be the mobile-on-site computerized analytical system that can provide immediate results for planning and design.

Processing of logging data is one of the more critical aspects of the recommended program. Considerable sophistication in multiple log interpretation presently exists for hard formation analyses:

transference of the technology to the soft-ground environment and modifying the techniques for this specific use offers very high potential benefits in engineering use of the data. Advances in computer hardware also offer the potential for a field-worthy on-site system which greatly enhances probability of acceptance of the results by a broad cross-section of those concerned with all aspects of tunneling.

6.5 RECOMMENDED TEST AND DEVELOPMENT PROGRAM - GEOPHYSICAL TOOLS

Since some of the techniques recommended in the comprehensive borehole logging system are at a stage in development where they are already useful, a parallel program of Test and Development is feasible. A parallel program provides for evaluation of factual signal processing developments early in the program, thereby enhancing the opportunities for an optimum system within a three year time frame. The basic logging methods may also all be tested because most tool developments are directed toward changing the physical dimensions of devices; the characteristics of outputs from available instrumentation can be fully evaluated in larger diameter boreholes than recommended for the final system requirements.

a. Tasks to be accomplished in the test and development program (see figure 6-3) should include:

1a. Development of computerized analytical programs to interpret all anticipated logging outputs and interpret combinations of the outputs in terms of useful engineering parameters.

1b. Selection of soft ground tunneling projects that are in an investigation stage or will be in a stage suitable for obtaining detailed geotechnical information for comparison with logging results from (2).

2. Field test existing tools and techniques, including those requiring large diameter boreholes, to verify concepts and aid in defining processing requirements.

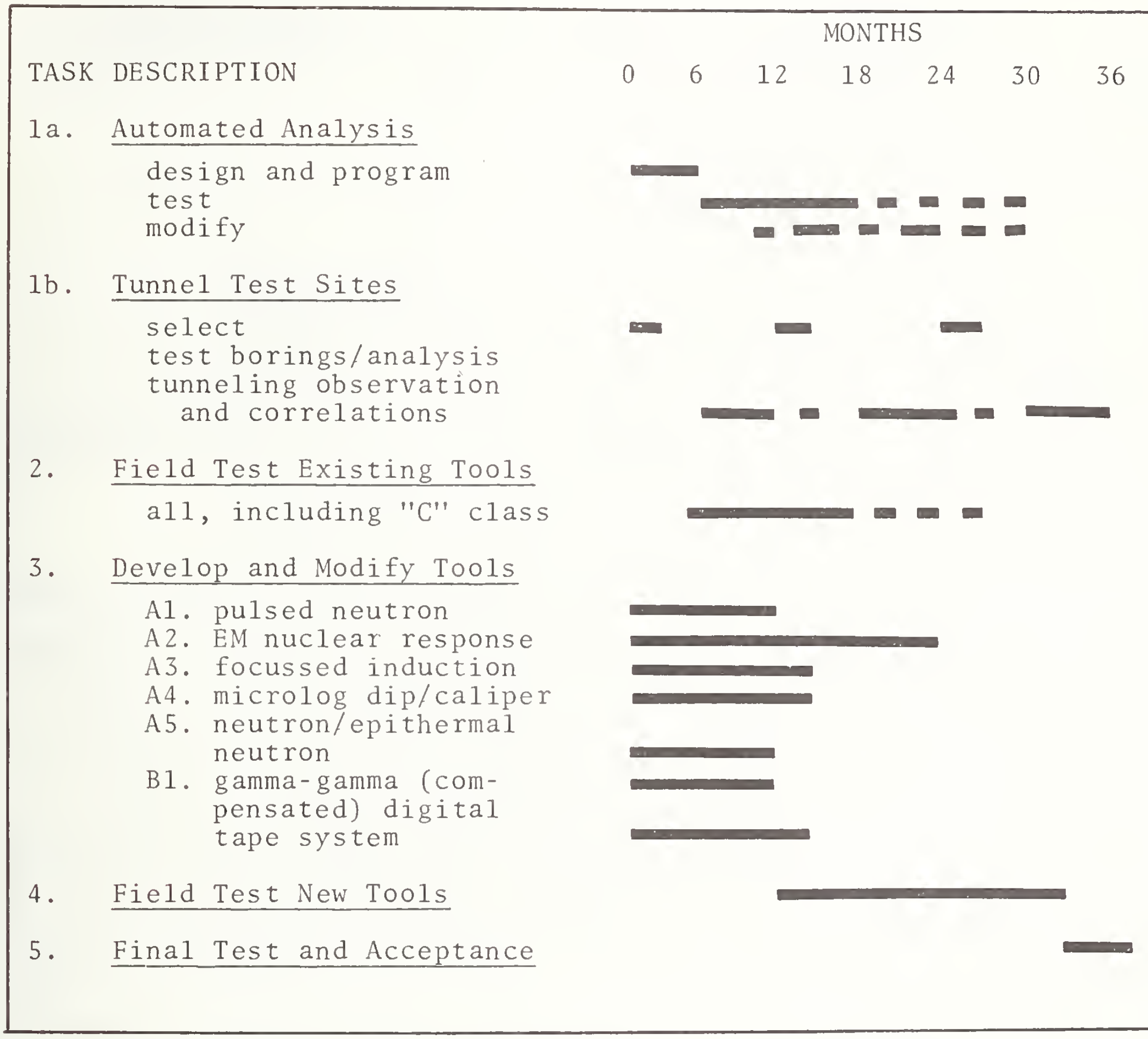


Figure 6-3. Tentative Test and Development Program. Borehole Geophysical System for Soft Ground Geotechnical Explorations.

3. Development and modification of recommended tools to dimensions suitable for logging in NX sized boreholes (2.25" maximum tool diameter).

4. Test and verify status of developed and modified tools as they become available.

5. Final test and acceptance of total system.

Tasks 1, 2 and 3 may be conducted almost simultaneously, with some planned lag in 2 and 3 to permit basic structuring of the computer programming requirements, and test site selections. Task 4 is accomplished in the continuing test program as tool developments are completed.

The entire program recommended above is intended to make efficient use of the technology at hand by comparing logging results with standard geotechnical observations to establish the value of the concepts early in the program. This step is paralleled by initial development efforts according to projected requirements that can be redirected or emphasized on the basis of factual information gained as the program progresses. A primary goal of carefully correlating boring and laboratory geotechnical data with logging data and observation of actual tunneling conditions can be satisfied by approaching the required test and development in this way.

b. Time and Effort. A tentative time and effort scheduling for completion of a Test and Development program is also shown in figure 6-3. The various tasks recommended above are given in more detail on the figure to show the breakdown of estimated efforts for each. Estimated costs for each are shown in table 6-2. These do not include consideration for travel required, computer time, general and administrative costs, fee/profit, or contingency, but are intended to reflect estimated laboratory analysis and materials costs.

TABLE 6-2. ESTIMATED EFFORT/BUDGET FOR TEST AND DEVELOPMENT

Borehole Geophysical System for Soft Ground Geotechnical Explorations.

		Estimated man/months	and/or	Total Estimated Costs* (thousands)
Task 1a.	Automatic Analysis			
	design and program	18		72
	test	28		112
	modify	6		24
Task 1b.	Tunnel Test Sites			
	select	6		24
	test borings/analysis	12		90
	tunneling observations	12		48
	and correlations	24		96
Task 2.	Field Test Existing Tools			75
Task 3.	Develop and Modify Tools			
	A1. pulsed neutron	36		185
	A2. EM nuclear response	114		275
	A3. focussed induction	42		105
	A4. microlog dip/caliper	24		60
	A5. neutron epithermal neutron	30		75
	B1. gamma-gamma (compensated)	30		75
	digital tape system			75
Task 4.	Field Test New Tools			100
Task 5.	Final Test and Acceptance			100
	Total Estimate Cost, Three Year Program			$1581

*Estimated costs include design/develop/laboratory analysis/materials, etc., but exclude travel, computer time, G&A, fee/profit, or contingency.

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