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IMPROVED DESIGN OF TUNNEL SUPPORTS: EXECUTIVE SUMMARY

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16. Abstract This report focuses on improvement of design methodologies related to the ground-structure interaction in tunneling. The design methods range from simple analytical and empirical methods to sophisticated finite element techniques as well as an evaluation of tunneling practices in Austria and Germany. The purpose of this report is to provide the tunneling profession with improved practical tools in the technical or design area. These design tools provide more accurate representations of the ground-structure interaction in tunneling.

The Executive Summary is the first of six publications to be published on the Improved Design of Tunnel Support. Volumes 1 through 5 will be published in March, 1980. This Executive Summary summarizes improvements in the methodology available to tunnel designers with the objective of reducing the cost of tunnel construction in the United States. This report summarizes each of the five volumes. Volume 1: Simplified Analysis for Ground-Structure Interaction, describes a simplified analysis method, which incorporates the effects of relative stiffness, face-support distance, and ground yielding on ground-structure behavior; Volume 2: Aspects of Yielding in Ground-Structure Interaction, addresses the effects ground yielding has on ground-structure interaction; Volume 3: Finite Element Analysis of the Peachtree Center Station in Atlanta, reports the application of a three-dimensional finite element analysis of an Atlanta, Georgia station; Volume 4: Tunneling Practices in Austria and Germany; and Volume 5: Empirical Methods for Rock Tunneling--Review and Recommendations, examines empirical methods in tunneling and provides a guide to the advantages, limitations, and applicability for the best known empirical methods.

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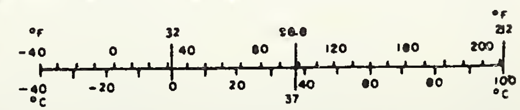
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

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

Approximate Conversions from Metric Measures

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



PREFACE

The uncertainties associated with the design and construction of transit tunnels have resulted in inflated construction costs which include sizable margins for error to reduce the risk of tunnel construction for contractors. The Urban Mass Transportation Administration (UMTA) through a series of contracts to universities and private engineering firms has attempted to improve existing design methodologies, construction techniques, and contractual arrangements in order to reduce the associated risks and produce more cost-effective tunneling for transit and other tunneling applications.

This contract with the Massachusetts Institute of Technology (MIT) focuses on improvement of design methodologies related to the ground-structure interaction in tunneling. The design methods range from simple analytical and empirical methods to sophisticated finite element techniques as well as an evaluation of tunneling practices in Austria and Germany. The information contained in these six publications will be invaluable to tunnel designers and constitutes a major step toward more cost-effective tunneling.

We would like to acknowledge contributions made by members of the project review board: Messrs. R. Beale, H. Casp, G. Fox, T. McCusker, H. Parker, and H. Sutcliffe. In addition to the authors, several undergraduate students worked on the project notably B.K. Low and E. Whitbeck.

Finally, the information retrieved in Europe was possible only with the generous help provided by our colleagues. They are individually mentioned in Volume 4.

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1. INTRODUCTION

This six volume series of reports presents the results of a one and one-half year effort sponsored by the Urban Mass Transportation Administration (UMTA), U.S. Department of Transportation (DOT), under Contract No. DOT-TSC-1489. The work reported here is a part of ongoing systematic research to improve tunnel design and construction that began with the tunnel Cost Model and with studies under grant OS-60136, Office of University Research, DOT. Improvement of tunnel design and construction through this research is achieved by advancing specific technical, operational, and contractual aspects of tunneling and, in particular, by employing these advances to integrate the entire tunnel design-construction process. As indicated in previous work and as documented in these reports, major improvements leading to more economic tunneling must come from integration of the entire tunneling process. Nevertheless, in order to provide the tunneling profession with some practical tools as early as possible, the research is structured such that the investigations of the individual components not only contribute to the overall integration of the tunneling process, but also produce results that can be applied directly and independently. The nature of these individual components were previously identified (Einstein, et al., 1977). Specifically, they are: (a) improvements in analytical and empirical methods to be used during design and construction, (b) procedures for better decision making and cost assessments in all phases of the tunneling process (planning, design, construction planning, and construction), and (c) contractual details that will lead to more economical tunnel construction. The decision-making procedure will, in addition to its direct use, serve as the framework for improving the tunneling process and fully incorporating other new advances into this process. During the research, strong but not exclusive consideration is given to observational methods, since some of these methods have already achieved considerable integration of the tunneling process and have incorporated some innovative individual components. Many of the technical and economic advances in European and particularly in Austrian and German tunneling practices can be traced to the use of observational methods as an approach toward cost effective tunnel design and construction.

The goal of this research is far-reaching and encompassing. For this reason, and because the results not only benefit transportation tunneling, it is a long-term effort supported by two government agencies: UMTA and the National Science Foundation (NSF). In order to have identifiable research tasks under each sponsorship, the technical or design oriented aspects are supported by UMTA under the aforementioned contract (period January 15, 1978 - August 1979), while the operational and contractual aspects, as well as the overall effort to improve the tunneling process, are funded by NSF under grant DAR-7709116 (period March 15, 1978 - March, 1979). Since the UMTA-sponsored research started first, it included an information collection trip to Austria and Germany. This trip produced information on the technical aspects of European tunneling practice, and on the overall tunneling process for transportation tunnels in both urban and mountainous environments; thus, this trip served as a basis for the NSF-funded project.

The purpose of this report, which documents the results of the UMTA-supported research, is to provide the tunneling profession with improved practical tools in the technical or design area. These design tools provide more accurate representations of the ground-structure interaction in tunneling. They range from simple analytical and empirical methods to sophisticated finite element techniques, thus reflecting the practical differences in input information and output requirements of the various phases in the design-construction process. Also, some findings on integration of the tunneling process are reported, and practitioners are given detailed descriptions and evaluations of tunneling practice in Austria and Germany. Throughout the report, contributions to a better understanding of ground-structure interaction, including several specific new developments, are made.

Volume 1 describes a simplified analysis method, geared toward hand calculations, that incorporates the effects of three of the most significant factors influencing the ground-structure behavior: (1) the relative stiffnesses of the ground and support, (2) the distance between the face and the point of support installation, and (3) yielding of the ground mass. The method is intended for use in preliminary design, for parametric studies in final design, and for updating the design during construction.

Volume 2 addresses a specific aspect of ground-structure interaction, the ill-understood and controversial topics of ground yielding and loosening, and reports new findings in this area. It is based on previous research, on the knowledge gained during the development of the simplified analysis and the application of the more sophisticated finite element techniques, and on specific studies of strain softening ground behavior. It should be emphasized, however, that many developments and discussions in Volume 1 and 3 (introduced below) also contribute to improved understanding of the ground-structure interaction around tunnels.

Volume 3 reports the application of the three-dimensional finite element program ADINA to the Peachtree Center Station in Atlanta. In particular, the excavation sequences for the

Atlanta research chamber and the main station cavern are simulated and the instrument readings are predicted. This application of the three-dimensional finite element model is intended to illustrate some of the advantages and limitations of such methods when used for design or to compare predicted with measured movements. The latter objective has not yet been achieved due to problems with the monitoring program.

Volume 4 documents and evaluates the information gathered in Austria and Germany. A large number of transmountain tunnels (Austria) and subway tunnel sections (Germany) were visited, and many discussions were held with owner-authorities, design firms, and contractors. The report provides a detailed review of technical, operational, and contractual aspects of Austrian and German tunneling practice and discusses the reasons why tunneling there is often more economical and technically innovative than it is in the U.S.

Volume 5 evaluates empirical methods in tunneling. This evaluation provides the practioner with a guide to the advantages, limitations, and especially the ranges of applicability for the best known empirical methods. In addition, improvements are made to arrive at empirical approaches best suited to observational methods.

The executive summary provides the reader with extended abstracts of each of the aforementioned volumes.

2. SIMPLIFIED ANALYSIS FOR GROUND-STRUCTURE INTERACTION IN TUNNELING

This simple, design-oriented analysis method has been developed for determining the loads on tunnel supports. It is generally intended for circular tunnels with closed-ring primary support systems in ground masses that can, for practical purposes, be treated as time-independent continua. The method is also aimed at tunnels that are excavated full-face under free air at depths greater than about two tunnel diameters. Examples of practical tunneling situations suitable for analysis using the simplified method include--but are not limited to--circular steel ribs, prefabricated segmented liners, continuous shotcrete supports in soil, heavily jointed rock, and massive rock formations.

It is doubtful that the complex interrelationships among the nearly countless variables in any tunneling problem can ever be rigorously analyzed, even using the most sophisticated numerical techniques. As an alternative approach, the simplified method focuses on the essential elements of very complicated physical phenomena in order to isolate the few major factors that have an overriding influence on the support loads. These three major factors are explicitly considered: (1) the relative stiffness of the support and the ground mass, (2) the spatial lag or delay of support construction behind the tunnel face, and (3) the yielding of the ground mass as its shear strength is exceeded. The method is structured where each of these major factors is handled in a separate step, with subsequent steps building on the preceding ones.

Step 1. Relative Stiffness

The effects of relative support stiffness on the tunnel support loads is incorporated into the simplified analysis through closed-form relative stiffness solutions. These solutions assume: (1) plane strain conditions, (2) elastic behavior for the ground and support, and (3) simultaneous excavation and support of the tunnel. They explicitly consider the effects of the support stiffness and the ground stress conditions (the lateral in situ stress ratio, in particular) on the support thrusts, moments, and displacements at all points around the circumference of the opening. However, they do not consider the effects of support delay and ground yielding; these effects are treated in subsequent steps of the analysis. The loads calculated from the relative stiffness solutions can be considered as the "basic" loads in the simplified method.

The input parameters required for this step of the simplified analysis method are:

- Elastic constants (Modulus and Poisson's ratio) for the ground and for the support.
- Geometry of the support (radius, cross-sectional area and moment of inertia).
- In situ stress field (vertical and lateral stresses).

Some of these parameters are used to calculate the dimensionless stiffness ratios for the ground-support system, the compressibility ratio, C*, (a measure of the circumferential stiffness), and the flexibility ratio, F*, (a measure of the flexural stiffness). The circumferential support thrusts are primarily related to C* and the support bending moments, to F*; decreasing values for C* and F* imply an increasingly stiffer support (or softer ground).

The analysis considers the two limiting conditions "full-slip" and "no-slip" for the shear transfer at the ground-support interface. Also, and very importantly, the correct "excavation unloading" condition for tunnels is incorporated into the solution, i.e., the tunnel is excavated in an initially stressed ground mass. The results from the analysis are the support thrusts, bending moments, and displacements at any point around the circumference of the tunnel. These quantities can be easily calculated either by hand or with a programmable pocket or desk-top calculator; program documentation for a Hewlett-Packard HP97 calculator is provided.

From parametric studies, the following conclusions can be drawn regarding the sensitivity of the thrusts and moments to variations in the input parameters:

(1) Thrust is strongly dependent on C^* only within the range $0.05 < C^* < 50$ and is relatively insensitive to variations of F^* (for practical values of F^*)

(2) Moments are near zero for $F^* > 100$ and are insensitive to variations of C^*.

(3) For excavation unloading conditions, both thrust and moments are insensitive to variations in Poisson's ratio for the ground.

(4) Thrusts and moments vary linearly with K.

The overall bending moments due to the nonuniform in situ stresses are usually small; support moments due to factors like faulty erection, inadequate blocking, or incomplete grouting are usually more critical. The tunnel designer must check for these "local" critical moments in his particular support system.

Step 2. Support Delay

Support delay refers to the spatial lag of support construction behind the tunnel face. Increasing the support delay usually decreases the tunnel support loads. The reduction of the support load can be represented by the multiplicative support delay factor λ_d:

$$T_2 = \lambda_d T_1$$

$$M_2 = \lambda_d M_1$$

in which T_1, M_1 are the thrusts and moments derived with the relative stiffness solution in Step 1 and T_2, M_2 are thrusts and moments corrected for support delay, Step 2 of the analysis.

The primary input parameter in this step is the normalized support delay length, L_d/R. The delay length L_d is defined as the distance between the face and the midpoint of the leading active support element.

The relationship between λ_d and L_d/R was determined from parametric finite element studies for K=1 stress conditions:

$$\lambda_d = 0.98 - 0.57\,(L_d/R)$$

Based on physical consideration, λ_d varies between the extremes of 1.0 (no support delay effect) and 0 (full support delay effect). The equation can be used with reasonable accuracy for values of L_d/R greater than approximately 0.15 and less than about 1.5.

If in addition to the ground movements arising from the support delay there are other ground movements that develop before the support contacts the ground (e.g., from an incompletely grouted tailpiece void behind a shield), these must also be incorporated into the delay factor λ_d. Defining u_o' as these additional pre-support ground movements and u_f as the total elastic radial displacement of the wall of an unlined tunnel, the support delay correction factor is expressed as:

$$\lambda_d = 0.98 - 0.57\left[\frac{L_d}{R}\right] - \frac{u_o'}{u_f}$$

The factor λ_d is still limited to the range $0 \leq \lambda_d \leq 1$.

The sensitivity of λ_d to $K \neq 1$ stress conditions was investigated using a modified plane strain relative stiffness solution that approximately models the effects of support delay. Based on the analyses for both K=1 and $K \neq 1$ conditions some general conclusions can be drawn about the applicability of λ_d:

1) λ_d can be used with reasonable accuracy to modify both support thrusts and overall bending moments.

2) λ_d is substantially independent of the relative support stiffness, as expressed by C* and F*.

3) λ_d is independent of the lateral stress ratio, K.

The support delay correction factor λ_d is a very important parameter in the analysis. Unfortunately, it is also a parameter that is very difficult to calculate in practice. The support delay length L_d in a real tunnel is usually only approximately known; small variations in blocking or grouting procedures, for example, may significantly move the point at which the support becomes "active" --i.e., comes into contact with the ground.

Step 3 Ground Yielding

Yielding in the ground mass surrounding the tunnel tends to increase the support loads. The quantitative effects of this yielding were investigated using both axisymmetric and plane stress elasto-plastic finite element analyses. A ground yield factor λ_y was devised to represent the effects of ground yielding:

$$\lambda_y = \frac{P_s^*}{P_s'}$$

The term P_s' is the equilibrium support pressure in the elastic ground case, reduced for the effect of support delay, and P_s^* is the support pressure in the yielding case; P_s^* includes the effects of both support delay and ground yielding. The yield factor λ_y has a physical lower limit of 1 (corresponding to completely elastic ground behavior) but no upper bound.

The third step in the simplified analysis method, then, is the calculation of λ_y. This factor is primarily a function of the strength parameters of the ground mass, although it is also indirectly dependent upon the support delay and the relative support stiffness. The input parameters required for this step are:

- The input parameters for Step 1 (elastic constants for support and ground, geometry of support, and stress state)
- The support delay factor from Step 2
- Strength (or yield) parameters for the ground, e.g., c (cohesive strength parameter) and ϕ (frictional strength parameter)

The yield factor can be calculated from approximate plane strain plasticity solutions. These solutions can be easily programmed on a pocket or desk-top caluclator; program documentation for a Hewlett-Packard Model HP97 is provided.

Because of the interactions among the relative support stiffness, support delay, and ground yielding variables, λ_y will be indirectly dependent on C* (and F*) and λ_d; this fact was substantiated by the findings from the axisymmetric finite element analyses. The primary purpose of the plane stress finite element analyses was to investigate the sensitivity of λ_y to variations in the lateral stress ratio K. The principal conclusions from these analyses were:

1) For small to moderate amounts of yielding (λ_y less than or equal to 2, approximately), λ_y is reasonably insensitive to variations in K between 0.5 and 1.5. As the level of yielding increases, this range for K decreases; at very high levels of yielding, λ_y can only be calculated for K=1.

2) The insensitivity of λ_y to variations in K is the same whether the yielding is due to low ground strength properties or a long support delay, or both.

3) λ_y is not significantly affected by the shear transfer conditions at the ground-support interface.

4) Stiff supports will generally produce values for λ_y that are small and reasonably independent of K.

The calculations of λ_y represents the final step in the simplified analysis method. The support thrust, which is proportional to the magnitude of the pressure P_s^*, is calculated as:

$$T^* = \lambda_y \lambda_d T$$

In this equation T is the "basic" thrust from Step 1; it includes the effects of relative support stiffness and the lateral stress ratio. The term λ_d is the support delay factor from Step 2; this factor, which is independent of the support stiffness and the lateral stress ratio, modifies T for the effects of support delay. The last term, λ_y, is the ground yield factor from Step 3; this factor, which is a function of the ground strength, relative support stiffness, and support delay but which is independent of the lateral stress ratio, at least for small amounts of yielding, modifies $\lambda_d T$ for the effects of ground yielding. The term T* is then the final design thrust.

In order to verify the accuracy of the simplified analysis method, it was applied to five tunnel projects (a total of 11 tunnel sections) reported in the literature in which the actual support loads were measured during construction. These cases span a representative range of tunneling situations for which the simplified analysis is applicable. Two of the case studies are tunnels in soft rock and three are in soil (various types of clay). The supports in the case studies include steel ribs, precast concrete segments, and cast iron segments; several hand and machine excavation systems are also represented.

Given the streamlined, approximate nature of the method, it was surprisingly accurate in predicting the support loads measured in the case studies. The errors in the predicted support thrusts ranged between the extremes of -79% (unconservative) and +62% (conservative). However, for 7 of the 11 tunnel sections analyzed, the errors varied between the more limited bounds of ±30%. On the whole, there was a slight conservative bias in the predictions.

In all, the simplified analysis method is an appropriate and accurate design technique in many types of tunneling situations. It reduces the tunneling problem to its bare essentials, capturing the fundamental aspects in a few variables. Since the method does require only a few, relatively easily determined input parameters, it is very simple to apply. No large computers are needed, as they are for the more sophisticated numerical techniques; the support loads can be readily computed using simple desk-top pocket programmable calculators. However, the engineer must be aware of the deviations between the actual and the assumed conditions and, as in any practical engineering problem, judgement and ingenuity must be exercised when applying this simplified analysis to an actual tunnel design. Nevertheless, since the support loads can be computed with little effort, the simplified analysis is perfectly suited for parametric sensitivity studies when designing for uncertain conditions. This computational ease, coupled with accuracy sufficient for any practical tunnel analysis, makes the simplified analysis method a valuable and effective design tool.

3. ASPECTS OF YIELDING IN GROUND-STRUCTURE INTERACTION

The present research on improved design procedures for tunnel supports, as well as preceding and parallel research on underground construction and rock and soil behavior, has led to a better understanding of ground-structure interaction. Studies on ground-structure interaction were an integral part of the review of observational and analytical methods for tunneling reported previously (Einstein et al., 1977). These studies were intensified during the development of the simplified analytical method (Vol. 1 of this report), the three dimensional numberical analysis of the Atlanta Research Chamber (Vol. 3), and the review and extension of empirical methods (Vol. 5). They also benefited substantially from the review of tunnel design and construction procedures in Austria and Germany, since the application of the principles of ground-structure interaction has been a significant factor responsible for the advances in tunneling practice in these countries.

Improved understanding of ground-structure interaction has led to and is implicitly contained in the specific technical developments presented in this series of reports. The design profession may benefit, however, from a more basic review of ground-structure interaction in tunneling, particularly if a better understanding of some of the complex phenomena and an insight into some controversial aspects can be provided. Previous work (Chapter 8 in Einstein et al., 1977) attempted to review the entire ground-structure interaction phenomena and to highlight the most important factors, which were then taken into consideration in the development of analytical and empirical methods (Vols. 1 and 5 of this report). The discussion in this volume concentrates on a particularly complex and often ill understood aspect of ground-structure interaction, that of ground yielding. In addition to providing the reader with some basic concepts that will increase his understanding of ground yielding, this report will also describe and compare analytical solutions for plastic ground behavior.

The excavation of an underground opening leads to an increase of the shear stresses acting on elements at or near the surface of the opening. If these increased stresses lead to yielding, two major types of ground behavior can be visualized. As the ground is excavated, the stresses acting on the circumference of the future opening (the virtual "internal pressure") approach zero. The corresponding strains may increase beyond the elastic limit, eventually reaching a large but finite value. The unsupported opening will be stable, albeit with possibly unacceptably large displacements. Alternatively, the strains may initially increase beyond the elastic limit as described above, but instead of stabilizing at some point, they will increase even if the stress at the circumference (internal pressure) is kept constant or actually raised. This phenomenon is commonly referred to as <u>loosening behavior</u>, and it has been the subject of intense discussion and dispute among tunnel designers.

This report attempts to clarify this problem by first examining possible conceptual mechanisms and then by applying analytical methods to study their quantitative effects. The most obvious mechanism is that of strain softening ground behavior. Such behavior may, in some circumstances, lead to increasing internal pressure with increasing strains, i.e., to loosening. However, it can be shown conceptually that the occurrence or non-occurrence of loosening behavior depends strongly on the assumed material behavior, i.e., the precise relation between strength deterioration and strain. As a consequence, some of the existing analytical methods that model loosening are inconsistent. We therefore developed a closed-form solution for predicting displacements, strains and stresses around a circular opening in a strain softening medium. The solution is based on the following idealizations: 1) plane strain; 2) in situ principal stresses are equal, 3) gravity effects are neglected; 4) material obeys the Tresca yield criterion; and 5) the ground mass behavior can be represented by a linear three-segment stress-strain relationship, namely elastic, strain softening and perfectly plastic segments. Extensive parametric studies with this analytical method did not produce any loosening behavior. The often advanced opinion that strain softening ground <u>necessarily</u> leads to loosening is thus incorrect; nevertheless, it still cannot be concluded that strain softening never leads to loosening.

Loosening can also be examined using the concept of a stable ground arch around the tunnel. Given a certain displacement at the opening circumference, a ground arch will form at a certain distance and the ground between the arch and the opening can be held in place by a certain counterpressure. If the displacement at the opening circumference is increased, the ground arch will form at a greater distance from the opening, more ground between this arch and the opening has to be held in place, and the counterpressure has to increase--i.e., loosening occurs. The concept is appealing and can be substantiated by some simple models like Rabcewicz's shear body and an extension of Terzaghi's arching theory. Analytical approaches that model the stable ground arch mechanisms described above do not seem to exist; in practical terms, the only situation that approaches such a mechanism is the behavior of a blocky rock mass in a low stress field.

The purpose of the above-mentioned analysis method for strain softening ground goes beyond the examination of loosening behavior. It, and the graphs developed from the parametric study, is intended to give the designer a convenient tool to investigate various characteristics of strain softening behavior, for instance the magnitude of the stress drop. Using the analysis, the designer can easily develop ground characteristic curves and determine the extent of yield zones, information that can then be used to determine ground-structure interaction as it is described in Volume 1 of this report series.

The reader will thus obtain from this volume a better understanding of ground-structure interaction, especially of some aspects of ground yielding. In addition, an analytical tool for treating strain softening behavior is provided.

4. FINITE ELEMENT ANALYSIS OF THE PEACHTREE CENTER STATION IN ATLANTA

In this volume, the application of the three-dimensional, 3-D, finite element program ADINA to the Peachtree Center Station in Atlanta is described. The study is intended to shed some light on the practical usefulness of 3-D finite element methods. In particular, it was intended to show where such methods have an advantage over simpler ones and to determine what efforts and costs are involved. To be practically meaningful, such a study had to be conducted for an actual case, even if this meant a loss of generality. The Atlanta Research Chamber at the Peachtree Center Station provided a good opportunity for this study for three reasons: (1) it involved a relatively complex geometry; (2) the ground conditions were well established through thorough testing; and (3) the extensive monitoring program would make comparisons between predicted and actual behavior possible. The prediction of the ground movements and stresses caused by the enlargement of the pilot tunnel to form the test chamber and by the excavation of the main station cavern were of particular interest in the study. Plots of calculated stresses and deformations were generated in a form suitable for practical comparisons with instrument readings.

Before starting the analysis, some slight modifications of ADINA were necessary, and pre- and post- processor programs with plotting routines were developed to construct the finite element mesh and to produce the output in practically usable form. A three-dimensional mesh consisting of 1093 3-D isoparametric elements and 2915 nodal points was devised to model the geometry of the research chamber, the running tunnels, and the adjacent part of the main cavern, including two major side drifts. Elastic isotropic material properties and an anisotropic stress state were found to reasonably approximate the real conditions. The finite element model simulated the research chamber enlargement and the main station excavation; the ground deformations and stresses were determined at each step in this simulation. The major findings regarding the ground deformations are:

- The rock mass displacements are very small. At the walls of the main station cavern, the rock displacements reach a maximum of 0.025 inches radially and 0.06 inches longitudinally. At the walls of the research chamber, the respective movements are 0.0048 and 0.018 inches. These small displacements are a consequence of the low deformability of the rock and the comparatively low in situ stresses.

- The excavation of the main station cavern induces relatively large longitudinal movements in the rock surrounding the research chamber. The research chamber does not tilt measurably in the longitudinal plane as a consequence of the main station cavern excavation; instead, it settles uniformly.

- The comparisons between rock displacements measured during the excavation of the pilot tunnel and movements predicted by this analysis are unsatisfactory. The discrepancies in these results may be due either to the use of incorrect rock mass properties and in situ stresses in the analysis or to malfunctions of the field instruments resulting from excessive blasting. More field measurements are needed to determine the exact causes.

- Comparisons between the predicted and measured movements due to the research chamber enlargement cannot be made for two reasons: (1) the excavation sequence employed by the contractor was different from the one originally planned by the designer and assumed in this analysis, and (2) no measurements are yet available from the research chamber instruments.

Regarding the stress state in the rock mass, the 3-D analysis shows that:

- The maximum compressive stresses around the openings are low, relative to the strength of the rock mass.

- A tensile stress zone forms at the south wall of the main station cavern which may cause problems, such as excessive overbreak, during construction of the running tunnels at this location. In addition, radial tensile stresses form at the flat parts of the main station cavern's crown, sidewall, and invert.

- In the transverse cross-sections through the research chamber, the major and minor principal stresses are approximately tangential and radial with a maximum tangential stress concentration (relative to the in situ vertical stress) of about two.

In addition to the specific predictions discussed above, this study has shed some light on the use of three-dimensional finite element analysis as a tool in the analysis and design of underground structures. Several features of the analysis and results could not have been modelled or predicted using two-dimensional finite element model:

1. The complex geometry of the station.

2. The longitudinal in situ stresses. In the 2-D model, these stresses are dictated by the plane strain assumption. In the 3-D model, the measured values of stresses are incorporated into the analysis. These longitudinal stresses have an overriding effect on the instrument movements, and they are also largely responsible for the tensile stresses at the south wall of the main station cavern.

3. The excavation sequence. Because of the plane strain assumption, the 2-D model cannot include any effects from the main station cavern excavation.

4. Inclinometer movements. Because the inclinometers are approximately located in the longitudinal plane of symmetry, a 2-D model is incapable of predicting their movements.

The effectiveness of the 3-D finite element analysis for design is constrained by the significant time and high cost required to prepare the input, conduct the analysis, and interpret the results. However, this cost is not usually a major limitation when compared to the total cost of a subway station. For example, for this case it is estimated that the computer and manpower cost of a 3-D analysis would represent a maximum of 0.25% of the total project cost. In cases where ground-structure interaction in complex geometries must be modelled, the potential design savings will very likely outweigh these analysis costs.

5. TUNNELING PRACTICES IN AUSTRIA AND GERMANY

Information on European tunneling practice has been collected and evaluated and is documented in Volume 5. Since the documented material is so voluminous, an extended summary is necessary.

The information was received from the literature obtained during a trip to Austria and Germany in January 1978, and from professional contacts in Europe. Without the generous and continuing assistance of many professional colleagues in these countries, it would not have been possible to write this report. The assembled information covers cost (economical), contractual, and technical aspects of tunneling. This report, as well as this summary, will be structured along these lines. However, as seen in this summary and the report, there is significant interaction amongst these aspects and the role that integration of these aspects plays is one of the major findings of this study.

Cost information consists of: general cost data and costs of specific tunnels in Austria and Germany; studies conducted in Germany in which various effects on subway tunneling costs were investigated; similar, but less extensive, investigations on the data collected by the authors and a cost comparison between the U.S. and Europe.

The major factors affecting construction costs of shallow and deep tunnels are: ground conditions, material availability, site accessability and other restrictions, market conditions, and size (cross-sectional area) of the tunnel. Ground conditions affect shallow and deep tunnels differently; consideration of surface effects in shallow tunnels leads to a more conservative design and thus higher costs than for deep lying tunnels in the same ground. The effect of market conditions has been illustrated dramatically during the past few years. Tunnels of the same size and located in similar, or less favorable, ground have recently been bid, or completed, at the same or up to 20% lower prices than five years ago, mainly due to increasing competition in a somewhat depressed economy. Very important in this respect is the possibility that contractors can submit alternate proposals in addition to, or instead of, bidding for the official design. This permits the contractor to adapt design and construction to his expertise, crew capabilities, and equipment, and thus optimize his approach. One result, which is probably due to a combination of market conditions, the possibility of submitting alternate proposals, and the restrictions in inner cities, is the price equivalence of open-cut and mined tunnels in such locations.

Tunneling costs per lineal unit in the U.S. seem to be between 30 and 80% higher than in Europe for mined tunnels and 100 to 300% for stations; the cost per unit volume is between 50 and 100% greater. Major causes for this difference seem to be the smaller support quantities, smaller crew sizes, flexible equipment, and a substantial, if not full, integration of design and construction.

<u>Contractual information</u> is based on a detailed review of contractual standards and procedures in Austria and Germany and of contractual setups at individual projects. This is supplemented by opinions of owners, engineers, and contractors and a consideration of recent and future developments in the contractual area. In addition, special attention is given to payment and incentive aspects, as well as to dispute settlement procedures.

The first impression that one gains in reviewing contractual standards and procedures in Austria and Germany is that the recommendations of the report "Better Contracting for Underground Construction" (National Academy of Sciences, 1974) are standard practice; even more important, however, is how these procedures are realized in all phases of design and construction. Most notable are the detailed contractual and technical standards according to which the specifications, schedules, and bids have to be prepared. Although there are national standards, the individual owners have the possibilities to modify them. The detailed contractual and technical provisions (amongst the technical provisions there is frequently a detailed ground classification) facilitate adaptation during construction. These detailed provisions, together with the usual unit price bidding, make it possible to cover all contingencies by assembling bid items corresponding to the actual design construction procedure for the particular contractor, ground conditions, and other boundary conditions. Thus, rather than making the design-construction procedure rigid, the detailed setup seems to make it more flexible. In most cases, these procedures also spell out in detail how disputes have to be settled; usually through mediation-arbitration or through an administrative appeal process. The inherent flexibility, the dispute settlement procedures, and a very careful legal preparation, and naturally also the riskier European trial procedures*, make court cases very rare (for instance, there were only two court cases in Munich, where 30 km of subway tunnels have been constructed so far).

Payment is usually for work performed based on a very detailed price system. Since "all possible" conditions have been anticipated in the bid and contract documents, payment can be uniquely established. The aforementioned dispute settlement procedures take care of most remaining disagreements. It is important to realize that the payment system is not a simple cost reimbursement. Considerable incentives are built-in to make it financially interesting for the contractor to work carefully, particularly by letting the contractor reap the full benefit of effective construction procedures. Contractors have significant possibilities in this respect due to the partial or full integration of design and construction.

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*The losing party has to pay the court and trial costs of the winning party.

Technical information consists of general information on design philosophy and construction procedures and of detailed information on analytical and empirical methods and on design aspects. In addition, crew and equipment aspects in construction-planning and execution are also discussed. A substantial part of the technical information involves data on geotechnical conditions and related performance of tunnels. Most important in the technical areas is the fact that, in one sense or another, only alternate proposals are actually constructed and that these proposals include considerable changes compared to the owner's official design and construction procedures. The extreme consequence is the situation in Munich where the specifications basically provide only the alignment and required cross-section (and references to the detailed contractual and technical standards) and where the contractor performs the detailed design and construction planning. This integrated design-construction approach is facilitated by the usual in-house design capabilities of the contractor, and it assures the most effective use of the contractor's expertise, crews, and equipment. The liberal use of alternate proposals or even full design construction approaches does not involve technical risks since any design has to be examined and approved by a designated inspection engineer. Since the official design, which is usually prepared by the owner's staff, also has to be approved in this manner, no extra time or cost is involved in accepting alternate proposals.

In addition to the integration of design and construction, it is very significant that design is flexible and construction procedures are adaptable. In this context, ground classification systems that relate geotechnical conditions to design and construction procedures are frequently used. The adaptation is practically achieved by assigning appropriate ground classes. Flexible design and adaptable construction procedures lead to considerable economic benefits where there is a great variety of tunnel shapes and sizes in shallow tunnels and in uncertain ground conditions in deep tunnels. A prerequisite for the successful use of design flexibility and construction adaptation, and proper conservation of safety aspects, is the extensive use of performance monitoring during construction. The advantage of flexibility is reflected in the fact that, at the time of information collection in Munich, the somewhat less flexible shield tunneling is only economical if the tunnel length is greater than 1400 m. Below this length, the possibility of having several points of attack and the liberal use of mobile equipment in non-shield tunnels overcome the higher production rates of a semi- or fully mechanized shield. The emphasis on flexibility is also obvious in the preference of several pieces of smaller equipment instead of a single, highly productive piece. This permits the contractor to easily adapt the procedures to varying conditions and to have redundancy in his operations that increases the overall productivity. The technical and related contractual conditions are not only reflected in the design and construction approaches in general, but also in the fact that practically every new tunnel or tunnel section has innovative design and construction features. All this is only possible with the generally outstanding quality of the personnel, from the owner's staff to the miners in the tunnel.

As far as analysis methods are concerned, some interesting details of finite element methods have been developed in Germany. In general, the analysis methods are not advanced and they have not been fully integrated in the design-construction approaches. This can be explained by the presence of personnel on all levels who have a great amount of experience and are using it effectively. Nevertheless, a trend toward greater use of analysis can be observed.

Finally, in the context of technical information, it was possible to receive two large sets of geotechnical and performance data from the Tauern and Arlberg Tunnels. Together with data from several mountain and subway tunnels, they will serve as a basis for improving empirical design approaches and will make possible realistic sensitivity studies with analytical methods.

What has been summarized above is discussed in detail in the text and the appendixes of this volume. It seems useful to conclude this summary by emphasizing the major findings on tunneling practice in Austria and Germany.

- Technical, contractual, and cost (economic) aspects are closely related. The lower tunneling costs compared to the U.S. are to a significant extent due to contractual setups that make technical innovations and contractual changes easily possible.

- Most important amongst the contractual conditions seems to be the possibility of submitting alternate proposals that allow the contractor to use his expertise, personnel, and equipment most effectively.
- The contractual and technical documentation as well as the bids are so detailed that most conditions can be anticipated, work performed correspondingly, and payments made without dispute.
- The three items above show that flexibility in contractual procedures is the underlying philosophy that in turn makes flexibility in design and construction possible. This flexibility exists on many levels from the overall design to the adaptation of detailed construction procedures; in the latter it is frequently based on well developed ground classification systems.
- The technical and contractual flexibility is the prerequisite for the most important finding, the integration of design and construction. The most significant cost and time savings and technical innovations have been achieved by fully considering construction aspects in design. This is reflected in the technical features of design and construction as well as in the contractual setups of particular projects.

6. EMPIRICAL METHODS FOR ROCK TUNNELING
REVIEW AND RECOMMENDATIONS

The complexity of ground and structure behavior and particularly of ground-structure interaction in tunneling makes it difficult to understand the underlying principles. Consequently behavioral models are only approximate and analytical predictions that have to be based on such models are either generally inaccurate or accurate over very limited ranges of application. Empirical methods that avoid the use of an explicit model by relating ground conditions to observed prototype behavior have thus always played a major role in tunneling. As a matter of fact, the relative significance of empirical methods in tunneling is much greater than in any other civil engineering area. Interestingly, the last few years has seen the creation of additional empirical methods. As knowledge and understanding of tunnel behavior increases analytical methods will become more accurate provided the input parameters can be determined at a corresponding level. However, given the usual limitation in parameter determination it can be foreseen that empirical methods will continue to be used in tunnel design albeit at a reduced level.

In reviewing tunnel design practice and establishing areas that need improvement it became readily apparent that empirical methods had to be considered. There is understandable uncertainty amongst designers and contractors as to what method to use. Comparative predictions made with different methods lead to substantially different results. Some methods require a minimum of easily determinable parameters and others require a large set of relatively complex ones. Some methods are based on qualitative descriptions of the soil and others are highly quantitative. Subjective assessment by the user may be required or not. This list could be further extended to show that - deciding on a suitable empirical method may be a difficult task. An additional problem arises in the context of this research project and report series. With the exception of the empirical procedure for the New Austrian Tunneling Method (NATM) none of the methods fully integrate design and construction.

It was decided that the tunneling profession could gain considerably from a systematic review of the best known empirical methods for rock tunneling. The review describes the correct application procedure of each method; it compares each empirical method with a set of carefully determined and structured criteria and based thereupon identifies advantages and limitations of each method. This review is the main objective of the report and can serve as a guideline for tunnel designers and contractors. Nevertheless, recommendations are also made as to what requirements an empirical method should fulfill if it is to be used in an observational (adaptable) tunneling procedure - since such procedures provide at the present time an optimum integration of design and construction. Based on these requirements and the preceding review, modifications of existing empirical methods can be recommended.

Empirical methods in tunneling all incorporate the same basic structure. Ground conditions are quantitatively or qualitatively characterized in form of numerical parameters and their states or in form of verbal descriptors. Usually combinations of verbal descriptors or combinations of parameter states are grouped into ground classes - thus the term ground classification is often used in this context. These combinations of quantitative or verbal descriptors are then related to support (and excavation) requirements either directly or via rock load (support pressure).
A direct relation is, for instance, between a ground class and a certain support type and quantity (e.g., steel sets, bolts, shotcrete, concrete); the other involves applying the rock load in standard structural analysis to obtain support quantities and dimensions.

It is possible, and has been illustrated in this report, to establish criteria that any correct and practical empirical method (be it for tunneling or otherwise) should satisfy and, built thereupon, to formulate requirements that empirical methods in tunneling should fulfill. Specifically empirical methods have to fulfill several user requirements:

- they should be economical and safe; i.e. supports should not be overly conservative nor should they fail, ideally the factor of safety should be known
- they should be generally applicable and robust; i.e., a method should be applicable to a wide range of conditions

or as a minimum clearly define to what range it can be applied. Robustness means that the method should be insensitive to vagaries in judgement.

- the parameters or descriptors should be readily determinable. Before construction accessibility is limited but time is not; during construction the opposite is usually true. Methods can only be based on parameters that can be obtained under these restrictive conditions.

In addition to satisfying user requirements empirical methods have to be basically correct, they have to fulfill requirements regarding methodology and derivation:

- The underlying models should be accurate. Although not based on explicit formal models (in contrast to analytical methods) empirical methods rely on an implicit model. Such a model should represent the inherent variability of ground and construction processes as closely as possible. However, there are trade-offs, to be made. A detailed model is more accurate but requires more parameters than a simplified one. Since measurement and inference of parameters involves (statistical) uncertainty, the more (interdependent) parameters there are, the greater the uncertainty in inferences of each. Model uncertainty and parameter uncertainty have to be balanced.

- Empirical methods have to be representative and complete. If a method is based on cases in which a parameter was predominant generalization may be erroneous. All relevant influence factors have to be considered.

- The subjective character of empirical methods has to be recognized. Because models are abstractions of reality and because parameter estimates involve uncertainty no procedure for establishing support requirements can be "objective", they are all substantially subjective. Subjectivity may enter mostly on the part of the user, for instance in classifying geology, or it may enter on the part of the developer of the method in making hypotheses in test case evaluation (for instance assumptions underlying regression analysis). Subjectivity cannot be avoided and the method should clearly state where subjectivity occurs.

These requirements make it possible to assess existing empirical methods. The review of empirical methods for rock tunneling, which is the main purpose of this report considers the methods by Ritter, Bierbaumer, Stini, Terzaghi (Proctor and White), Deere, Barton et al., Bieniawski , Wickham et al. and by Louis and Franklin. For each method an extensive guideline is given, to serve two main purposes, 1) to set the stage for the review and 2) to provide potential users with information on how the method should be used. This latter point is practically very important since many methods are applied in an inconsistent and incorrect manner. The guideline does not intend to replace the background information given by the developers of the method, it rather emphasizes the necessity to carefully study the basis of whatever method one wants to use. Related to these guidelines and providing the major substance for the review is a detailed description of the development and underlying philosophy of each method. Many aspects can only be understood by examing in detail the thoughts and assumptions that went into the development. A critique is then made of each method by comparing the aforementioned requirements with the capabilities and the basis of each method.

A complete review cannot only rely on an abstract consideration of criteria but has to include a comparative application of the methods. Example applications performed by the authors of this report as well as from the literature are used for this purpose. The result of the review is a detailed description of advantages and disadvantages of each existing empirical method and a series of general conclusions:

The result of any 'tunnel design method' should be an optimum combination of support features and construction procedures for the particular ground conditions, opening dimensions and use. Due to the variety and variability of influencing factors and the interdependent character of support and construction, the problem is usually very complex. The use of analytical methods relying on prior creation of a model is thus limited. Empirical methods that relate ground conditions to tunnel design and construction are a very appropriate tool substituting for or complementing analytical methods. However, the complexity of the problem affects empirical methods also -- none of the methods completely represents all the influencing factors. This has two consequences.

- A particular method can only provide accurate predictions conditions similar to those of cases by which it was calibrated (base cases).
- Applying different methods to the same case will usually lead to different predictions.

No method is generally and consistently more accurate than others; however, optimum methods can be defined or developed for a limited range of applications. Present methods are limited in their consideration of construction procedures and of some characteristics of geologic structure.

This leads to the first conclusion:

The user has to carefully study the base cases or (as a minimum) the assumptions, comments on development and limitations formulated by the developer of an empirical method. This should be done for every application.

An accurate method should not only predict what has been done under similar conditions but what is adequate, i.e., the optimum support features and construction procedures. Empirical methods depend on base cases and since these were usually designed conservatively the empirical methods will also lead to overdesign. This can only be corrected if the degree of overdesign in the base cases is adequately known.

The second conclusion is:

Present empirical methods over-estimate support requirements; the degree of overestimation is usually not known.

While predictions of support requirements (dimensions, materials) are often not accurate for the reasons discussed above, support pressure predictions are usually even less reliable. Support pressures based on design assumptions or analytically backfigured from the design have often no similarity to the actual support pressures (ground support pressure relations have been inferred by analyses but this introduces further questions).

The <u>third conclusion</u> is:

Ground-support pressure relations should not be used unless they are based on measurements or analogous observations that include all components of ground and structure. Ground-support pressure relations may be necessary if support systems different from the base cases are to be used, but the additional uncertainty has to be taken into account.

Even if the three previous conclusions are taken into consideration and a relatively accurate method chosen, the user has to be aware that the prediction will not be precise. This is due to the inherent uncertainty of the problem caused by the variability of the influencing factors and the difficulty determining them. Precision can be improved by setting an optimum between parameter uncertainty. Since our knowledge on tunnel behavior is still limited, it seems more appropriate to rely on empirical methods whose underlying models are simple.

The <u>fourth conclusion</u> is:

Methods with a small number of parameters and a large data base per parameter may provide more precise results at present than very complex methods do.

Another consideration is always the practicality of parameter determination. Boreholes, outcrops and observations in the tunnel provide substantially different information; the time required prior to or during construction is also important.

The fifth conclusion is:

The selection of an empirical method has to reflect the availability of information on parameters and the time limitations affecting information collection.

The last conclusion relates to the subjective character of empirical methods. The inherent uncertainty and complexity of the tunneling problem makes empirical methods inevitably subjective. Subjective aspects may exist in the parameter determination by the user or in the formulation of the method by the developer or both. One relies thus in other words to varying degrees on one's experience or judgement and on that of the developer. Relying on somebody elses judgement may be wise but does not make the method "objective." Subjective character is not unique to empirical methods. In a complex problem like tunneling analytical methods cannot be built on first principles alone but also involve many subjective hypotheses.

Empirical methods are useful tools if informed judgement is applied to their use. Users of such methods might be constantly aware that the methods can be improved only by enlarging the data base and by monitoring and incorporating actual behavior in future predictions.

Although the main purpose of this report is to provide the tunneling profession with a review on empirical methods it should also give some guidelines as to what empirical methods are best suited for observational (adaptable) tunneling procedures. If necessary, existing methods have to be modified to be applicable in observational tunneling.

Observational tunneling methods integrate design and construction. Pre-construction design consists of developing a number of design alternatives for the anticipated ground conditions. During construction the appropriate design alternatives are implemented based on extensive observation of ground conditions and performance monitoring. Usually the design alternatives are further modified to optimally suit the encountered conditions. In other words support and construction procedure are physically adapted to the encountered conditions through updated empirical (very rarely analytical) relations between ground conditions and support-construction procedure. The updating is often implicit and based on judgement.

With a few exceptions, notably the New Austrian Tunneling Method, none of the existing empirical methods is readily applicable to observational tunneling procedures. It is however possible to specify requirements that empirical methods should satisfy and to describe updating procedures for these methods, such that they can be applied in observational tunneling. One has to distinguish the preconstruction and construction phase. Empirical relations prior to construction have to be based on few representative parameters (descriptors), include an assessment of uncertainty, and fulfill the standard (previously described) requirements for empirical methods. Also the simple parameters should be easily relatable to the more detailed information obtained during construction. In this latter phase a procedure has to be provided that updates the relations between ground and support (construction procedures) and between ground, support (and construction procedures), and performance. The main requirement for the updating procedure is the observation and identification of (now more detailed) ground parameters that significantly affect support (construction procedure) and performance. Based on the updated empirical relations and on observed trends in ground conditions it is then possible to predict support and construction procedure for the next round (excavation step).

Existing empirical methods are modified or combined to satisfy these requirements. For the preconstruction phase empirical methods rely now on two parameters describing ground conditions, one representing a normalized 'rock mass strength' (including strength of intact rock and discontinuities, water, stress state, and to some extent attitude of discontinuities) and one representing discontinuity spacing (including the effect of several sets and of attitude). These two parameters are related to the parameters used in existing methods. However, the "strength" parameter may require substantial judgement at the present state of the art, if it is to be directly determined. Performance predictions based on empirical relations from the literature are also made in the preconstruction phase.

During construction it is mainly necessary to systematically record and scan the information on ground conditions, support and construction procedures, and performance. This makes the identification of significant ground parameters, support characteristics and performance values possible which in turn serve to update the empirical relations. Guidelines for this updating procedure and for the required information collection and documentation are given in the report. It should be emphasized that these modifications and procedures are recommendations and not practically proven. Their main purpose is to show that empirical methods can be modified to suit observational procedures. This would have the great advantage of eliminating many of the above-mentioned limitations of empirical methods in tunnels: economy and safety, representativity, model accuracy, and correct derivation are all properly considered through updating the empirical relations and by adapting the tunneling process to fit actual conditions.

7. REFERENCES

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APPENDIX

REPORT OF NEW TECHNOLOGY

The work performed under this contract, while leading to no new technology, has led to the development of improved practical design tools to provide more accurate representations of the ground-structure interaction in tunneling. They range from simple analytical and empirical methods to sophisticated finite element techniques which satisfy the requirements of the various phases within the design construction process.