A Quarter Century of Geotechnical Research

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Research, Development & Technology
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FOREWORD

This report summarizes Federal Highway Administration (FHWA) geotechnical research and development activities during the past 25 years. The report includes significant accomplishments in the areas of bridge foundations, ground improvement, and soil and rock behavior. A fourth category included important miscellaneous efforts that did not fit the areas mentioned. The report will be useful to researchers and practitioners in geotechnology.

T. Paul Teng
Director, Office of Infrastructure
Research, Development, and Technology

NOTICE

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16. Abstract

The Federal Highway's Geotechnical Research Program was formally initiated in the 1970's. During the early 1970's, FHWA field personnel and the State Highway Agencies (SHA) recognized the need for more definitive technology for solving various soil and foundation problems. This fact, along with the stimulus of sympathetic management and funds for research, permitted the establishment of the geotechnical research program. The purpose of this report is to synopsize the program, highlighting some of the more significant findings and contributions.

This report gives an overview and summarizes the results of three geotechnical research programs. The project or program areas were; soil and rock behavior, bridge foundations, and ground improvement techniques. A fourth program area, tunneling, is outside of the research reported here and is covered elsewhere. A fifth category, summarized here, included important miscellaneous studies that did not fit categories given above.

The report presents narratives and a comprehensive reference list for the various research categories. Items covered, for example in foundation engineering, include pile foundations, pile groups, drilled shafts, spread footings, and foundation load testing. Ground improvement efforts and soil and rock behavior are also given in appropriate detail. Outputs, including guidelines and implementation items, are given for the various topics covered. Finally, an outline of future geotechnical research needs is presented.

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Special thanks are extended to other FHWA personnel who have also contributed to the success of this program. There are too many to mention them all by name, but a few stand out above the rest. In the Headquarters office, Jerry DiMaggio and Dick Cheney have provided advice concerning which topics needed to be researched, and critiqued the work on many of the studies from start to finish. They have used many of the results to prepare design and construction guideline manuals, technical advisories, and engineering circulars that have been distributed to FHWA and State Highway practitioners all over the United States and many foreign countries.

Special credit is due John Hooks and Chien Tan Chang for their efforts to promote the technology transfer and implementation of the R&D products from this program. They provided the resources to enable Cheney and DiMaggio to accomplish their goals to bring the research results to fruition. The author is also indebted to all of the Regional Geotechnical Engineers who actively supported the program, especially Barry Berkovitz (Atlanta), Ron Chassie (Portland), Andy Munoz (Dallas), and Barry Siel (Denver). There is considerable satisfaction in knowing that these outstanding field engineers have taken our research products and used them to help make roads better in their regions.

The single most important person in the success of this program was Don Fohs, who, like Chuck Scheffey and Dick Hay, is now retired from FHWA. The author is very grateful for his support and guidance throughout the entire period of performance.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

NOTE: Volumes greater than 1000 l shall be shown in m^3.

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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CHAPTER ONE

INTRODUCTION

The roots of the Federal Highway Administration's (FHWA) geotechnology research program can be traced back to the 1970's when FHWA field personnel and State Highway Agency (SHA) engineers requested assistance in solving numerous soil behavior and foundation engineering problems. The FHWA Office of Research responded by establishing three geotechnical related research projects, plus a major geotechnical task in the Tunneling Research Project. Together, these research projects and a few other "stand-alone studies" were grouped to form the FHWA Geotechnology Research Program.

The first geotechnical research project dealt with soil and rock behavior problems such as soil stabilization, compaction, frost action, expansive clays, and deteriorating shales used in embankment fills. The second project dealt with bridge foundations, including piles, drilled shafts, and spread footings. The third project covered specialized ground improvement techniques for compacting, draining, and reinforcing ground materials to withstand heavy loads under typical highway applications. The geotechnical research under the tunneling project covered site investigation, soil parameters for design, instrumentation monitoring techniques, plus ground movement prediction and control. Chapter Five covers the separate research studies that did not fit well under the four major projects previously mentioned.

This report gives an overview and summarizes the results of the research conducted under the four geotechnical projects established during the 1970's. It describes the efforts and results of 25 years of research spanning three decades from 1973-1998. The main purpose of the report is to provide a summary of the FHWA geotechnical research activities over the last quarter of the 20th century. It is intended for the general engineers and administrative managers of FHWA and the SHA's.

Also presented are descriptions of the various problems that were addressed; and the report discusses the objectives and scope of each project in detail, except for the Tunneling Project, which is reported elsewhere (see appendix B). A review of each project's organization and approach is presented before the results are noted and evaluated. Technology transfer and future research needs are also covered separately to highlight the important nature of each topic.

This report demonstrates that the state of the art was significantly advanced by the many contributions from this research program. It also provides a concise reference for other researchers and practicing engineers concerned with designing and constructing geotechnical structures for highway applications.

1.1 Background

During the 1970's, a series of FHWA studies determined that various segments of the field of highway geotechnology needed significant improvement in design and construction applications. This was especially important considering that bridge foundations, retaining wall systems, embankments, and cut slope operations account for well over 50 percent of the total cost of most highway projects. It is therefore imperative that accurate and rational guidelines be developed for geotechnical related design and construction applications to ensure safe and efficient highway structures.

The assessment studies found that pile design was more guesswork than it was scientific, especially for group behavior of piles. Other foundation systems such as drilled shafts and spread footings were starting to replace piles in a few cases, but piles were usually selected in the vast majority of projects, although in some cases they may not have been the best choice. Reasons most often cited were the lack of adequate performance records for the alternative choices and/or the need for better design and construction guidelines.

Also, at this time, there was a significant influx of innovative geotechnical methods to retain earth masses and/or improve ground materials to withstand heavy loads or resist environmental effects in typical highway projects. Some of these ground improvement technologies were imported from foreign countries where it was less important to understand how the improvement mechanism worked, only that it had a strong history of being successful and it carried a written guarantee from the specialty contractor. The lack of specific guidelines and specifications was slowing their adoption here in the United States where our society is more content to specify and control construction than to accept guarantees from the contractor.

Early in the life of this program it was discovered that geotechnical engineering for foundations and earth structures lagged behind most other highway engineering disciplines in evolving from an art to a science. Many of the commonly used design techniques of the early period suffered from a lack of precise definitions and a very imperfect understanding of fundamental behavioral mechanisms that govern geotechnical structures. Also, the difficulty and expense associated with properly defining soil and rock behavior under foundation loads significantly impeded the development of rational theoretical solutions, thus fostering the growth of empirical methods of design and analysis.

Most of the difficulty and expense of defining soil and rock behavior involves the inconsistencies and uncertainties associated with applying engineering principles to non-homogeneous ground materials. Predicting the response of soils to bridge loads that are transferred by various piles in a pile group or tensile elements in a reinforced soil mass are two special cases where more precise definitions of soil behavior and the failure mechanisms would lead to more economical designs.

1.2 Objectives

The objectives of this program were to develop improved predictive techniques for foundation design and soil behavior, and improved design and construction guidelines for ground improvement techniques, such as reinforced soil, stone columns, dynamic compaction, soil nailing, tieback anchors, and prefabricated vertical drains.

1.3 Scope

This program dealt with research and development of improved design and analytical prediction procedures for foundation systems such as piles, spread footings, and drilled shafts, as well as the development of improved design procedures for using ground improvement techniques on retaining walls, embankments, and highway cut slopes. Research efforts were also directed toward developing construction guides to complement the improved design procedures.

The development of improved analytical techniques requires accurate measurement of the stresses and strains in expensive full-scale models that are load tested to failure to serve as a benchmark for less expensive mathematical and reduced-scale physical modeling studies. Knowledge of the appropriate scaling effects is also required in some cases, because structural interaction with soil is strongly dependent on the properties of the soil that are very difficult to reduce in scale. For example, research has shown that the response of different size model piles is not generally defined in any simple, direct relationship, such as those derived by ordinary dimensional analysis.

1.4 Approach

The basic research approach was to begin the study of each topic or technique with a state-of-the-art investigation to collect all available information on use, design methods, construction practices, case histories and performance evaluations. Laboratory studies to evaluate physical and engineering properties and some small-scale model testing in the laboratory were used to supplement the physical testing and subsequent field tests. Full-scale field tests and performance evaluation studies were conducted for some of the most promising techniques, especially those that were found lacking in well-documented field data. Design and construction guidelines were developed for each technique on the basis of lab and field test results.

Because many of the newer techniques were proprietary and/or only performed by highly skilled specialty companies, the researchers coordinated their efforts with skilled specialists in the various areas. Personal interview programs were conducted during the early stages of development and draft manuals were later submitted for their review and evaluation.

State highway departments were encouraged to work with us and assist in this research and development effort. In many cases it proved to be economically attractive to "piggyback" the research efforts onto an ongoing State highway department construction project to reduce the costs of mobilization and capitalization of materials, equipment, and labor.

During the conduct of the early studies of this program, it became increasingly apparent that advancements were coming too slowly and with great difficulty because of two major obstacles or shortcomings: 1) the lack of comprehensive data bases containing research-quality information on the behavior of geotechnical structures subjected to both working stress and failure conditions, and 2) the lack of research-quality test sites available for testing developing technologies and new products at locations where soil and site conditions are well-known, and therefore can provide a standardized base with which to compare the results. Of course, more money and personnel would also have helped to speed progress as well.

When these lessons were learned, the program was modified in mid-stream to divert some funds and resources to correct these deficiencies. The development of these major resources has also been coordinated with the development of an Automated Geotechnical Information and Design System (AGIDS), which will incorporate all of the design improvements resulting from the research efforts, and also will make use of the FHWA databases in retrieving information for various correlations, analyses, or predictions that can be done with AGIDS. A detailed description of AGIDS is presented in section 5.2. The establishment of a system of research-quality test sites is described in section 5.3

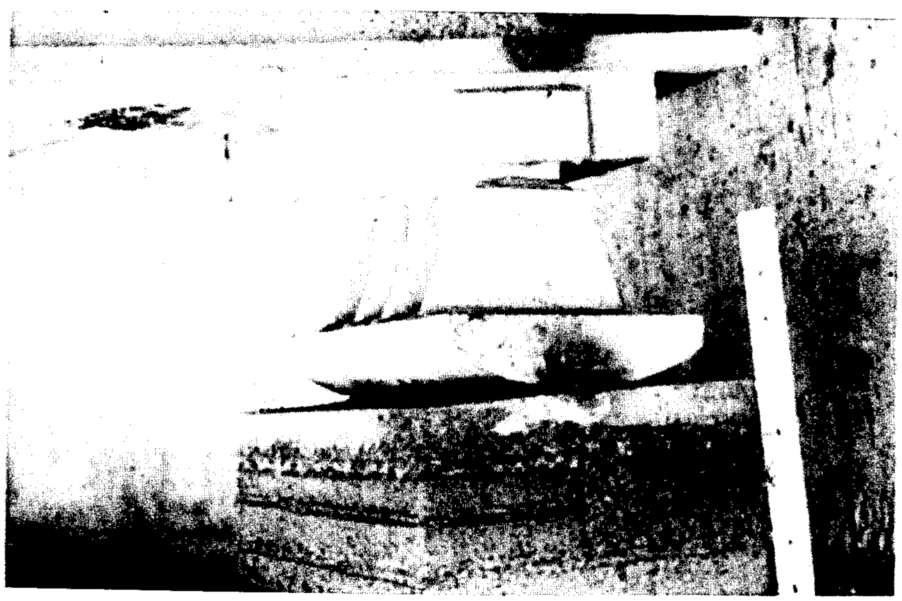

Figure 1. Significant shimming beneath bearing device.

CHAPTER TWO

FOUNDATION ENGINEERING PROJECT

Prior to the establishment of this research program, foundation engineering guidelines were mostly empirical and barely sufficient for most highway applications. The result was an inability to accurately predict the performance of foundation systems, which, in turn, led to very conservative design procedures as well as an occasional foundation failure. A comprehensive research plan was initiated in the late 1970's to develop improved design and construction guidelines for building safer and more cost-effective bridge foundations. Engineering improvements were expected to reduce the cost of these foundations and stretch the highway dollar to buy more bridges that will last longer.

An analysis of future needs for highway bridge foundations was completed under this project to provide essential planning information for conducting effective research on bridge foundations. Estimates of the number of new bridges to be constructed and those that would need to be replaced or rehabilitated during the remainder of this century were made in 5-year increments using data from FHWA bridge inventory and inspection reports. An analysis of FHWA foundation management review reports was also made to determine typical foundation types used in each State and likely to be used on future construction. The analysis was also supplemented with personal interviews with selected State and FHWA bridge engineers from various regions of the country (1).

Results of these analyses indicated that more than 100,000 bridges would be constructed, replaced, or rehabilitated in the United States during the last 20 years of this century. Approximately 20,000 new bridges would be built and more than 15,000 existing bridges had deficient foundations. Many of the satisfactory foundations would also have to be replaced because of retrofit problems caused by replacing the superstructure. A large number of reusable foundations required special design and construction procedures that needed to be developed. It was also noted that more than two-thirds of these bridges were likely to be supported on piles, one-fourth of them on spread footings, and the rest of them on drilled shafts or other types of foundations (1).

2.1 Background

Because the safety and cost-effectiveness of bridge foundation systems is of major importance, an appropriate research program to develop better design tools has long been advocated by both structural and geotechnical engineers. Foundations represent about 30 percent of the cost of highway bridges in typical applications; however, this cost can be even higher where bridges are built near or on difficult soil conditions. The total annual expenditure of public funds for bridge construction is conservatively estimated to be more than $2 billion, which means that foundations are costing more than half a billion dollars per year.

Because the predominant type of foundation system used in the highway industry is piles, the first priority for this project was the efficient design of piles. Research was also needed to develop new concepts for reducing our excessive reliance on pile foundations. In situations where deep foundations are required, the overall cost can be significantly reduced by using smaller piles and fewer of them as a result of design economies developed under this research project.

The indiscriminate use of pile foundations was partly due to a lack of confidence in the safety and dependability of drilled shafts and shallow foundations, but mainly due to unreasonably restrictive deformation and movement constraints. Therefore, the establishment of rational criteria for tolerable movements was a necessary first step toward improving foundation design (see section 2.5).

Assuming a 25 percent reduction in the use of piles can be accomplished by substituting cheaper drilled shaft or shallow foundation units, the use of piles will still account for much more than half the foundation systems used for highway structures. Therefore, the continued investigation of pile-soil behavior will provide cost-effective improvements. One of the most incongruous aspects of foundation design is the overwhelming use of a system (friction piles) that is the least understood.

2.2 Objectives

The overall project objective was to develop improved foundation design and construction methods for highway bridges. This objective was approached through efforts directed toward accomplishment of the following four separate, but related goals:

1. Determine the structural consequences of foundation movements and define the limits of tolerable movements for use in the design of efficient foundation systems.

2. Establish a fundamental understanding of the behavior of soils during and after foundation installation for use in analytical predictive methods.

3. Improve the efficiency, reliability, and use of less expensive shallow foundations.

4. Develop more accurate concepts and guides for the design and construction of deep foundations.

2.3 Scope

Research efforts in this project were directed toward developing new predictive techniques for foundation design, better criteria for tolerable movements, and permissible stress levels in piles and drilled shafts, as well as improved construction control techniques. Each component of the total foundation system was studied individually and each total system was evaluated as a whole. The behavior of the foundation systems was also examined under both working and ultimate stresses.

2.4 Project Description

The major research efforts were organized into five tasks:

1. Structural Consequences of Foundation Movements - Research was conducted to develop improved criteria for tolerable foundation movements. A practical limit to the amount of foundation movement that can be tolerated without serious structural or functional distress by various types of highway bridges was defined and established through structural analysis and supporting field data.

2. Predicting the Behavior of Piles and Foundation Soils Under Structural Loads - This task involved the development of improved analytical predictive techniques for the design of piles. Special emphasis was placed on the study of load transfer between a pile and the surrounding soil to include both single piles and groups of piles. An important associated objective of this task was to determine the effects on soil properties of installing the pile and other remote stress applications such as negative skin friction. The predictive techniques were to consider the "before" driving case (in situ soil properties), the "during" driving case (the changes in soil properties brought about by the installation method), and the "after" driving case (soil recovery with time).

   Another major emphasis was on full-scale load tests on piles and groups of piles to develop correlative relationships between the performance of an individual pile and a group of piles. The corresponding values of bearing capacity and settlement were of primary concern; however, valuable information concerning pile spacing, sequence of driving, and efficient shape of the group were also obtained. Load test studies were also performed on drilled shafts.

   Another important associated objective of this task was the development of rational criteria for allowable stresses in piles to replace the blanket stress level codes that were being used in the highway industry. The criteria were developed in terms of driving stresses and static loading, as well as environmental exposure and soil conditions (see section 2.6.5).

3. Improved Design and Construction Techniques for Drilled Shaft Foundations - Research under this task investigated the behavior and efficiency of drilled shafts as a suitable alternate for pile foundations in a similar manner to the Task 2 approach for piles, except with less emphasis on groups and more emphasis on construction problems such as free-fall of concrete heights, nondestructive evaluation techniques, and the use of drilled shafts in intermediate geo-materials such as soft rocks, hardpan, and glacial till.

4. Innovative Load Test Methods - Research under this task was to develop economic load test alternatives for bridge foundations. Systems that were evaluated under this investigation were Statnamic, Smartpile, Osterberg load cell, and several dynamic load test systems.

5. Improved Design for Shallow Foundations - Research under this task was to investigate the behavior and efficiency of shallow foundations, with emphasis on demonstrating the reliability and cost-effectiveness of spread footings. A survey of the problem areas, current practices, and the performance records of highway bridges supported on spread footings was conducted to demonstrate that the use of spread footings in many cases can be made a more acceptable and attractive alternative to expensive pile foundations.

   An important associated objective of this task was to determine the enhancement potential of various soil and site improvement techniques for reducing the reliance on pile foundations. Research was conducted to evaluate methods for improving a marginal foundation site to permit the use of shallow foundation systems in design situations where the soil or site conditions would normally dictate the use of piles.

The Foundations Project was the "flagship" project of the FHWA Geotechnology Research Program. It could and probably will be a separate report by itself; in fact, each of the five main tasks could also be a separate report. The following six sections of this chapter provide a summary of the major highlights of this project.

2.5 Structural Consequences of Foundation Movements

During the development of the FHWA research project on foundations, it was determined that one of the major reasons that bridge foundations were over-designed had its roots in the lack of rational criteria for tolerable movements of the superstructure. The American Association of State Highway and Transportation Officials (AASHTO) design code at that time was relatively silent in this area, and basically promoted a "zero" settlement design procedure. This resulted in a very high cost of obtaining little or no settlement in terms of utilizing the soil load-carrying capacity because it is almost impossible to achieve this objective. The cost was often extremely high and very wasteful.

Foundation movements under highway bridges (figures 1 and 2) had occasionally been predicted and measured; however, there had been very few investigations of the effect these movements would have on the safety and serviceability of the bridge structure. As a result, tolerable foundation movement had not been established beyond the conceptual stage, and much controversy among engineers was prevalent.

In addition to the disagreement on the definition of tolerable settlement, there was also disagreement on the accuracy of settlement predictions. As a result, many engineers still prescribed strict settlement constraints to guard against erroneous predictions. In many cases, the precautions were unrealistic and underestimated the accuracy of the prediction techniques, which are normally accurate within 10 to 20 percent on average and are rarely more than 50 percent off the measured value.

It was noted in earlier studies that using piles did not guarantee that there would be little or no settlement, unless the piles were founded on hard rock. The nature of load transfer from the pile to the soil surrounding (side friction) and beneath the pile (tip bearing) requires some movement of the pile to mobilize the load-bearing capacity of the soil material. The relative movement required to mobilize maximum frictional strength is approximately 6.35 mm (0.25 in), while the displacement required to mobilize the soil's shear strength under the pile tip is usually much larger than that value. If the allowable settlement is restricted to a smaller value than what is required to mobilize tip resistance, the load-carrying capacity of the pile is artificially reduced to the level of side friction support. The support capacity available at the pile tip then becomes an additional safety factor.

Figure 2. Bridge girder jammed against abutment and excessive rocker tilt.

Overly restrictive settlement constraints can reduce significantly the supporting capacity of friction piles. To comply with the prevalent requirements of zero or near zero settlement, the foundation engineer must reinforce his or her design by adding more piles, using longer piles, or increasing the diameter of the piles. The conservative effect of this design philosophy is evident by examining any load-settlement curve from a pile load test. A slight increase in the allowable settlement value can impact significantly the allowable design load for a pile foundation, especially within the straight line portion of the curve.

A relaxation of the stringent movement criteria was also expected to impact significantly the use of spread footings, whose major drawback is the risk of some settlement. Because the economic breakpoint in the normal design procedure for spread footings centers around 25 mm (1 in) of settlement, the majority of bridge engineers were reluctant to use this less expensive method of foundation support. As a result, the highway industry has been accused of having numerous "buried treasures" beneath bridge abutments and piers, because piles were used instead of spread footings or because more and/or larger piles were used than necessary.

Research performed under this project indicated that bridge structures can withstand a reasonable amount of settlement, and the amount varies according to the span arrangement (simple versus continuous) and length of span as well as other design variables. This indicates that the AASHTO blanket criterion approach was inappropriate and the zero settlement design approach was too conservative.

2.5.1 Preliminary Studies

Prior to the initiation of a comprehensive research study by FHWA, a series of smaller studies that were conducted in Ohio, Washington, Connecticut, Canada, and by FHWA staff were evaluated to help develop a detailed research plan. Studies done for the building industry were also included in the evaluation. A study of the measured movement data and corresponding damage assessments were very enlightening, but insufficient to establish rational tolerable movement guidelines. It was also noted that the building codes in many major U.S. cities actually permitted larger settlements than AASHTO bridge specifications, even though building elements, such as glass doors and windows, elevator shafts, utility lines, and brittle wall panels, are more sensitive to foundation settlement than bridge elements.

Although no well defined set of criteria was generally agreed upon, all of the researchers agreed that the development of a rational set of tolerable movement criteria for bridges was a high priority research need. Everyone then turned to FHWA's Office of Research to conduct a major effort to solve this problem.

2.5.2 FHWA Tolerable Movement Study

A comprehensive analysis of the data from the earlier studies that evaluated field measurement surveys was conducted as part of an overall analytical investigation of the effect of different magnitudes of settlement on the potential level of distress produced in a wide variety of steel and concrete bridge structures of different span lengths and stiffnesses. A total of 314 bridges in the United States and Canada was analyzed to determine if the measured foundation movements and corresponding damage assessments could yield sufficient insight toward the development of rational criteria for tolerance to movement. The data by themselves proved to be insufficient, but when combined with the structural analysis studies, and an appraisal of existing design specifications and practice, a rational set of criteria was developed.

The researchers determined that functional distress is more difficult to assess than structural distress because of its subjectivity. Functional distress is defined under this study as damage to the architectural elements or a reduction in ride quality. Architectural damage is less severe than structural damage that affects the integrity of a main supporting element of the bridge; however, architectural damage is usually more visible and causes an annoying or insecure feeling on the part of the motorist. It is also referred to as "cosmetic damage" and includes cracking or misalignment of bridge railings, curbs, decks, abutment wing walls, and damage to light poles and utility lines. The deterioration of ride quality involves the "bump" at the end of the bridge and other roadway unevenness associated with bridge foundation settlement.

The specific results of this study have shown that, depending on type of spans, length and stiffness of spans, and the type of construction material, many highway bridges can tolerate significant magnitudes of total and differential vertical settlement without becoming seriously over-stressed, sustaining serious structural damage, or suffering impaired riding quality. In particular, it was found that a longitudinal angular distortion (differential settlement/span length) of 0.004 would most likely be tolerable for continuous bridges of both steel and concrete, while a value of angular distortion of 0.005 would be a more suitable limit for simply supported bridges.

For continuous steel bridges, differential settlements of 25 mm (1 in) or more would be intolerable for span lengths up to 15.2 m (50 ft) because of the significant increase in stresses caused by these settlements. However, for span lengths between 30.5 and 61.0 m (100 and 200 ft), the stress increases caused by differential settlements up to 76 mm (3 in) were quite modest, and for spans longer than 61.0 m (200 ft), the stress increases caused by 76 mm (3 in) differential settlements were negligible.

A basic design procedure was developed that permits a systems approach for designing the superstructure and the foundation system. This design procedure incorporates the tolerable movement guidelines that are based on strength and serviceability criteria which, in turn, are based on limiting longitudinal angular distortion, horizontal movements of abutments, and deck cracking (2,3).

2.5.3 Publications and Implementation Items

Research and development activities for the establishment of tolerable movement criteria were very successful. The FHWA R& D reports documented the efforts that were made to develop the rational criteria and presented detailed recommendations on how the new criteria should be used in typical bridge and foundation engineering scenarios. A technology sharing report was developed to help practitioners implement the new criteria in standard design situations (4). Workshops and presentations were also held to aid the implementation process. A new article was developed for the AASHTO Bridge Specifications (see chapter 7).

2.6 Pile Foundations

The first difficult problem confronting the designer of a foundation is to establish whether or not the site conditions are such that piles should be used. The most common case is that in which the upper soil strata are too compressible or generally too weak to support heavy vertical reactions transmitted by the superstructure. In this instance, piles serve as extensions of columns or piers to carry the loads to a deeper, more rigid stratum such as rock (point-bearing piles). If such a rigid stratum does not exist within a reasonable depth, the loads must be gradually transferred by friction along the pile shaft. Scour and the relative inability of spread footings to transfer inclined, horizontal, or uplift forces and overturning moments also require the use of piles in many instances.

Another problem facing the pile designer is choosing from among the 100 or more different kinds of piles. There are many variations in materials, configurations, and installation techniques. Guidelines for selecting the best pile for various situations can be found in one or more of FHWA's guidance manuals (5, 6, 7) and the general literature.

After a particular kind of pile has been selected for use, the designer then must determine the number, length, and size of the piles required. Simple guidelines were not available at the start of this research program to design and analyze piles for the various situations that can occur in bridge foundations; however, improved pile design guides are now available in various FHWA references listed at the end of this report. The ultimate load that can be supported by a certain kind of pile depends on the strength of the soil and/or pile material. Usually the ultimate load is determined by soil failure; however, the pile itself may fail if forced to penetrate difficult site conditions such as dense soil or rock.

Calculating the ultimate load on the basis of soil failure is one of the most difficult problems confronting the foundation designer. Because available theories for determining the ultimate load of a pile and a group of piles were not accurate enough to provide economical foundation designs, research was conducted to define the complex mechanics of load transfer between pile and soil and among the various piles within a pile group.

Load transfer in piles and pile groups was measured in the laboratory and field to develop and refine analytical models of the pile behavior process to provide more economical design procedures.

Assuming the pile material is not over-stressed, the ultimate load capacity of a pile is equal to the sum of two major soil components — point resistance and side friction. The amount of support contributed by each component varies according to the soil properties and pile dimensions. These resistances can be calculated through mathematical relationships; however, the required input data are difficult and expensive to obtain. As a result, less expensive index testing usually is performed to obtain approximate values for estimating the resistances.

Pile capacity usually is predicted using static and dynamic analysis procedures. On large, expensive structures, pile load tests often are used to verify the design loads. Recently completed FHWA experimental studies of instrumented piles load tested to failure have increased our understanding of load-transfer behavior of single piles and pile groups; however, more tests are needed to confirm the new prediction methods.

A mathematical model of pile group behavior was deemed to be a valuable analytical tool that systematically can convey engineering experiences from one site to another. Several mathematical models had been developed, including one by FHWA; however, none had been validated adequately because of the lack of precise field data on pile group behavior. This was especially true of new foundation design methods based on finite element analysis. To date FHWA has performed most, if not all, of the pile group load tests to failure. These results have been used to validate and refine the FHWA pile group design model called PILGP (8).

2.6.1 Areas of Emphasis

Because of the high reliance on driven piles, a large portion of FHWA funds for foundation research was directed at improved design and construction procedures for driven piling. FHWA pile research was divided into the following three major areas of emphasis:

- The interaction between a single pile and the surrounding soil to develop accurate prediction methods for pile capacity.

- The behavior of groups of piles to determine appropriate efficiency factors that must be applied to predictions based on single pile design.

- Pile materials and driving systems.

2.6.2 Single Piles in Clay

Field load tests on single piles in soft clays have provided experimental data to evaluate a promising pile capacity predictive technique based on the general effective stress method. The effective stress method for predicting pile capacity was validated and its accuracy and general applicability were improved. Figure 3 shows a full-scale pipe pile being instrumented in the laboratory prior to field installation.

The accuracy of the method was limited by the assumptions made to describe the changes in effective stress between pile driving and subsequent loading. Major uncertainties arise in attempted modeling of the effective stresses after the disturbed soil has reconsolidated. Current analysis techniques were considered applicable to full displacement piles driven into normally consolidated clays (9).

Figure 3. Lab instrumentation of a pipe pile for field load testing in clay.

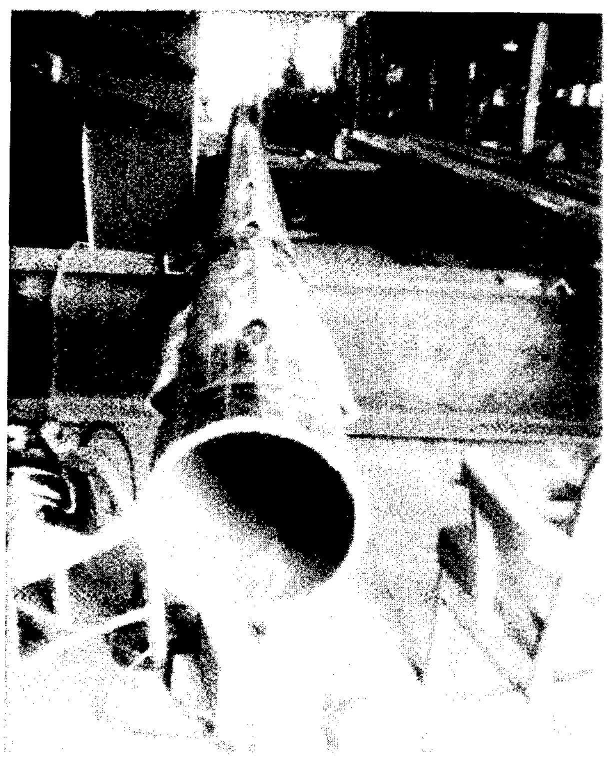

Figure 4. Field instrumentation of a pipe pile for field load test in sand.

2.6.3 Single Piles in Sand

Previous methods for predicting the behavior of driven piles in sand gave widely different results because of several sources of error. Variability of the soil and methods used to obtain the design parameters also contributed to the different results as did some of the simplifying assumptions made in developing the theoretical methods.

An FHWA research study on the behavior of piles in cohensionless soils involved the analysis of data on instrumented piles (figure 4) tested to failure under vertical loads. The data, collected through an extensive literature search, consisted of 35 pile load tests at 10 different sites. The piles were of various kinds, lengths, and diameters and included steel pipe and H-piles and prestressed concrete and timber piles. Average pile diameter was 0.4 m (1.27 ft), and average pile length was 15.1 m (49.6 ft).

Statistical analyses determined the vertical and horizontal variability of the soil at each case history site. Load transfer characteristics were analyzed for each pile without consideration of residual driving stresses. In those few cases where residual stress data were available, the load transfer characteristics were reanalyzed to learn the effect of residual driving stresses. It was found that residual stresses play an important role in pile design and that proper consideration of residual stresses can result in shorter pile lengths for driven piles in sand (10).

2.6.4 Allowable Stresses in Piles

In addition to the ability of soil or rock to carry the load transferred from a pile, the load capacity of the pile also is important. The load capacity of a pile is governed by its structural strength and, to a lesser extent, by the surrounding environmental conditions. The structural strength is a function of the allowable stress levels that apply to the particular pile material and the cross-sectional area of the pile.

To provide a factor of safety against failure (figures 5 and 6), allowable stress levels normally are specified as a percentage of the peak strength value of the pile material (for example, steel, concrete, or timber). Allowable stress levels for piles vary

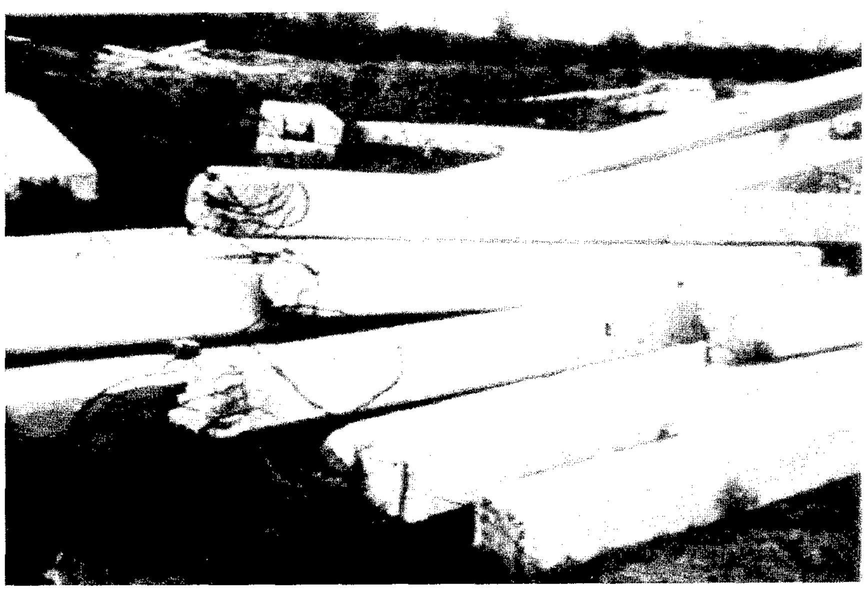

Figure 5. Concrete piles damaged by difficult driving conditions.

significantly because of different building codes in different jurisdictions. Significant controversy had arisen concerning the allowable stress levels used in the highway industry at the time of this research project (circa 1980) because the choice of allowable stress values greatly affects the dimensional analysis and thus the economy of the foundation system. Another factor to be considered was that competition between materials producers was keen and significantly affected by changes in the allowable stress codes.

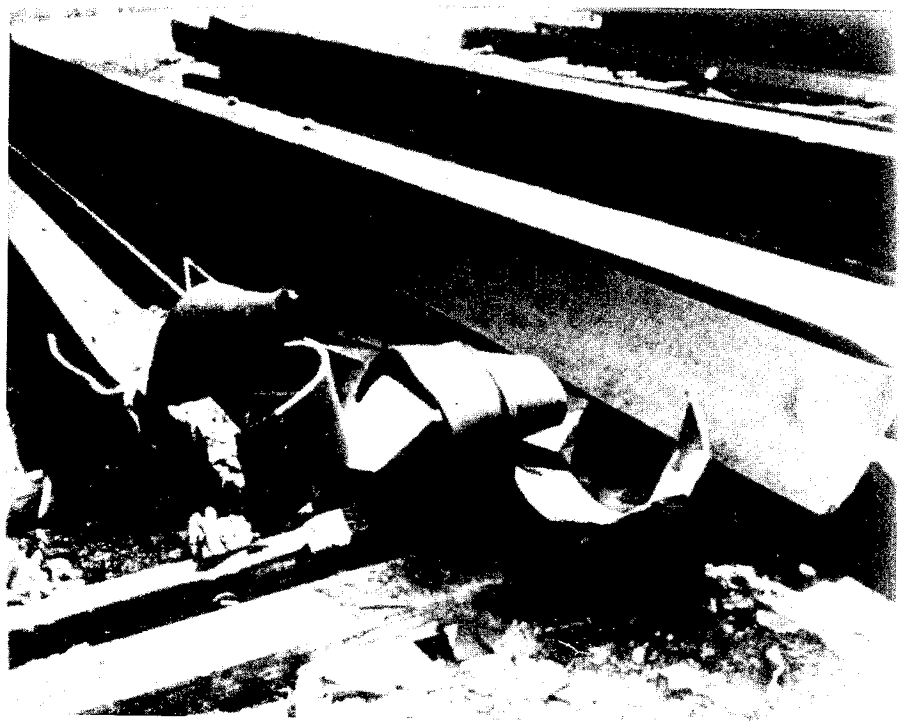

Figure 6. Steel H-piles badly damaged by hard driving.

A comprehensive investigation of the design of piles as structural members was performed to define and establish, through structural analysis and supporting field data, a rational guideline or design methodology for determining allowable stress levels for pile design codes used in highway bridge foundations. These methods must take into account not only the material properties of the pile itself, but also the individual effects of long-term loads, driving stresses and driveability, imperfections in form or material, and various environmental conditions that tend to reduce pile capacity.

As part of the overall review, the investigators studied the codes and specifications of an array of national and foreign organizations and code bodies. The basis for each code was reviewed and corroborative data were assembled to develop improved values of allowable stresses. The claims of material suppliers for increased allowable stress levels also were evaluated and documented. Some of the claims were found to be overstated, and all of them ignored at least one or more of the important factors that govern the structural strength of a pile.

In general, it was recommended that allowable stress values in use at that time be decreased for concrete and timber piles and increased for steel piles. The new procedures for determining appropriate allowable stress levels on a case-by-case basis according to the major factors governing structural strength of piles are a significant improvement over the previously unsubstantiated blanket stress levels. Reasons for each suggested change to then current methods for determining allowable stress values are documented in the FHWA report (11).

2.6.5 Performance of Pile Driving Systems

Proper construction control of pile driving operations is as essential as good design practices. Construction control is more difficult for piles than for spread footings because the excavation and construction of footings can be observed. The construction control for pile driving involves checking the pile materials and the installation equipment. The pile inspector can visually check many requirements; however, some of the most important checks require instrumentation. The high cost of pile foundations prompted FHWA to seek more efficient pile driving systems as well as more efficient design methods.

Pile driving technology has evolved from an archaic system of pounding a "stick" in the ground with a heavy mass to a sophisticated system of installing long, slender structural elements in a well-defined soil mass. In the previous era it didn't matter how efficient the pile driving system was because the only objective was to pound the stick into the ground. However, the vertical advance of a pile under a given hammer blow can be used as a measure of the pile's bearing capacity. Thus the hammer takes on a second function, and doubles as a piece of testing equipment.

A comprehensive study of available pile driving systems and corresponding measurement techniques was completed under this research program. In addition to the direct measurements of output, researchers investigated the usefulness and practicality of installing gauges (figure 7) and other instrumentation on the pile driving system to determine performance rating, spot the cause of erratic or inadequate operation, and evaluate the significance of erratic behavior in terms of performance capability.

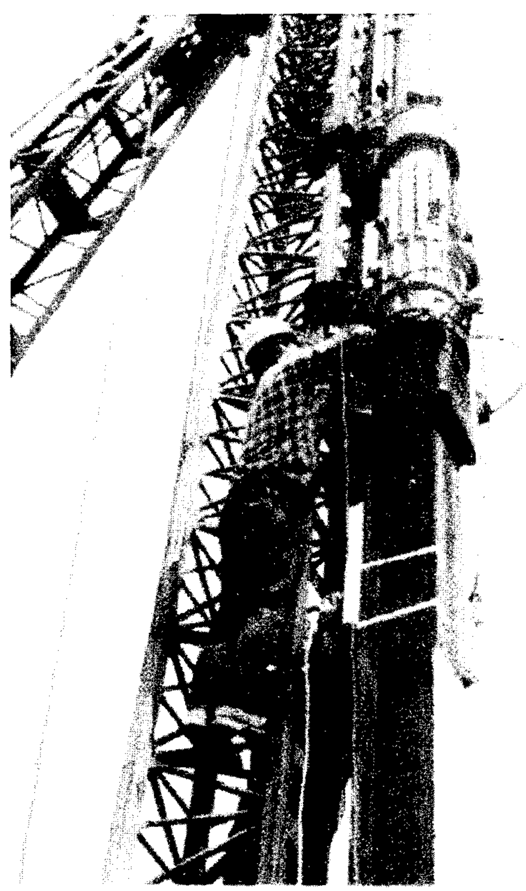

Figure 7. Installing pile driving analyzer (PDA) instrumentation.

The researchers developed three devices to evaluate the field performance of pile hammers. The ram velocity measurement (RVM) apparatus uses radar to record ram velocity as a function of time for conversion to kinetic energy for driving. The study also developed a system that uses piezoelectric accelerometers to measure pile hammer impact velocity. This system is referred to as AMS (for Acceleration Monitoring System). Both the RVM and AMS are expensive and complicated devices for routine use on pile driving projects. A simpler device, the Saximeter II, was developed for FHWA to aid the pile inspector in log keeping and monitoring pile driving performance. It electronically measures blows per minute and converts time duration to the corresponding fall height (stroke) of the ram, and converts stroke to the potential energy.

An inspection manual was also developed to aid construction engineers in evaluating the performance of pile driving systems (12). It can be used to ascertain that the pile hammer conforms to certain minimum standards, and to record observations on hammer and driving system behavior. The manual explains the theory of operation and inspection procedures for various hammer types, describes all components of the driving systems, includes a glossary of pile driving construction terms, and provides summary sheets and forms to aid the inspector in recording the pile installation process. A slide-tape show was also developed to provide a visual rendering of the inspection manual for instructional purposes.

2.6.6 Pile Wave Equation Technology

For many years, pile design used pile driving formulae that were established to relate dynamic driving forces to available pile bearing capacity. The original dynamic formula was developed more than a hundred years ago and was based on a simple energy balance between the kinetic energy of the ram at impact and the resulting work done on the soil. The concept assumed a pure Newtonian impact with no energy loss.

A close examination of the pile driving process recently disclosed that the concept of a Newtonian impact does not apply. It was also noted that when the hammer strikes the pile, a force pulse is created that travels down the pile in a wave shape. The amplitude of the pile wave decays before reaching the pile tip because of system damping properties; however, a portion of the force in the wave reaches the tip and forces the pile to penetrate the soil.

Before the demise of the dynamic driving formulae and before the wave equation analysis was fully developed, pile designers relied on static pile analyses to predict pile capacity and determine pile sizes and lengths. The success of this method depended greatly on the accuracy of boring data and the engineer's ability to properly classify zones in the subsoil with regard to relative pile support capability. Static analysis methods will always be very useful because they are much more accurate than the old driving formulae; however, the value of wave equation type methods has been steadily increasing.

The wave equation method is a computer based analysis that was developed from the classical wave theory, which models wave propagation in a slender rod subjected to an applied force at one end. Modifications to the classical theory are necessary to account for changes in the traveling wave form due to pile and soil properties. If the wave is completely dissipated by the pile material and soil properties before reaching the pile tip, no penetration will occur. This can be due to either too small a hammer for the pile, or too small a pile cross-sectional area specified for the length being driven. Wave equation analysis can detect both of these scenarios before they happen in the field, plus it can also predict pile damage if too large a hammer is selected.

Soil data input requires both an understanding of site-specific soil properties and the effects of pile driving on those properties. These dynamic properties are known as damping and quake and are roughly correlatable with soil type. These properties are best determined by experienced geotechnical engineers. Research was needed to provide better methods to determine soil damping and quake values from laboratory and/or in situ soil testing equipment to better predict pile capacity.

2.6.6.1 Pile Capacity Prediction

In response to this need, FHWA initiated a contract research study to perform an in-depth assessment of current techniques and potential methods for determining soil quake and damping input parameters to the wave equation computer analysis program. The contractor was required to develop a data base of pile foundation sites containing research-quality soils data, pile driving records, load test information, and Pile Driving Analyzer (PDA) data. These data were to be used to make correlations among quake and damping factors, Wave Equation Analysis Program (WEAP) capacity predictions, and soil test data. It was also a requirement to locate 6 to 10 actual projects where load testing and dynamic measurements were made, plus good soil data had to be available to perform the required correlations to evaluate the newly developed procedures and propose additional modifications, if necessary.

The following is a reprinting of the report's abstract:

"Research has been conducted on the potential improvement of dynamic wave equation analysis methodology using in-situ soil testing techniques. As a basis for this investigation, the literature was reviewed and a summary was compiled of efforts made to date on the development of models and associated parameters for pile driving analysis. Furthermore a data base was developed containing more than 150 cases of test piles with research quality data on static load tests, dynamic restrike tests, soil information, driving system data and installation records. One hundred data base cases were subjected to correlation studies using the CAse Pile Wave Analysis Program (CAPWAP) and various static analysis methods. This work yielded dynamic soil model parameters which did not indicate a specific relationship with soil grain size" (13).

2.6.6.2 Simplified Capacity Predictions

Static load testing (figure 8) to failure is probably the best method available to determine the actual static capacity of a pile; however, these tests are expensive and time consuming. As a result, they are not routinely conducted. In many cases a load test to twice the design load is conducted to verify safety factors and save money on the cost to extend the loads to the failure range. These tests give some measure of assurance to the project design team, but do little to advance the knowledge of how to design a particular pile in a particular soil. The simple act of striking a pile with a heavy hammer can also be thought of as an instantaneous load test to failure; because in order for the pile to penetrate further into the soil, the soil must fail under the driving forces. In other words, pile driving is actually a very fast load test under each hammer blow. With the right type of instrumentation, the engineer can take advantage of these failure measurements and use the information to make a prediction of potential static capacity in the field during pile driving operations.

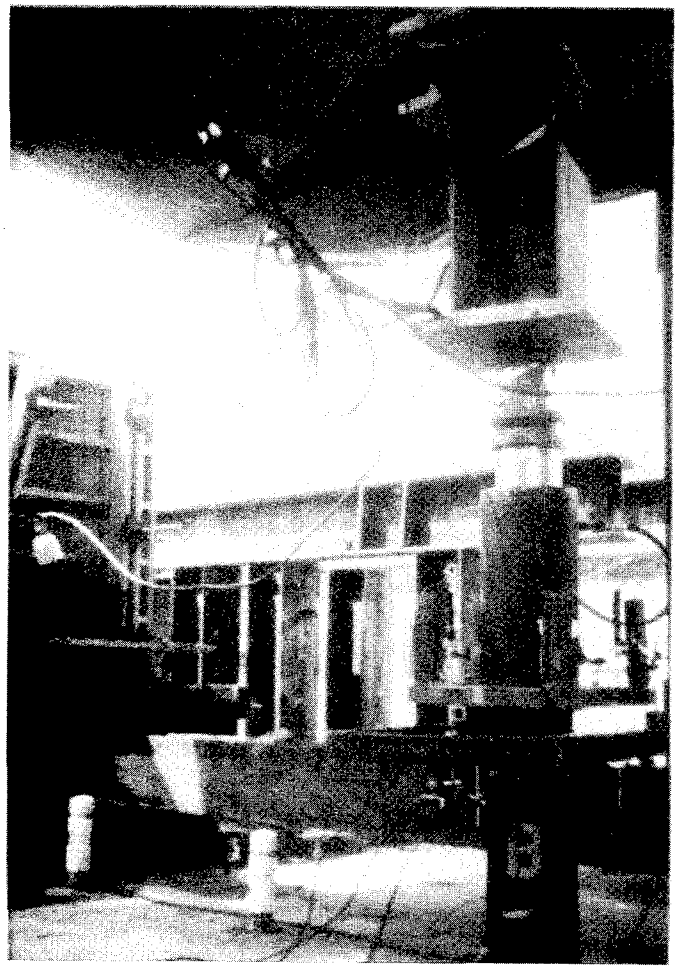

Figure 8. Close-up view of single pile load test in sand.

This concept was proposed to FHWA by the developer for further study. The idea to develop a simplified method based on energy balance between the total energy delivered to the pile and the work done by the pile/soil system was examined under a research contract study in the early 1990's. This method, called the "Energy Approach", uses the calculated transferred energy and maximum pile displacement values from the measured data, together with the field blow counts as input parameters to calculate the pile capacity.

To verify and refine the new method, two large data sets were retrieved from the FHWA Deep Foundations Load Test Data Base (see section 5.2). One set contains 208 dynamic measurement cases on 120 piles monitored during driving and followed by a static load test to failure. These cases reflect various combinations of soil-pile driving scenarios. The other set contains data on 403 piles monitored during driving, but without static load test data.

The Energy Approach method was found to be very accurate in predicting the pile capacities that were measured in the static load tests. These estimates were also found to be more accurate than the sophisticated office methods commonly used in engineering practice. This comparison was especially true for records obtained at the end of initial driving. This approach can be used in place of or as an independent check of the office methods (14).

2.6.7 Micropiles

Micropile technology was conceived in Italy in the early 1950's to fill the need for an economical and versatile foundation system that could be used to underpin, repair or retrofit badly damaged infrastructure elements in war-torn Italian cities. It was introduced in the United States about 20 years later; however, it did not catch on near as much as it did in Europe, especially, in the late 1980's and early 1990's. In addition to static applications, significant growth in the use of this technology has occurred in seismic and slope stabilization applications.

All of these uses are directly applicable to highway projects, which caught the eye and interest of FHWA geotechnical engineers. Two major earthquakes in California and one in Japan also stirred interest in the use of micropiles for seismic retrofit of highway bridge foundations. At the same time, the French Highway Administration began a major research project to investigate the basic mechanisms and engineering characteristics of micropile systems.

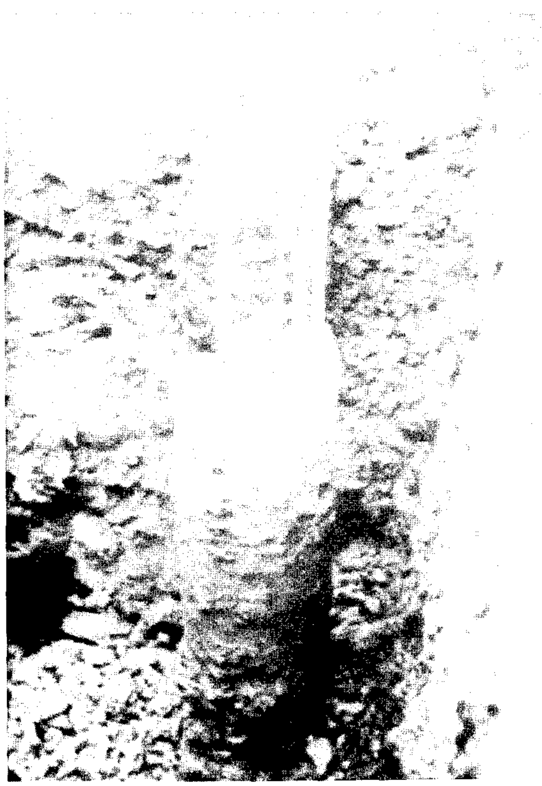

Figure 9. Exhumed micropile.

Micropiles are defined as small-diameter, drilled piles composed of placed or injected grout with some form of steel reinforcement in the center of the grout to resist the bulk of the design load. The central reinforcing element is either a high-strength steel bar or tube that is secured in the grout that is injected under high pressure to improve bonding with the surrounding soil. Micropiles can be installed through virtually any ground condition and at any inclination. Modern construction techniques keep noise and vibration to a minimum, and they can be constructed under limited headroom conditions to within a few millimeters of adjacent properties. Figure 9 shows an early model micropile that was exhumed for inspection purposes.

In 1992 FHWA was invited to become a cooperative research partner in the French micropile project.

The major objective of this cooperative research project was to establish reliable engineering guidelines and safe design methods for the use of micropiles in the reinforcement and stabilization of foundations and slopes. It was anticipated that the development of reliable engineering guidelines, combined with site monitoring for field performance assessment of micropile systems, would significantly increase the engineer's confidence in the technique and, thereby, greatly enhance its expansion to new fields of application.

The initial investigations included a comprehensive review and critical assessment of available information on current state of the practice, research case studies, site performance monitoring, quality control issues, and any comparisons or analyses of current codes of practice. Several ongoing micropile construction projects were also instrumented and monitored to provide researchers with additional case histories to study and evaluate. The major physical experimental tasks involved centrifuge modeling and related analytical/numerical simulations, full-scale testing, and field monitoring, which were designed to study the engineering behavior of individual micropiles and micropile groups and/or systems under axial and transverse load response modes (figure 10). Buckling, corrosion, and seismic aspects were also investigated under actual working conditions as well as at failure under ultimate loading.

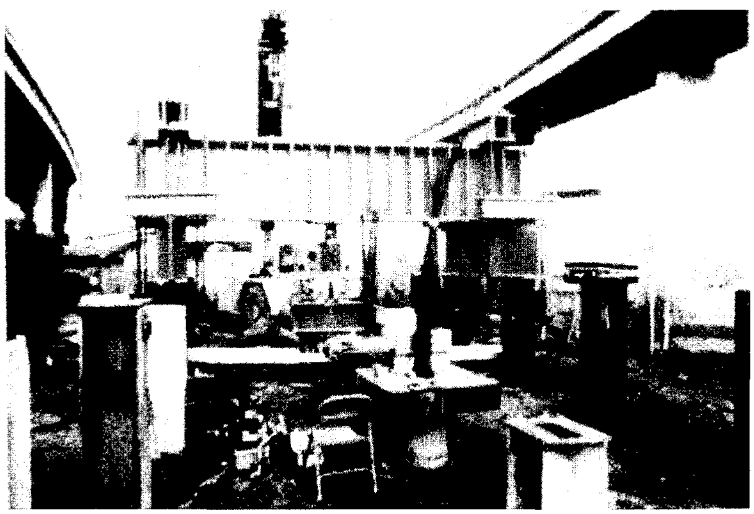

Figure 10. Load testing of micropiles in California.

2.6.7.1 State-of-the-Practice Review

In 1993 FHWA initiated a contract to produce a comprehensive review document that would delineate all of the known information about micropile technology that could be gathered from various organizations around the world. The contractor put together an international group of experts to evaluate the information obtained in the surveys. The review report (15) provides a comprehensive introduction to micropile technology, and assisted FHWA in developing an engineering guidelines manual (7) containing reliable design guides, construction specifications, and quality-control procedures for the wide spectrum of micropile applications.

2.6.7.2 Seismic Behavior of Micropiles

In 1995, FHWA initiated a contract research study to develop improved seismic design methods for micropile systems used in new construction in earthquake zones, seismic retrofitting of bridge foundations, vertical excavation retainment systems, and slope stabilization. Laboratory centrifugal model tests were conducted to correlate with numerical model studies on various micropile systems (isolated piles, groups, and networks of piles) to evaluate their behavior under axial, lateral, and combined loadings in selected engineering applications. Shaking table tests were also conducted at Christchurch University in New Zealand as part of the overall study to improve seismic design methods. This study is scheduled to be completed after this report is printed.

2.6.8 Publications and Implementation Items

Research and development activities for pile foundations were very successful. Results were documented in numerous reports, and several technology sharing reports were issued to help implement the findings. Several workshops and symposia were held to promote the new guidelines and prediction methodologies that were developed under the research program. Several new articles were added to the AASHTO Bridge Specifications and many others were updated based on the FHWA pile foundation research results (see chapter 7).

2.7 Pile Groups

The state of the art for pile foundation design at the beginning of this project did not include an accurate method for relating the ultimate bearing capacity and settlement behavior of a single pile to the behavior of a group of closely spaced piles. To develop such a method, it was necessary to conduct field load tests to failure of full-scale pile groups to obtain field data that were useful in interpreting fundamental phenomena that control the behavior of groups of driven piles.

Older methods of pile group design treated the group as a collection of individual piles requiring an adjustment factor. Predicting the behavior of pile groups required correction of the load capacity of the individual piles in the group for the interaction effects transmitted through the soil mass. How this should be done was never certain, and it was recognized that it would probably be different in cohesive as contrasted to granular soils.

In 1980, FHWA initiated a research program to investigate pile group behavior through carefully performed experiments. First, existing mathematical models used to design pile groups were identified and evaluated. From this evaluation, the “hybrid model” was selected and used to analyze a proposed full-scale pile group to be load tested.

The hybrid model, a load-deformation model, reasonably predicts load versus settlement, load transfer patterns, and load distribution to pile heads. The model was especially helpful in designing the instrumentation system for the full-scale pile group load test. The field data acquired from the load tests were used to refine the hybrid method, which led to the FHWA PILGP1 computer program, a modification and refinement of the hybrid model (see section 2.7.3).

2.7.1 Pile Groups in Clay

To develop the field data required to verify and refine PILGP1, 11 instrumented steel pipe piles were driven into a very stiff, saturated, over-consolidated clay soil at the University of Houston, Texas, campus. The outside diameter of the piles was 273 mm (10.75 in), with a wall thickness of 9.27 mm (0.365 in). The piles were driven closed-ended 13.1 m (43 ft) deep. Nine piles were driven in a 3 x 3 square array on a spacing of three pile diameters. The two remaining piles were driven apart from the group to serve as control piles.

Each of the 11 piles was instrumented with full bridge strain gauge transducers and mechanical telltales to monitor load transfer from the piles to the surrounding soil. Four of the group piles and one control pile were instrumented with piezometers and lateral total pressure cells. The surrounding soil also was instrumented with piezometers and vertical ground movement devices. Electronic load cells measured applied loads, and settlements were measured at each pile head. Three-dimensional translations were measured on the massive concrete pile cap that was suspended off the ground.

The load testing program consisted of 11 compression and 6 uplift (tension) tests, all of which were carried to ultimate failure loads. The control piles were load tested in compression at three time intervals to study the effect of soil setup. Each control pile also was tested in uplift. The nine-pile group (figure 11) was tested in compression at

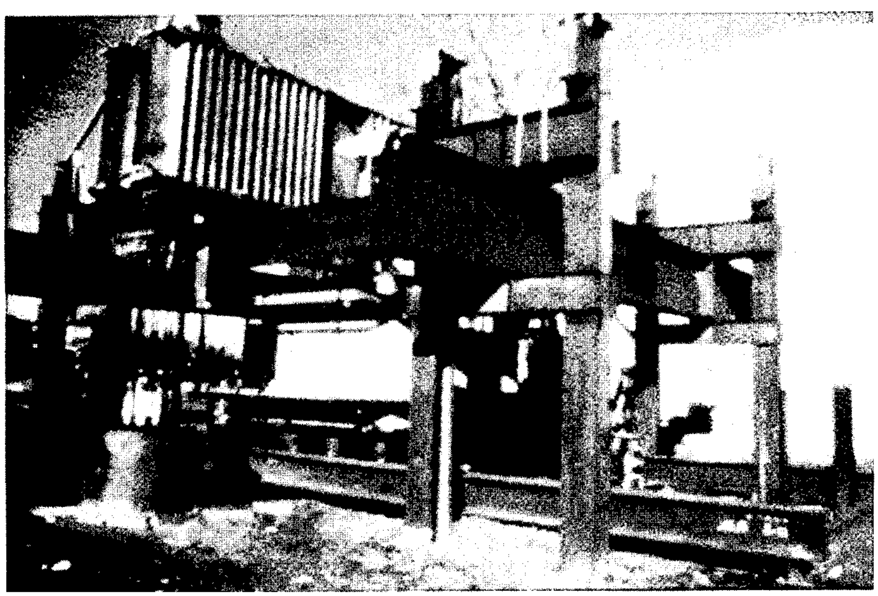

Figure 11. Pile group load test in clay.

three time intervals to assess setup characteristics of the group. Four of the group piles were tested in uplift; however, these tests were preceded by compression tests on two smaller groups of four and five piles. The five-pile subgroup was formed by cutting away the four corner piles, leaving the four edge piles and the center pile. The four-pile subgroup was formed by removing the center pile (8,9).

2.7.2 Pile Groups in Sand

A second pile group load test study was performed on a group of eight timber piles in sands at the Locks and Dam No. 26 near Alton, Illinois, as part of an evaluation of several rehabilitation schemes for the distressed locks and dam structures. The timber piles were instrumented to measure load transfer and deformation up to and including the failure load. The acquired field data were used to evaluate and refine the PILGP1 program (16).

The third pile group study involved load testing five single piles and a group of five piles in sand at a test site in Hunters Point, California (figure 12). The load test results were also used to evaluate PILGP1 and a simplified procedure developed under previous studies of the behavior of single piles and pile groups. Data were obtained on the comparative behavior of piles of different types with the same relative geometry. Residual stresses, load transfer, and load-settlement characteristics were measured and used to evaluate the effectiveness of the new pile design and analysis procedures. An isolated control pile and three of the five group piles were fully instrumented, to obtain the load-response data for the analysis. Soil and ground water conditions were evaluated with standard and state-of-the-art equipment, such as Standard Penetration Test, Dutch Cone, Stepped Bladed Vane, Dilatometer, and Pressuremeter testing

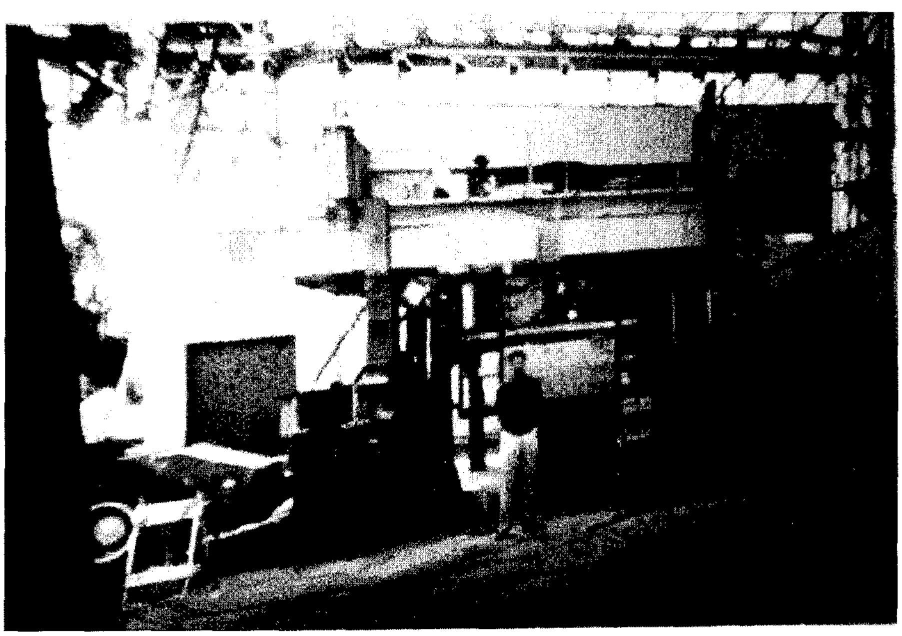

Figure 12. Reaction frame for pile group load test in sand.

devices (17). Figure 13 shows a closeup view of the test pile group and two soil instrumentation boreholes.

Figure 13. Instrumentation bore holes adjacent to pile group.

After each of the first and third pile group load test studies, a pile group prediction symposium was held to discuss the test results and evaluate the most popular pile group design methods in use at that time (18,19,20).

2.7.3 Predictive Model for Pile Group Design and Analysis (PILGP1)

A comprehensive computer-aided design method called PILGP1 was developed for FHWA at the University of Houston for the design and analysis of pile groups. It is a load deformation model that predicts load versus settlement behavior, load transfer patterns, and load distribution to pile heads. The model designs the pile group as an interactive element rather than as a collection of individual piles requiring an adjustment factor. It was developed from the results of the first full-scale field load test program on single piles and pile groups. Two additional full-scale field load test programs were later completed to further refine and validate the computer model. The current version of the model (PILGP2) is being tested by several consulting firms, States, and Federal agencies. Continued testing, evaluation, and refinement of the model is currently under way.

The development and verification of PILGP1 was based primarily on the full-scale field tests of pile group behavior under both working loads and failure conditions. Because of the many variables involved, numerous full-scale field tests needed to be conducted to provide a statistically meaningful data base. However, the costs involved in full-scale field testing significantly restricted the number of tests that could be conducted. The alternatives to full-scale field testing are model field testing, laboratory model studies, and centrifuge model testing.

2.7.4 In-Service Monitoring of Pile Groups

The three full-scale pile group load tests to failure produced very accurate and valuable data; however, they were very expensive to conduct. In addition to the pile group load tests to failure, four full-scale field projects were initiated with FHWA research funding to observe pile group behavior under working loads. The short- and long-term behavior of the in-service piles was compared with analytical predictions made by PILGP1.

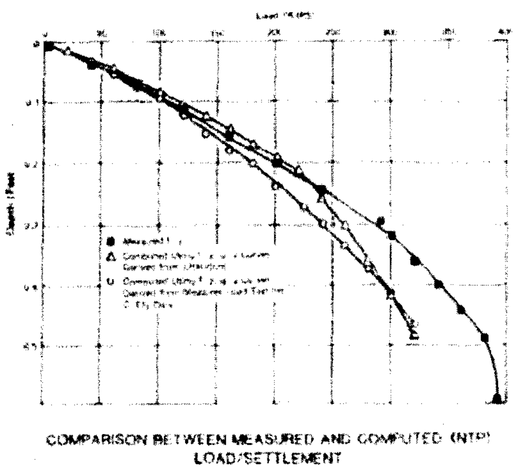

Figure 14. Load/settlement for Natchez Trace Parkway bridge.

One of the projects was located on the Natchez Trace Parkway (NTP) in Mississippi, where a pile-supported bridge abutment was instrumented to obtain load transfer data on a group of six steel piles (12 HP 53) in soft clay and silt. Samples of load/settlement curve data are shown in figure 14. Another project was located at Fort Belvoir, Virginia, where soil and pile conditions were similar to those at the Mississippi project. Instrument readings were taken weekly during the first year at each site, monthly during the second year, and quarterly for several years.

The third site, at the Mocks Bottom over-crossing in Portland, Oregon, near Swan Island, is underlain by a thick compressible clayey silt deposit. High down-drag loads were expected because of the approach embankment loads on the compressible soil. A bitumen coating was used to reduce down-drag loads by about 90 percent. Although the bitumen-coated piles cost about 15 percent more than the uncoated piles, fewer piles were required. Pile instrumentation included settlement and load transfer monitoring.

The fourth site was located at the West Seattle Freeway in Washington where a group of twelve 310-mm- (12-in-) diameter concrete piles supports a pier in medium-dense sands. The bridge pier and pile cap were instrumented to measure the amount of load transferred to the pile cap, and each pile was instrumented to measure load transfer from the pile cap to the top of the piles. Three piles were instrumented for load transfer along the entire pile length of 30.5 m (100 ft).

2.7.5 Model Testing

The high cost, measured in both time and money, of obtaining high quality data from full-scale load tests on single piles and pile groups, led to the FHWA staff study to determine if accurate data could be obtained by conducting model tests in simulated ground conditions.

Using carefully controlled large test pits located at FHWA's Turner-Fairbank Highway Research Center (TFHRC), more than 200 model tests on single piles and pile groups have been completed on several different types of piles in sand and clay soils. These data are being compared with the carefully controlled centrifugal and full-scale single pile and pile group load test data. This work is continuing as more variables are studied, and results are entered in the load test data base to be used for verifying and refining the PILGP1 model.

An investigation of scale effects is an important part of this study to determine if the model test data can be productively correlated with the load test data of the full-scale field tests. The establishment of appropriate scale factors allowed more model tests to be substituted for expensive full-scale tests. Small-scale models permit numerous parametric studies at a reasonable cost, and allow soils and other conditions to be carefully controlled.

The first series of laboratory model tests was patterned after the timber pile field study at Alton, Illinois. The sandy soil at the Alton test site was matched as closely as possible at TFHRC. Model load tests were run on single piles and pile groups (figure 15) at 1/20, 1/15, 1/10, and 1/3 full scale. As a minimum, three load tests were performed for each scale. Each pile was instrumented with strain gauges to measure load transfer.

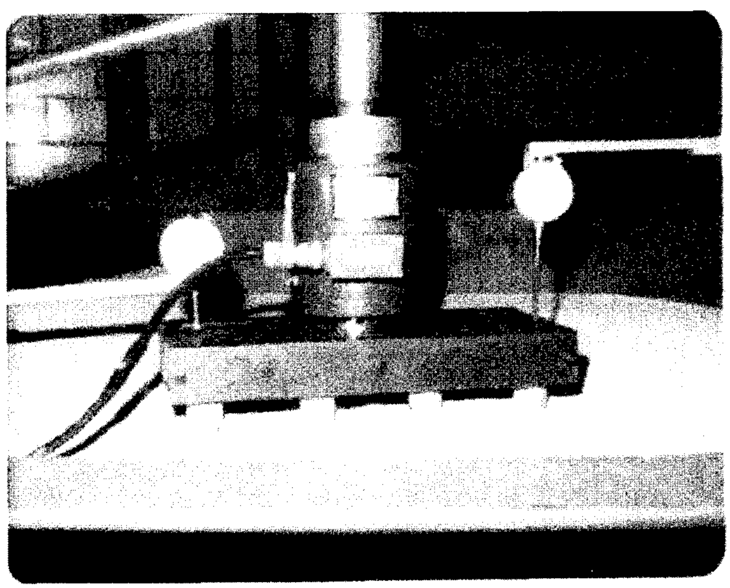

Figure 15. Load test on small-scale model pile group in test tank.

The second series of laboratory model tests was patterned after the full-scale load test on steel pipe piles in clay. Model tests were run at 1/15, 1/10, 1/6, and 1/4 full scale. The laboratory model tests on the 1/20, 1/15, and 1/10 scales were performed in a steel tank 1.5 m (5 ft) in diameter and 1.5 m (5 ft) deep. Because the 1/6, 1/4, and 1/3 scale models were too large to be tested in the laboratory test mold, outdoor test pits were constructed at the TFHRC site (figure 16). The third series of tests was patterned after the full-scale pile group load test to failure at Hunters Point, California.

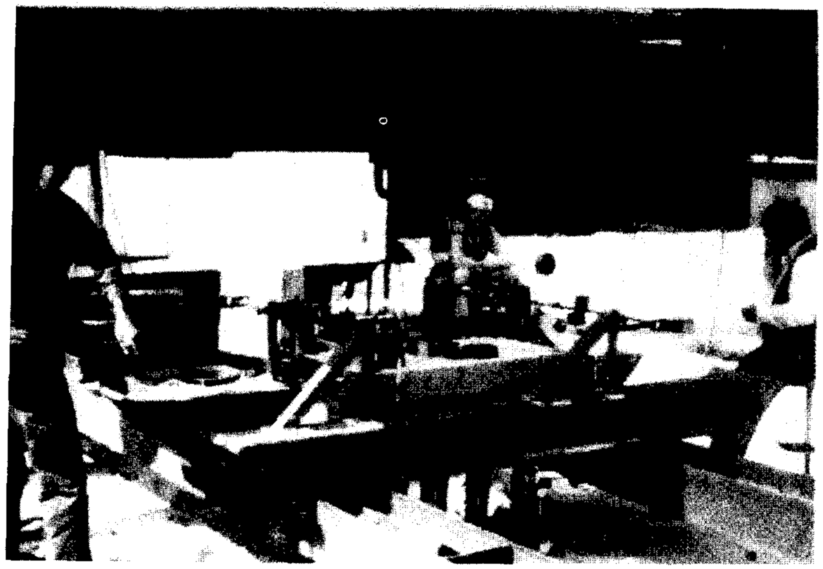

Figure 16. Load test on large-scale model pile group in test pit.

The scaling factors identified in this study were used to establish relationships between load deformation behavior of reduced-scale and full-scale piles and pile groups. These small-scale tests provided a significant amount of data to validate PILGP1 at less cost than full-scale field testing.

2.7.6 Centrifuge Model Testing

Small-scale models permit parametric studies at reasonable cost and allow soils and other conditions to be carefully controlled; however, it is difficult to achieve similitude between corresponding stresses and strains in the model and prototype. The response to load of a small pile and a large pile cannot be modeled by any simple, direct relationship derived by ordinary dimensional analysis. The question of scale effects must be resolved before any useful relationships for pile design can be developed.

Models of large, heavy structures where gravity is a principal loading factor are not effective indicators of prototype behavior because the state of stress in the model caused by self-weight will be much lower than in the prototype. If the model can be placed in an artificially high gravitational field, the state of stress limitation can be counteracted almost entirely. A centrifuge apparatus provides the necessary accelerated gravity rate to load test the model under simulated gravitational forces. However, to accurately measure stresses and strains, the centrifuge must be able to accommodate a model that is large enough to handle the required instrumentation. The larger centrifuge capacity provides more accuracy in direct modeling of large prototype structures. A pilot study validated the feasibility of using centrifuge techniques for corroborating the PILGP1 mathematical model.

In a larger study, the centrifuge was used to test models of the full-scale pile groups that were load tested to failure in the previously described field studies. The combination of centrifuge model testing and small-scale laboratory testing of conventional models at TFHRC provided valuable physical data to establish relationships between pile groups of varying scales in the same environment.

The larger, more comprehensive centrifuge testing program on single piles and pile groups was performed in sand and clay soils. The results were used to test and verify assumed similitude relationships between scaled models and full-scale prototypes. The load deflection and load transfer data were used to predict full-scale performance and compared favorably with both measured results and predictions made by computer generated results. The experimental procedures developed and the verification established in the program has encouraged the investigation of the many factors that influence pile performance under controlled laboratory settings. The centrifuge technique should also be useful and very cost-effective in establishing the predicted behavior and the sensitivity to design changes of pile foundations for large projects (21).

2.7.7 Lateral Loads on Pile Groups

Several analysis and design methods for pile groups under lateral loading have been proposed, but none had been validated using carefully performed field experiments on full-scale structures. The theory of elasticity and a number of "efficiency" formulas often were used as analytical methods for lateral load design. One of the most promising methods is called the Poulos-Focht-Koch (PFK) procedure. This method was evaluated through field load tests. Data from the load tests also were used to develop an improved method of analysis.

The main objectives of the field load tests were to provide high-quality field data on the performance of a full-scale pile group under lateral loading and to compare measured response with that predicted by the PFK method. The load test was performed at the FHWA pile group test site at the University of Houston, Texas, campus using the same piles and some of the instrumentation used in the vertical load tests previously described.

The results of these tests were also evaluated under a cooperative study with the U.S. Army Corps of Engineers that was performed at the University of Houston site. After the lateral load tests in clay were completed, the researchers replaced the top 3 m (10 ft) of clay with sand backfill and repeated the load tests. The test results were used to refine and validate the predictive models (22).

2.7.8 Publications and Implementation Items

Research and development activities for pile group foundations were very successful. Numerous quality reports were generated from an unprecedented program of research into an area where few have ventured and none to the same extent. Textbooks and specification codes have incorporated the results of these tests, and the state of the art was advanced significantly.

2.8 Drilled Shafts

A drilled shaft is a machine-excavated circular hole in soil and/or rock that is filled with concrete and reinforcing steel to support heavy structural loads in single or multiple units. Vertical loads are resisted by both the base area of the shaft and in side friction which can be very significant because the concrete is cast wet and cures directly against the soil forming the walls of the borehole. They are sometimes socketed in rock, and steel casing is sometimes required for hole stabilization that may or may not be removed. Horizontal load is resisted by the shaft in horizontal bearing against the surrounding soil or rock.

Drilled shafts have many advantages that set them apart from piles and spread footings. In fact each foundation element has certain pros and cons that have to be weighed one against the other when deciding on which system to use in a particular design situation. Each system also has several disadvantages that have to be evaluated for each design situation. To give confidence as to performance with respect to the intended task, any foundation element requires both a reliable method of construction and a standard to define acceptance after construction.

In this regard, drilled shafts were considered to be less reliable than others because of the uncertainty of the effects of construction on the actual service behavior, and the limited knowledge of either reliable quality-control tests to locate and evaluate defects or inexpensive load test procedures. Even if there are only occasional failures, they highlight the variables and unknowns present when working underground, particularly in water-bearing and potentially caving soils. This results in a lower risk tolerance for a single or double shaft supported pier compared with multiple pile supported foundations.

Because drilled shafts for many design situations offer higher capacities with potentially better economics than driven piles, the FHWA has spent considerable time and money in research and development of improved design and construction guidelines for drilled shafts. Other advantages include less noise and vibration during construction and the ability to go very deep to avoid scour problems. A major research program was designed to evaluate existing nondestructive testing techniques for identifying defects and/or results of adverse downhole conditions that impact the load transfer/settlement behavior of drilled shafts. It was also planned to develop rational acceptance criteria for defective drilled shafts on the basis of quality control during construction, plus a field test program to verify the research findings that included a search for more economical methods to test shaft capacity with and without defects.

2.8.1 Nondestructive Evaluation (NDE) of Drilled Shafts

In July 1988, FHWA initiated a contract research study to examine drilled shafts for the effect of defects on performance, and to develop acceptance criteria for use by construction engineers to accept, reject, or modify a newly constructed drilled shaft. The

Figure 17. Full-scale drilled shafts for NDE study at Texas A&M test site.

study included the construction of 20 drilled shafts with and without defects for different soil sites located in California and Texas (figure 17). The shafts were constructed using different techniques: dry construction, and wet construction using drilling water, controlled bentonite slurry, and controlled polymer slurry. Five instrumented shafts were statically load tested (figure 18) to determine the effect of the man-made defects on shaft performance, and all shafts were dynamically load tested to correlate with static results. All shafts were tested non-destructively using both surface reflection and direct transmission techniques to determine their effectiveness in identifying defects and/or the results of adverse down-hole conditions that impact the load/settlement behavior of the shafts; results were summarized and evaluated in the report. The allowable defect criteria developed consider the design basis, the ratio of design stress to a maximum code allowable, the type of stress, the level of quality control, and the risk tolerance.

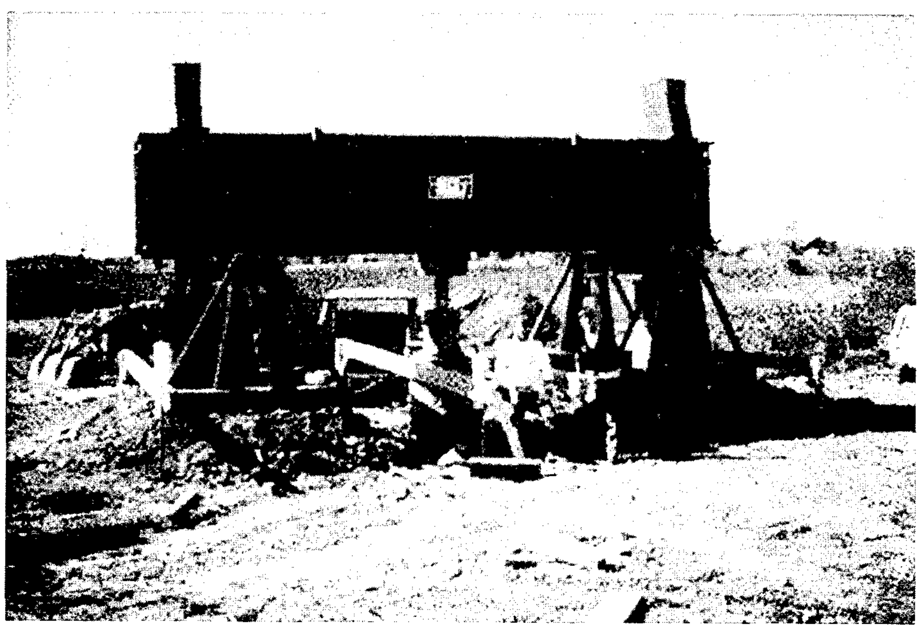

Figure 18. Vertical load test of defective drilled shaft.

In addition to the establishment of acceptance criteria, a rating guideline for implementing special integrity testing and a decision tree were developed to guide the engineer or decision maker through construction of a drilled shaft project that includes nondestructive testing. The report also includes detailed information on four promising low-strain NDE techniques (sonic echo, impulse response, cross-hole sonic logging, and gamma-gamma logging), which can be used as part of the quality control procedure, plus information on three alternative load test procedures that show high potential for being economical substitutes for expensive static load tests (see section 2.10).

The sonic echo (SE) and impulse response (IR) test methods use impact energy applied to the top of the shaft to generate energy waves down the shaft and return to a receiver that measures the vibration response. These methods are not able to locate deep defects and they aren't able to detect the size and location of the defects. Smaller defects lying below a larger defect are easily masked from above. Cross-hole sonic logging (CSL) and gamma-gamma logging (GGL) overcome these problems by being downhole methods that pass ultrasonic or radiation waves through the concrete between source and receiver probes in a water-filled tube or hole pair as the probe cables are pulled from the bottom back to the surface over a depth measurement wheel. These methods test the quality of the concrete lying between a pair of tubes. Four tubes installed in a shaft before concreting gives sufficient coverage to adequately inspect a shaft for defects. Figure 19 shows an end view of a rebar cage with four NDE access tubes.

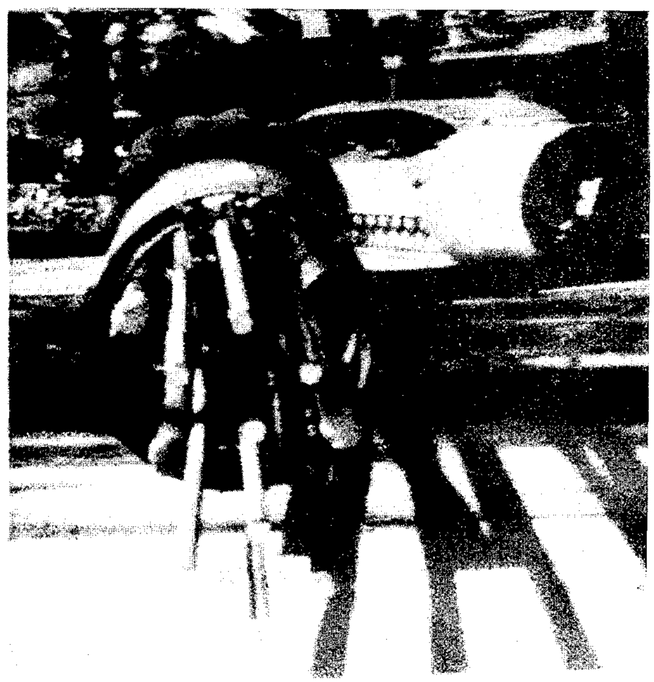

Figure 19. Instrumented drilled shaft showing man-made defect and NDE access tubes.

Results clearly show that the CSL method is superior. The GGL method requires a radiation source and requires PVC tubes because steel is not compatible with the radioactive materials. This method is also sensitive to defects close to the test tubes, and doesn't have the same range away from the installed tubes that CSL has. In addition, CSL is generally much faster to perform and does not use radioactive materials (23). Figure 20 shows a technician performing a surface deflection test on one of the defective shafts.

Figure 20. Low-strain impact test with instrumented hammer and geophone sensor.

2.8.2 Drilled Shafts in Intermediate Geomaterials

Current design methods for drilled shafts in soil or competent rock are reasonably well-founded; however, comparatively little effort has been expended to determine design parameters for intermediate materials such as shales, claystones, and marls. In September 1991, FHWA signed a second contract to develop, test, and recommend criteria for determining appropriate exploration, in-situ testing, and the necessary inputs to the load transfer function or other design methods for drilled shafts in intermediate geomaterials.

The contract consisted of essentially three tasks:

1. The first task required a literature search and discovery of case histories involving drilled shafts. Of particular interest were projects that employed analytical or semi-analytical methods based on soil mechanics principles and load-transfer function concepts, as well as locations where load test data existed.

2. Using existing exploratory and sampling techniques that were known to reliably characterize the geomaterials and quantify design material parameters, a preliminary set of criteria for exploration, in-situ testing, and load transfer design mechanisms was developed.

3. Using this pilot test program, specific plans, specifications, and estimates for conducting research tests were developed for locations where state or private projects included load testing of drilled shafts. The contractor performed soil characterization tests and predictions of shaft behavior, including instrumenting selected shafts for load-transfer analysis. Upon completion of these projects, the pilot criteria and design methodology were revised or modified to better predict drilled shaft behavior.

Data were collected from projects in Australia, Georgia, Texas, Massachusetts, and Kentucky. These data have been used to develop the criteria for exploration and sampling of soil materials to use for developing new load transfer functions for the design of drilled shafts in shales, tills, and other materials between soils and hard rock. A field test program was also designed to validate the new design methods (24).

2.8.3 Free Fall of Concrete in Drilled Shafts

This study developed information and data that were used to justify increased depths of free-fall placement of concrete into properly constructed clean and dry shafts without meaningful loss of strength or segregation of the concrete aggregate. The report of findings has had a significant economic impact on the drilled shaft industry.

Prior to this study, the question of whether the free-fall of concrete over long distances adversely affects the concrete strength and integrity in drilled shafts persisted in the minds of many engineers and construction inspectors. This question persisted despite past efforts to answer it and dispel the concern that concrete does not segregate during free-fall at any height, and that free-fall placement can be accomplished without adverse effect on the concrete.

To accomplish the research goals in a cost-effective way, four 18-m- (60-ft-) long, 0.9-m- (3-ft-) diameter shafts evenly spaced and tangent to a central 1.5-m- (5-ft-) diameter access shaft were constructed. The four test shafts were divided into six 3-m (10-ft) sections with one of four different concrete mixes placed in each section. The slump, maximum aggregate size, and placement procedures were also varied. The low slump mixes were also placed with and without super plasticizer. The three placement procedures were free-fall central drop with careful control to be sure that the concrete didn't strike the rebar cage, free-fall sloppy drop with effort actually made to see that the free-falling concrete did hit the rebar cage, and tremie placement with a tremie pipe extended all the way to the concrete placement level.

The results of the research were very conclusive and positive. Construction codes have been changed in many cities, counties, and States, accordingly. More specifically, the results were as follows:

None of the lifts placed by central drop free-fall procedures within the research program exhibited any signs of aggregate segregation. The design strengths of all centrally dropped lifts varied from 13 percent less to 20 percent more than the reference cylinder strengths. All of the strengths were well above the intended design strength.

Due to the small variation in the compressive core strength and lack of aggregate segregation, no definitive effect of slump, aggregate size, height of drop, depth of fluid pressure, or addition of super plasticizer was discerned.

Surprisingly, in six out of seven direct comparisons made between sloppy drop and central drop placement procedures, the sloppy drop methods actually resulted in higher average compressive core strengths than equivalent central drop procedures. Also, no segregation of aggregate was noted for any of the sloppy drop mixes placed. Thus, on the basis of this research, it is concluded that striking the rebar cage or the side of the shaft does not have a detrimental effect on the strength or integrity of the concrete.

Due to the high strengths and lack of segregation that were apparent in all of the sloppy drop lifts, the effects of aggregate size, slump, height of drop, height of fluid pressure, and addition of super plasticizer did not appear to affect the results in a meaningful way for the well-designed concrete mixes. Even though sloppy drop procedures were not found to affect the strength or segregation of the concrete, it is not intended that contractors should begin to place concrete in a haphazard fashion. The sloppy drop procedure adversely affected the placement of the rebar cage and also caused additional concrete contamination as a result of traveling down the soil sides of the shaft. In all cases, the shafts were fully formed and no honeycombing, voiding or exposed rebar was evident (25).

2.8.4 Load and Resistance Factor Design of Drilled Shafts

In early 1997, FHWA co-funded a research study on "Resistance Factors for Drilled Shafts with Minor Defects" with the Association of Drilled Shafts Contractors (ADSC) and a number of SHA's including California, Florida, Illinois, Minnesota, Montana, North Carolina, Pennsylvania, and South Dakota. The objective was to develop design techniques to account for sub-detectable minor defects that can occur during construction. The analytical study and most of the experimental work was done by the University of Houston at its National Geotechnical Experimentation Sites (NGES) facility. Some of the future testing will be done by FHWA staff at the TFHRC.

It is proposed to derive resistance factors (or "workmanship factors") for drilled shafts through analytical modeling that will be calibrated by performing field loading tests to structural failure on drilled shafts with selected defects. The load testing will primarily be lateral because the loss of moment resistance in the lateral mode of loading is potentially more severe than loss of axial capacity for drilled shafts with steel percentages normally used in highway bridge construction.

A computer program called LPILE Plus was modified to perform accurate and realistic modeling of the influence of minor defects on drilled shaft behavior. The modified version allows for the development of an independent stress-strain curve within the defect area. It also allows for a reduction in the tensile strength of both the defective and nondefective portions of the shaft section. A defect may be located in either the compressive or tensile portion of the shaft. It is also possible to include more than one defect in the same section. Six field lateral loading tests were conducted to verify and calibrate the modified LPILE model.

Lateral load tests were conducted by jacking a test shaft against a reaction frame consisting of a wide flange steel girder supported by two reaction shafts. A manual jacking system was used to jack the test shaft against the reaction frame. Loads were measured with a load cell and dial gauges were used to monitor lateral deflections of the test shafts. All test shafts were constructed under wet conditions using a polymer slurry.

The test shafts were then extracted and examined carefully to determine the location of the plastic hinges, and to caliper the exact dimensions along the shaft axes. The results of the load tests will be used to verify or to calibrate the modified version of LPILE. This modeling will be eventually used to develop recommendations for resistance factors for drilled shafts under combined axial and lateral loading. Preliminary recommendations will be developed in this phase of the research, while more general and refined recommendations will be developed in the following phases if the results of the preliminary phase justify further study.

Because typical drilled shaft defects are usually found at the boundaries between soil and concrete, they can have effects on both the structural performance of the drilled shafts and the soil-structure interaction. To isolate the effect of the structural defects from the variation in the soil resistance, structural laboratory tests will be conducted on slightly defective shafts out of the soil at the TFHRC, if the preliminary field test results appear to justify the effort. The results of this testing program will also be used to verify the method in the modified version of LPILE that is used to model the changes in cross-section and stress-strain behavior within the concrete drilled shaft.

Eight drilled shafts will be tested in the TFHRC laboratory experiment. Both the diameter and steel reinforcement of the laboratory experiment will be identical to those of the field load tests. The laboratory test shafts will include defects essentially similar to those included in the field tests. To investigate the effect of rebar corrosion, the diameter of the rebars of two additional defective shafts will be reduced to one-third of the original size within the defect. Six slightly defective drilled shafts will be tested under pure bending moment conditions. One of the other two shafts will be tested under combined shear and bending moment, and the last shaft will have no defects (reference shaft) and will be tested under pure bending moment conditions.

If the results of the load tests at TFHRC and NGES-UH prove successful, additional field loading tests will be conducted on slightly defective shafts over a larger range of soil conditions and for a larger range of defect types sufficient to provide recommendations for the AASHTO code committees. It is also possible that the testing will be extended to include fixed-headed shafts because the preliminary work only looked at free-headed shafts.

It is expected that these results will help to solve the problem or source of conflict between some (usually owners) who interpret any anomaly that shows up on NDE signatures as a defect and others (usually contractors) who believe that all anomalies are not necessarily defects that require attention. Serious defects require further probing, immediate repair, or penalty charges assessed against the contractor; however, minor defects should be accounted for in design through the derivation of appropriate resistance factors.

2.8.5 Publications and Implementation Items

Research and development activities for drilled shafts were very successful. Several quality reports were generated and appropriate specifications and codes were revised (see chapter 7) to reflect the positive results and improved procedures developed under the research program. The FHWA design manual and instructional workshops were also updated to reflect the advancements and contributions of this program.

2.9 Spread Footings

Foundation engineering is one of the oldest professions of mankind. The major decision in selecting a foundation system has always been whether to use shallow or deep foundations to support a superstructure. Foundation support is achieved by transferring the loads to the ground materials without incurring excessive settlements or distortions. Shallow foundations (spread footings or mats) normally are less expensive to construct than deep foundations (piles, drilled shafts, or caissons). However, surface soils usually are less capable of supporting heavy loads than deep soil deposits or bedrock. Deep foundations provide extra security against bearing capacity failure or settlement. A greater risk of unexpected engineering and contractual problems exists, however, during deep foundation installation. Engineering and cost analyses are necessary to determine the proper foundation system for major structures, such as bridges, buildings, dams, and nuclear power plants.

The use of spread footings to support highway bridges in the United States varies widely between States and appears to be far below the optimum level. A recent survey by FHWA determined that most States use pile foundations to support the majority of their bridges. The extensive use of piles to support U.S. highway bridges is contrasted by the extensive use of spread footings to support highway bridges in some foreign countries. For example, highway bridges in England seldom are founded on piles despite severe subsidence problems from coal mining. Another contrast can be seen in the building industry where spread footings and mat foundations are used quite extensively even though building elements (for example, doors, windows, elevator shafts, and utilities) have less tolerance to settlement than bridges.

In the United States, many tons (megagrams) of pile materials and large sums of money have been devoted to using pile foundations where spread footings might have been appropriate. The extensive use of piles in highway bridge foundations may have been encouraged by the AASHTO Bridge Specifications, which at one time stated that "piling shall be considered when footings cannot, at reasonable expense, be founded on rock or other solid foundation material" (circa 1990).

Some of the reasons that piles were preferred over spread footings as a foundation for highway bridges include the following:

- The lack of well-documented performance evaluation data.
- The lack of rational tolerable movement criteria for bridges.
- Skepticism and uncertainties concerning the potential cost-savings and the accuracy of settlement predictions for spread footings.
- Skepticism and uncertainties concerning the quality of fill or natural ground below the spread footings.

The advent of reinforced concrete in the early 1900's and recent improvements in excavation technology have increased greatly the appeal of spread footings for bridge foundations. Modern soil mechanics and improved methods of site investigation and laboratory testing have improved the accuracy of settlement and bearing capacity predictions. Also, compaction control and improved grading procedures have minimized spread footings being founded on weak and/or compressible soils. Finally, special ground improvement techniques such as soil reinforcement, stone columns and dynamic compaction have increased the attractiveness and applicability of spread footings.

Many highway agencies have a policy not to use spread footings on cohesive soils because of the concern for bearing capacity failure and/or excessive settlement. This is a conservative approach because some cohesive soil deposits (especially over-consolidated clays) can support heavy bridge loads without distress resulting. Although bearing capacity on sands is not a problem, some highway agencies do not use spread footings on cohesionless soils because of the concern for excessive settlement. This also is a conservative policy because a spread footing on sand usually will provide satisfactory support because consolidation of sands usually is minimal and occurs rapidly. Most of the settlement occurs before the sensitive superstructure elements are erected.

The use of spread footings on compacted fill also is infrequent. Although a properly compacted fill often is stronger and more stable than natural ground and easily able to support a spread footing, designers often use spread footings on in-situ soils and avoid their use on prepared fills. Large settlements from fills usually can be traced to older, nonuniform fills that may have been constructed of poor soils or uncompacted waste materials dumped on unprepared natural ground surfaces. However, the use of random, uncontrolled fill in modern highway construction, especially near bridges, is readily avoidable. The Connecticut and Washington State transportation departments frequently support bridge abutments on spread footings on compacted fill.

A foundation system must be functional as well as safe. There is a wide degree of engineering performance between an unyielding support system and one that fails. Persistent maintenance problems and failures of noncritical elements (such as parapet walls and joints) are expensive to correct and should be avoided if peculiar to certain systems, situations, or methodologies. To improve the design process, engineers should correlate functional distress (bumps, cracks, and misalignments) with system characteristics (abutment type, soil type, superstructure type, and amount and kind of movement) to determine where spread footings are and are not appropriate.

2.9.1 Performance Evaluation Studies

To increase the number of documented case studies of spread footing performance, FHWA staff, in cooperation with the Washington State Department of Transportation (WASHDOT), evaluated the performance of numerous highway bridge abutments supported by spread footings on compacted fill. During this review, the structural condition of 148 highway bridges throughout Washington State was visually inspected. The approach pavements and other bridge appurtenances also were inspected for damage or distress that could be attributed to the use of spread footings on compacted fill.

On the basis of this review and detailed investigations of the foundation movement of 28 selected bridges, it was concluded that spread footings can provide a satisfactory alternative to piles, especially when high embankments of good-quality borrow materials are constructed over satisfactory foundation soils. None of the bridges investigated in Washington displayed any safety problems or serious functional distress; all bridges were in good condition (26).

On the basis of the results of the Washington Department of Transportation study, FHWA decided to expand the idea of spread footing evaluations by initiating a comprehensive field investigation of 10 new bridges being constructed in 5 northeastern states. Under this research contract, a long-term study of the settlement performance of 24 spread footings supported on sand was completed to provide a reliable data base for engineering evaluation. Figure 21 illustrates the instrumentation monitoring plan for this study.

The results of the northeastern bridge studies served to confirm the performance results of the WASHDOT study and added to the value of the FHWA data base. The researchers were also able to locate 10 good-quality case histories in the literature for use in the data base. Many cases were identified but most were found to be lacking sufficient settlement or soils data to be included in the study. It was also noted that all of the case histories in the data base represented actual projects where loads were limited to working stress levels. A definite need existed to obtain settlement and soils data at failure loads to provide a larger and more comprehensive statistical basis to judge the effectiveness of settlement predictions and the satisfactory performance of spread footings on sand (27).

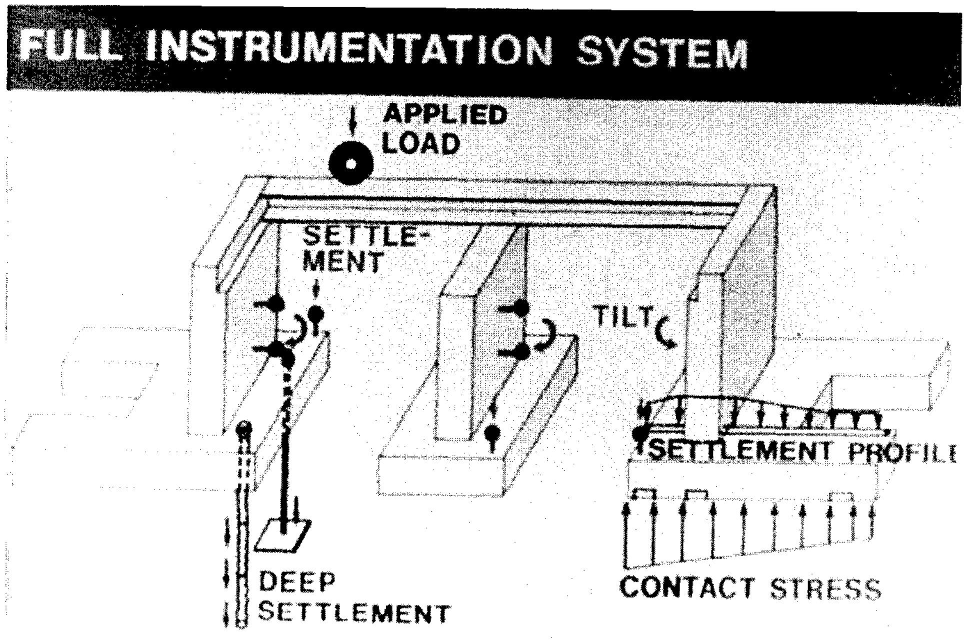

Figure 21. Schematic of instrumentation plan for spread footing performance evaluation study.

A follow-on study was initiated to develop a rational prediction method and a user-friendly data base with prediction and correlations modules for use in designing spread footings on sand. As part of this study, the contractor built five large model footings on sand at the Texas A&M University's National Geotechnical Experimentation Site. Each footing was carefully instrumented and load tested (figure 22) to failure (28). A prediction symposium was also held to discuss the results of the load test program and to evaluate the most popular settlement prediction methods in use at that time (29).

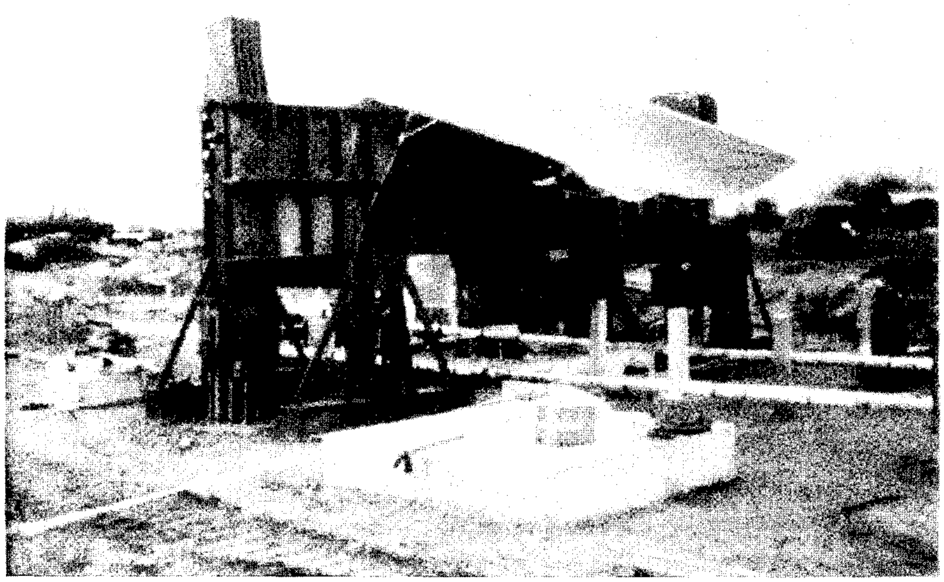

Figure 22. Load testing of large model spread footing.

2.9.2 FHWA Staff Research on Spread Footings

A series of smaller model load tests was concurrently conducted at TFHRC to evaluate the effects of a high water table, depth of embedment, size and shape effects, and the use of geosynthetic reinforcing elements within the sand beneath the footings (see section 3.5.3 for complete details). A total of more than 100 model footings was instrumented and load tested to failure. The test data were added to the data base (see section 5.2.2). All of the footing load tests were performed by following the ASTM Guidelines (D1194-72-1993).

A minimum of five nuclear density and moisture content readings were taken at each 0.3-m lift of sand during placement operations to characterize the soil fill. After filling the test pit, in-situ soil tests were done to complete the soil characterization work.

Results show that embedment has a very significant positive influence on the performance of footings of the same size, even when the water table is close to the bottom of the footing. Placement of the footing base at a depth equal to the width of the footing increases the ultimate bearing capacity by three to five times the value of a footing resting on the ground surface.

The depth of the water table also affects the ultimate bearing capacity of the footing. Those footings resting on sand with a high water table performed much worse than those where the water table was lowered some distance below the base of the footing. Bearing capacity values increased by a factor of two when the water table was lowered from the surface to a depth equal to the width of the footing. Also, as expected, the bearing capacity increased with increasing width of the footing and relative density. A comparison was made between the measured results of each footing load test and the predicted values for bearing capacity using the results of each in-situ test (30).

2.9.3 Dynamic Testing of Footings

At both the TFHRC and Texas A&M University (TAMU) sites, a separate but coordinated study was conducted to evaluate a novel idea to develop a dynamic measurement system that can be used to quickly determine a soil stiffness modulus beneath a footing in order to ascertain if the natural ground or man-made fill is of sufficient quality to adequately support the imposed loads on the footing. An NDE test, termed the Wave Activated Stiffness test, was proposed to be a more efficient, less costly method of checking for bearing capacity and settlement adequacy than conventional static load testing or performance observations. These are "after-the-fact" methods as opposed to the "before-the-fact" dynamic methods that are done during construction, just after the footing is built and before loads are applied.

This nondestructive impact test is called the WAK test for short, rather than WAS because of the common use of "K" to symbolize soil stiffness in most design equations, coupled with the fact that the impact of the instrumented hammer when it strikes the footing sounds like a loud "whack." The instrumentation consists of a force transducer attached to the tip of the sledgehammer and geophones placed at the diagonal corners of the footing to record the footing-soil response to each impact blow. The force transducer provides the input to the system (impact force) and the geophones yield its response (velocity of the footing).

The impact of the hammer causes the footing and a bulb of soil directly beneath the footing to vibrate. The velocity of this vibration is measured by the geophones. The theory is based on a simplified, linear system model of the soil-footing assembly. This model consists of a mass, a spring, and a dashpot, which is frequently used to describe the vertical vibration of soil-structure systems. The compression wave that travels down a steel pile when struck by a heavy hammer is another example of this modeling tool.

Twenty-two WAK tests were conducted at the FHWA TFHRC site and 16 at the TAMU site. Conventional static load tests were also performed on each footing where a WAK test was done. All results indicate good agreement between static load test stiffness and the dynamic stiffness from the WAK test. Each of the footings was tested four times with the WAK equipment; twice before and twice after the static load tests were conducted.

A plot of dynamic stiffness results against static stiffness results for the entire series of footing tests yielded a graphical relationship that allows one value to be picked off the plot if the other one is known or determined by testing. Therefore, a dynamic result can be used to approximate a static stiffness parameter K (which represents the slope of the initial part of the static load settlement curve) without actually running an expensive static load test.

The manufactured K value can be used to estimate the supporting capacity during construction when there is still time to correct any problems. This type of test can also provide a small measure of comfort to design engineers who fear that construction operations may not actually provide a solid foundation base beneath the footing. Such a test will help to identify poor compaction problems and other possible construction deficiencies that could occur when spread footings are used in lieu of piles (28).

2.9.4 Publications and Implementation Items

Research and development activities for spread footings were very successful. The research reports documented the testing and evaluation results and presented recommendations and supporting information for using spread footings in lieu of deep foundation elements in situations where foundation soils could safely transmit bridge loadings without damaged settlements resulting. Technology transfer items were developed to inform practitioners about the research findings and new ideas being promoted. The AASHTO Bridge Specifications were revised as a direct result of this research project on spread footings (see chapter 7).

2.10 Foundation Load Testing

During the past 20 years of bridge foundation testing and evaluation, FHWA researchers have learned a lot about what works and what doesn't work. Hundreds of load tests have been conducted at TFHRC by staff personnel, and hundreds more have been funded by FHWA in field and laboratory projects. Numerous innovative improvements have resulted from these efforts, which, in turn, have led to advancements in the testing techniques and in foundation engineering design and analysis.

All of the early work and most of the later work was done by static load testing, which is considered by most engineers to be the most reliable way to determine the bearing capacity and load/settlement behavior of a foundation element or groups of elements. It is, however, also very time consuming, cumbersome, and expensive to perform, especially on large elements or groups. Safety is also an important issue because of the sheer massiveness of the required loading systems. As previously discussed, dynamic pile driving methods have become a common alternative to predict the bearing capacity of piles, but these methods are empirical, their accuracy varies considerably, and the trend toward much larger and deeper elements reduces their applicability. Also, they do not provide direct measurements, they induce high accelerations, and the load/settlement behavior is controlled by the action of stress waves.

In an effort to overcome the practical difficulties of both conventional static and dynamic load testing, FHWA initiated a series of research studies to evaluate several promising load test methods that were developed by U.S. and European inventors. None of these methods came with sufficient documentation for standardized test procedures or for the interpretation of data produced by these tests. The following sections summarize the efforts to evaluate and refine several of these innovative methods.

2.10.1 Statnamic Load Testing

The term "Statnamic" is a combination of the two words — "static and dynamic" — because it was neither one nor the other, but somewhere in between. Upon closer study it is seen to be closer to being quasistatic than dynamic, especially now in its latest version where there is no dynamic impact. In Statnamic testing a high-energy, fast-burning solid fuel is ignited within a pressure chamber to act as an upward propellant force. As the fuel pressure increases, an upward force is exerted on a set of reaction weights while an equal and opposite force pushes downward on the foundation element. Loading increases until it reaches a maximum, and then it is vented to control the unloading cycle. Figure 23 schematically illustrates the statnamic concept.

In the original version the weights would come toppling down on the pile or shaft after the fuel had completely burned off, and possibly damaged the foundation element being tested. This problem was solved by placing sand in an outer, concentric container that allowed the sand to flow downward (while the weights were pushed up and off the foundation) and cushion the blow from the falling weights (dynamic impact). The extra time to set up the sand container, and cleanup for retesting created a different kind of problem that was later solved by the development of a catch mechanism and the pressure venting system. A calibrated load cell located between the piston and the pile top is used to measure the applied load and a photovoltaic laser sensor records displacement during

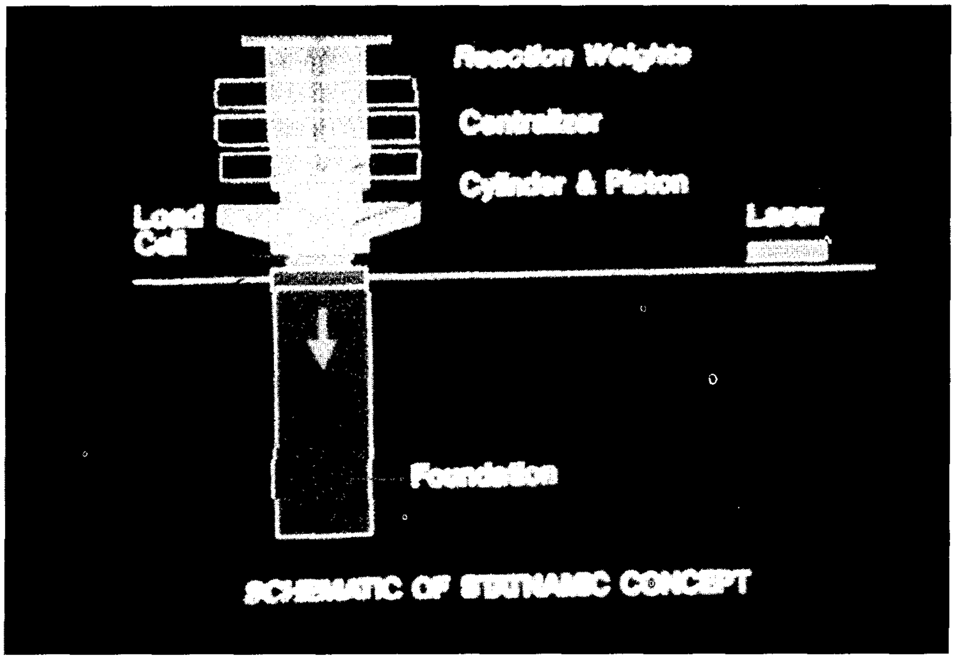

Figure 23. Schematic of statnamic load test method.

the test. The assembly and take down is very straightforward. All components are easily handled with a small hoisting rig. This system is capable of producing a given force or load using only 5 percent of the mass required in an equivalent static test. The original development in 1988 began with a 0.1 MN test device; however, current test devices are capable of producing loads up to 30 MN. Furthermore, because the direction of force is along the cylinder assembly, loading is perfectly axial or horizontal if the apparatus is shifted 90 degrees to perform a lateral load test. A batter pile test configuration can also be adopted if desired. The relatively slow application and release of compressive forces eliminates negative tensile forces, compressing the pile and soil as a single unit.

Throughout loading, load and displacement signals are digitized and sent to a raw voltage data file. After the event, the raw signal voltages are converted to load and displacement values using factory calibration values. Load-displacement graphs are presented immediately to on-site engineers for quick evaluations. Supplementary graphs of velocity and acceleration versus time can also be generated with simple post-processing commands. All data are stored for future analysis and reference.

During the 1990's FHWA has performed or funded many Statnamic tests and correlation studies with conventional static load tests to develop standardized testing procedures and improved data interpretation methods. Many SHA's and other domestic and foreign agencies are now conducting their own evaluation programs to further expand the data base of case histories and performance studies. Measurements made with the Statnamic device owned by FHWA compared very well with static load tests performed by TFHRC researchers on spread footings and pile groups in the research test pits (see appendix A). Measurements on full-scale piles and drilled shafts on other FHWA sponsored research projects have also compared well with static load test results. Figure 24 shows a test at FHWA's foundation load test facility.

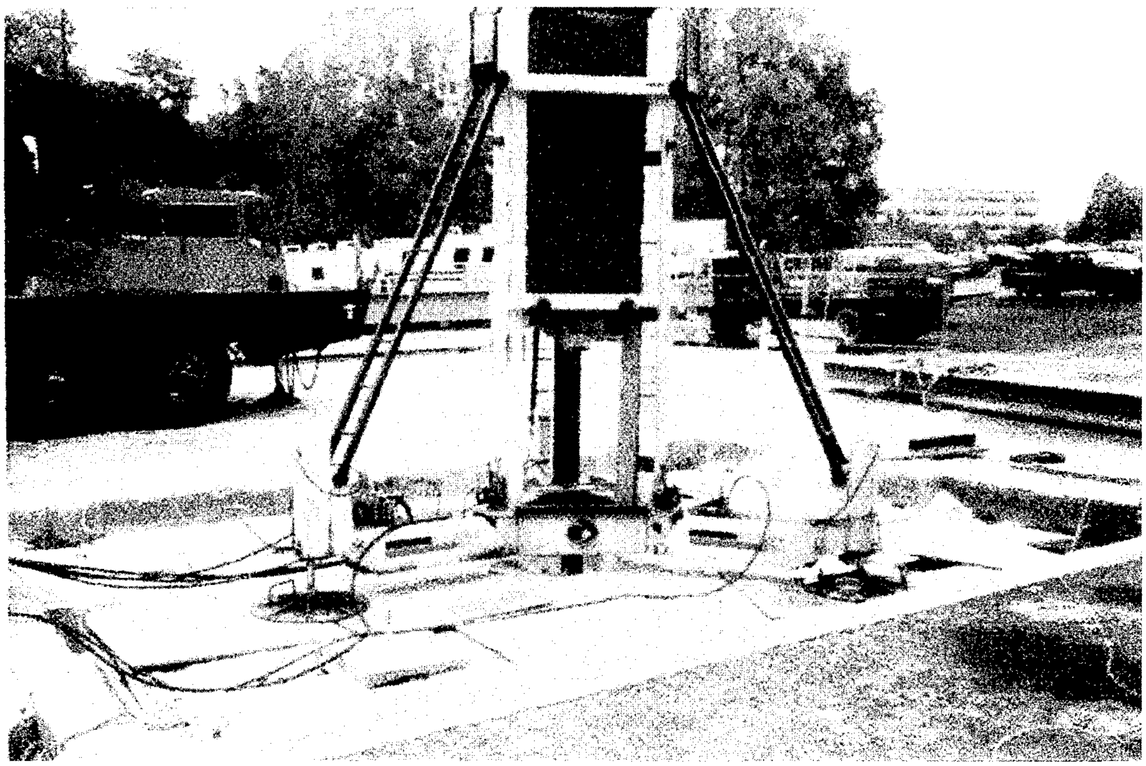

Figure 24. Vertical statnamic load test on model pile group at TFHRC.

In late 1996, FHWA participated in a research program with the Utah DOT on a major rebuilding project on I-15 in Salt Lake City. The research involved the lateral behavior of a nine-pile group that was tested in both a free and fixed head condition. A 14 MN device was used on the fully instrumented group. FHWA also funded a similar test program at the Auburn University NGES during the same time period (see chapter 5).

2.10.2 Osterberg Cell Load Testing

The Osterberg Cell is another innovative technique that has been evaluated by FHWA during the 1990's to determine its applicability and potential for reducing time and costs of performing foundation load testing, especially for drilled shafts. The drilled shaft designer must face both the problems of predicting subsurface soil and rock strength and compressibility characteristics, and the difficulty of estimating the impact of construction installation technique on the completed shaft. Model testing and laboratory investigations don't provide sufficient insight to assess the complex interaction between soil (especially intermediate geomaterials) and the concrete shaft. The Osterberg Cell, commonly called the "O-cell", is well suited for this problem and has provided an attractive short duration alternative for testing drilled shafts (31).

The O-cell is a hydraulically driven, high-capacity sacrificial jack-like device that is installed at the bottom of the reinforcement cage (figure 25) of a drilled shaft or at the tip of a driven pile. Unlike the conventional static and dynamic load tests that apply a

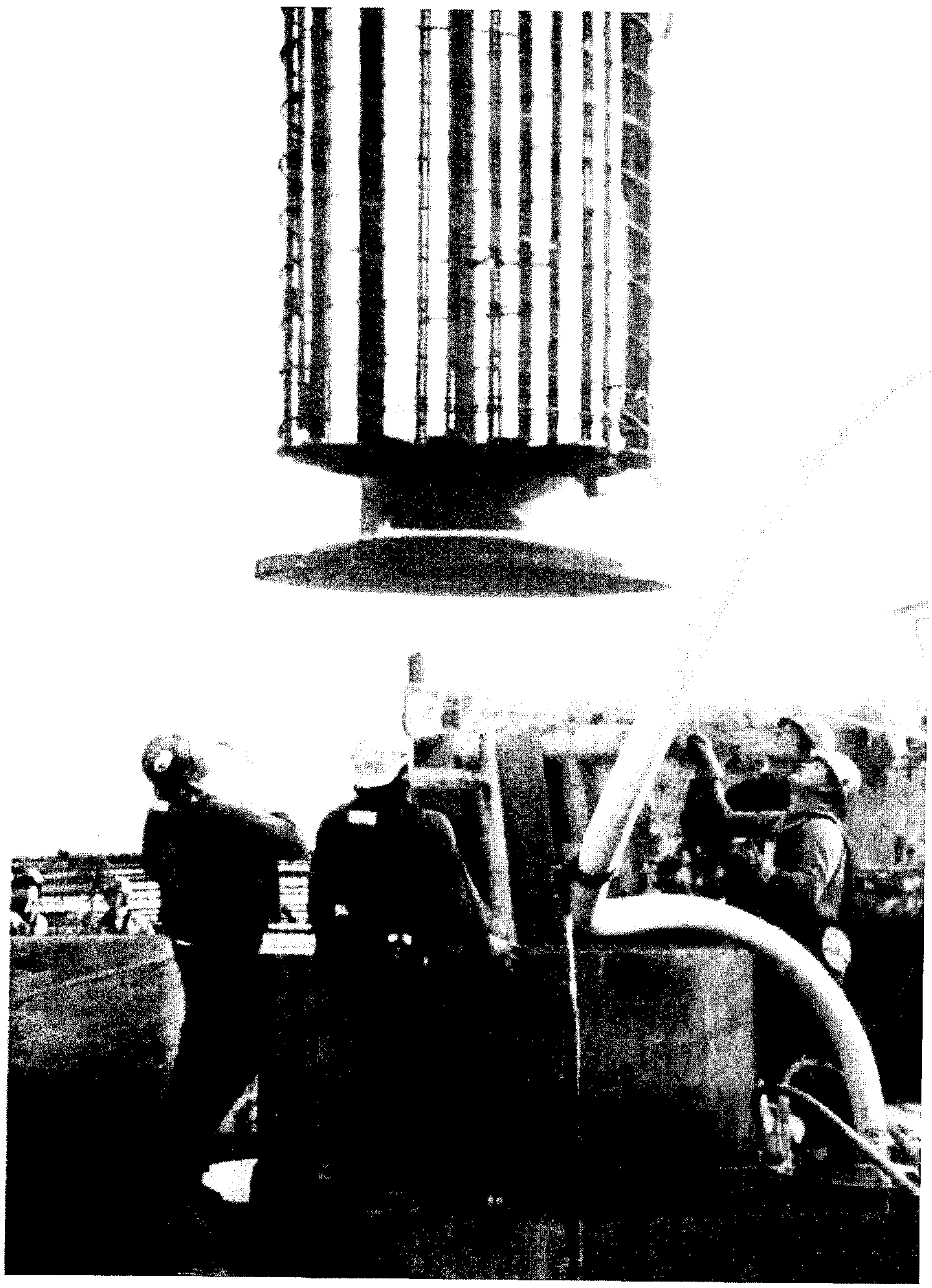

Figure 25. Osterberg load cell ready for placement in drilled shaft.

compressive force at the top of the pile or shaft, the O-cell loads the unit in compression, but from its bottom end. It requires no overhead reaction frame, dead load, or other external system. As the O-cell is pressurized and expands, the shaft and the soil provide reaction to the applied loads. The end bearing support provides reaction for the side friction along the shaft, and vice versa, until reaching the capacity of the cell or either of the two support components. O-cell tests automatically separate the end bearing support component from side friction values. Thus, an O-cell test load placed at the bottom of the shaft has twice the testing effectiveness of that same load placed at the top of the shaft. Production shafts can also be tested, if the device is grouted after testing is completed.

Movements of the foundation element during an O-cell test are measured by electronic gauges connected to a computerized data acquisition system. Linear vibrating wire displacement transducers (LVWDT's) are attached to the bottom plate of the O-cell. Telltales are used to measure both the compression of the test pile and the upward movement of the top of the O-cell. The downward movement of the bottom plate is obtained by subtracting the upward movement of the top of the O-cell from the total extension of the O-cell as determined by the LVWDT's. The upward movement of the top of the test pile or shaft is measured by digital gauges mounted on a reference beam. The loading mechanism has evolved from the original bellows-type expansion cell to the current piston-type jack. However, the piston extends downward instead of upward like that of a conventional load test.

The O-cell test offers a number of obvious advantages over conventional load testing, including economy, high load capacity, safety, reduced work area, and the ability to separate the end-bearing and side-friction components. Disadvantages include the need for advance installation, sacrificial expendability, unsuitability for certain types of piles, and the balanced component limitation, i.e., the test capacity is limited to twice the capacity of the support component reaching ultimate first. It has been noted that the majority of load tests on drilled shafts are now being done with the O-cell.

Boston Engineers were the first to use the O-cell in a practical application in 1987 on a bridge site near Boston, Massachusetts and later that same year at Rochester, New York. After testing, they recovered the cell and used it on another test site. In 1988, two more tests were performed with FHWA research funds at a bridge in Port Orange, Florida. More than 200 additional tests have been performed with O-cells in the United States on piles and drilled shafts during the 1990's, including some lateral load tests.

The Minnesota DOT recently completed a major load-testing research program featuring the use of O-cell devices in both axial and lateral load-testing modes. The shafts were 58 m deep and 1.3 m in diameter. One of the test shafts was instrumented with Sister Bar strain gauges to develop a better understanding of the load transfer distribution. The first-ever embedded O-cell lateral load test was on a second test shaft on this same project.

Other interesting applications in FHWA-sponsored projects include two previous record-setting performances in Massachusetts and Kentucky on highway bridge projects. The Owensboro, Kentucky record of 53.4 MN (6000 tons) was soon broken by the Boston Central Artery project record of 55.9 MN (6,280 tons), which was easily broken by the Florida project. The site conditions on Boston's Southeast Expressway (I-93) were treacherous because the test shaft was drilled between the two fast lanes inside two jersey barriers only 2 m apart. The testing was completed without obstructing or disrupting traffic flow.

No job appears to be too big or too small for the use of an O-cell. Several world records for load testing have been set recently, including the current world record for total load of 135 MN (more than 15,000 tons) set in Florida in 1997. Whether inside a building or under a bridge with limited access or low headroom, or within a cofferdam in the middle of a river, O-cell testing can perform well. It can be used to isolate portions of a pile or shaft by installing multiple cells, and is fast becoming a favorite of engineers and contractors because of its speed of installation and cost advantages.

2.10.3 Dynamic Drop Weight Load Testing

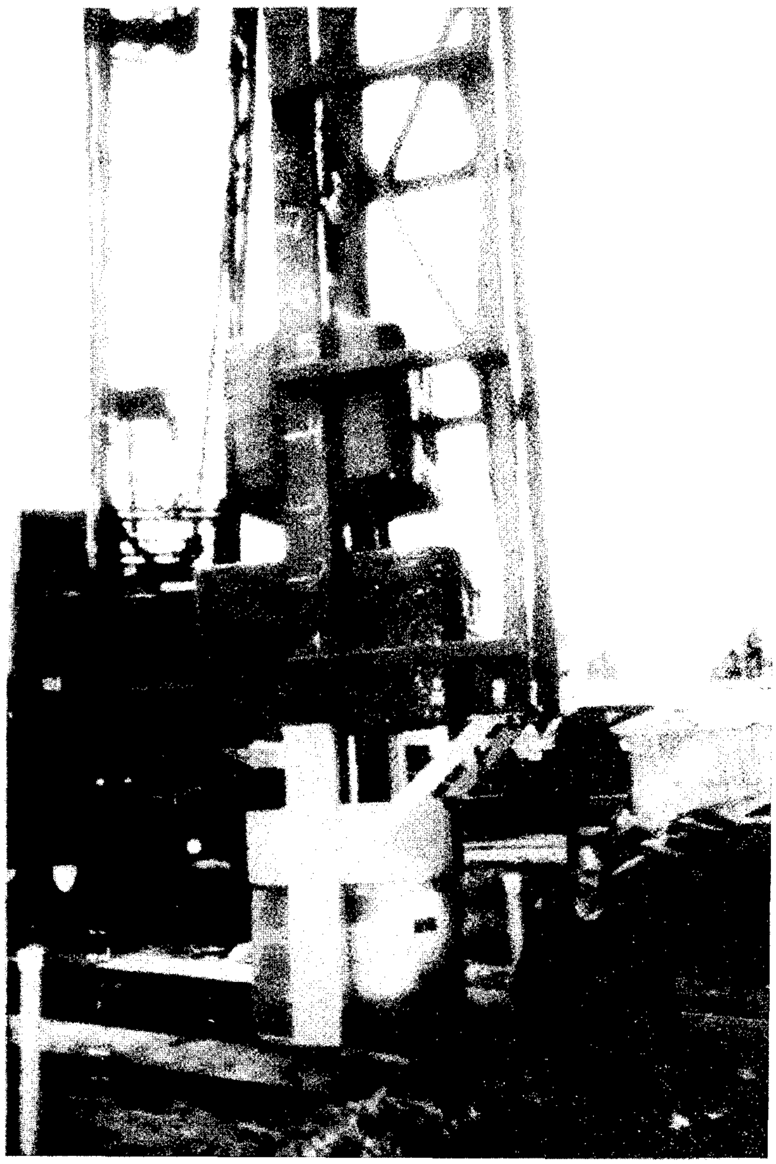

Figure 26. Large-strain dynamic load testing using drop hammer.

The use of a heavy weight (90 KN) falling from various heights (0.3 to 5 m) is another method to predict the load capacity of a pile or drilled shaft (figure 26). The foundation element is instrumented with strain gauges and accelerometers to measure the force and impact velocity of the stress wave generated by striking the element. The measured data are correlated to driving resistance to predict load capacity. An electric theodolite is used to measure the settlement associated with each hammer blow. The friction in the hammer leads and the cushion assembly cause the actual energy delivered to the pile or shaft to be much less than the free-fall energy of the ram. This is accounted for by the instrumentation gauges similar to the Pile Driving Analyzer equipment used during pile driving operations to monitor resistance to driving. A service crane is required on site to perform the tests.

Three different methods (one U.S. and two European) were evaluated on several FHWA research test sites to determine the applicability of this type of testing to check pile or shaft capacity. The GRL method was developed at Case Western Reserve University in Cleveland, Ohio, by the same people who developed the PDA, WEAP and CAPWAP. The "SIMBAT" method was developed by the French government's Center for Experimental Research on Buildings and Public Works (CEBTP). The TNO method was developed by the Dutch government at their national research center in the Netherlands. The Europeans have amassed a large data base of static/dynamic test result correlations. As a result, these methods have become established practice in several European countries, but have been slow to catch on in the United States because of the greater success of the O-cell and statnamic methods. Also, test results on FHWA projects have not measured up to expectations thus far, usually over-predicting the measured capacities. Further investigation is planned to complete the evaluations.

CHAPTER THREE

GROUND IMPROVEMENT PROJECT

Relatively few options are available in choosing the ground materials and site conditions that must be accounted for in the design of highway projects. The project must be constructed under the conditions that are present at the particular site; minimal disturbance to existing elements of the roadway is also a key control factor in the selection and design of the rehabilitation or reconstruction scheme. For example, the widening of existing roadways or bridges requires that the selected technique be one that can deal with the problem soil condition effectively, and also cause minimal damage to the existing facility.

This is especially true for roadway widening projects in areas of very soft foundation soils. If the existing embankment was placed in an excavated trench where the unsuitable material was removed, the same construction technique will cause serious problems because excavation adjacent to the existing embankment will jeopardize the stability of the existing facility. In those cases where the foundation soil is not removed, the pressure of the widened embankment causes significant differential settlements if the soft soil is not reinforced or otherwise strengthened.

The problem of economically constructing and maintaining stable slopes within limited right-of-way is a continuing concern. Where increasing traffic requires the addition of lanes within the same right-of-way, costly conventional earth retaining structures are often necessary. Such structures are also required where existing or proposed slopes are unstable and flattening of the slope is not feasible.

In urban areas where depressed freeways are to be widened or in rural areas where large cut slopes are to be reopened, the slope excavation can become a very difficult and expensive engineering problem to resolve. Innovative methods to stabilize or otherwise strengthen the existing slope prior to excavation must be identified and evaluated to increase the available inventory of design approaches that can be used to solve these particular problems.

In recent years, some of the most noteworthy advances in geotechnology have been in the area of earth reinforcement. Powerful, innovative techniques have been initiated and are still being developed here and abroad that have the potential for improving stability at reasonable cost. However, it should be noted that throughout their short history, commercial and technological innovations in ground improvement technology have almost always preceded research studies of fundamental performance and the development of engineering guidelines. Examples include: reinforced earth, micro piles, tieback anchors, and soil nailing. Some of the techniques under study were proprietary, and information on many of the innovative methodologies was not widely distributed. Therefore, there was an urgent need to collect, evaluate, and disseminate the current state of the art on their use and applicability.

To encourage widespread use of these systems, two pressing questions needed to be answered: (1) What new systems were available? and (2) Where will they provide satisfactory performance at a cost savings over conventional methods?

In the past, conservative thinking in the highway field hindered innovative development and cross-fertilization of special ground improvement techniques between the United States and foreign countries, particularly western Europe and Japan. Innovations from these other countries have fostered major changes in the United States in many areas of ground improvement and earth retention systems. These changes have occurred in both our approach to design and construction activities. They are good examples of how foreign innovations have shaped U.S. practice.

3.1 Background

At the time this research project was initiated, hundreds of miles of existing highways were scheduled to be reconstructed or upgraded in areas where difficult soil and foundation conditions would be encountered. In many cases there was considerable pressure applied to minimize the disruption to traffic flow, and to select courses of action that did not require destruction of or harmful effects to existing pavement systems or structural facilities such as bridges and retaining walls that still had a long useful life remaining.

Ground improvement techniques were found to provide benefits in the following five major areas:

- Utilization of less costly foundation systems,
- Reduction in right-of-way acquisitions,
- Less environmental disturbance,
- Reduction in construction time, and
- Improved traffic control through construction zones.

Recent developments (at the start of this research project) in Europe and Asia had shown great promise in providing cost-effective solutions to difficult soil and site improvement projects that heretofore were unavailable or extremely expensive to resolve. Many of these developments were reported to save large sums of money when used in lieu of conventional solutions; however, documented evidence of the actual savings as well as the mechanics of how the particular system worked was usually not available or very difficult to obtain. As a result, an accurate estimate of the potential benefits was impractical or very difficult to make; however, preliminary estimates indicated a very high rate of return on research expenditures was very likely to occur.

3.2 Objectives

The objectives were to identify and refine existing ground improvement techniques that can be used to stabilize or reinforce soil or rock masses that provide support for roads and structures. Design and construction guidelines were to be developed to reduce costs associated with providing adequate ground support for pavements, bridges, and retaining walls.

3.3 Scope

Research and development efforts in this project were directed toward analyzing and improving existing techniques for reinforcing and strengthening ground masses supporting or otherwise impacting highway facilities. The development of new techniques to replace or supplement existing techniques was also considered where appropriate. The utilization of ground improvement methods for the design and construction of new highways was covered; however, the main emphasis was on the bridge rehabilitation/ replacement program and the roadway restoration program.

This project included all materials and methods to reinforce, stabilize, or otherwise improve soil and rock masses used to support highway structures. The project evaluated the basic mechanisms underlying each technique and developed rational design and construction methodologies for each appropriate technique.

Design guidelines were developed for each technique and included the selection of design values and the determination of geotechnical design parameters, specifications and special provisions, and system geometrics such as spacing, depth of treatment, equivalent diameters, sizes, shapes, and weights. Other engineering considerations, such as effect of groundwater table location, energy attenuation with depth, effective compaction depth, and types of soils most suitable to each type of improvement technique, were also studied and appropriate guidance was provided.

Construction guidelines, including construction control and performance monitoring methods, were also developed for each technique. Units of measurement and payment and end product evaluation techniques were also developed and presented in a guidelines format.

Although the main emphasis was on existing techniques rather than developing new techniques, it should be noted that many of the existing techniques evaluated were very new and still in their infancy in terms of technical development and implementation. Some of these methods demonstrated significant savings over conventional methods and showed great promise for even larger cost savings when improved guidelines were developed under this program.

3.4 Project Description

The major research efforts were in two tasks:

1. <u>Soil Reinforcement</u>

   Research under this task investigated the behavior, efficiency, and cost-effectiveness of various reinforcement techniques such as tensile, compressive, and shear force resistance elements that are inserted into the soil mass to improve bearing capacity and settlement characteristics.

2. <u>Soil Treatment</u>

   Research under this task involved improvement techniques that do not require the insertion of reinforcing elements into the soil mass. Examples include compaction, drainage, and grouting.

The Ground Improvement Project was a major part of the FHWA Geotechnology Research Program. The following sections of this chapter provide a summary of the major contributions of this project.

3.5 Soil Reinforcement

Inclusions have been utilized since prehistoric times for the improvement of soil. The use of straw to improve the quality of adobe bricks dates back to earliest human time, when many primitive people used sticks and branches for reinforcement of mud dwellings. During the 17th and 18th centuries, French settlers along the Bay of Fundy in Canada used sticks for reinforcement of mud dikes. Some other early examples of man-made soil reinforcement include dikes of earth and tree branches, which have been used in China for at least 1,000 years and along the Mississippi River in the 1880's. Other examples include wood pegs for erosion and landslide control in England, and bamboo or wire mesh, used universally for revetment erosion control. Soil reinforcement can also be achieved by plant roots.

Retaining walls are an essential element of every highway design. Retaining structures are used not only for bridge abutments and wing walls but also for slope stabilization and to minimize right-of-way required for embankments. Not many years ago retaining walls were almost exclusively made of reinforced concrete, and were designed as gravity or cantilever walls. Such walls are essentially rigid structures and cannot accommodate significant differential settlements. With increasing height of soil to be retained and poor subsoil conditions, the cost of reinforced concrete retaining walls increases rapidly.

Reinforced soil walls and slopes are cost-effective soil retaining structures that can tolerate much larger settlements than reinforced concrete walls. By placing tensile reinforcing elements (inclusions) in the soil, the strength of the soil can be improved significantly such that the vertical face of the soil/reinforcement system is essentially self-supporting. Use of a facing system to prevent soil raveling between the reinforcing elements allows very steep slopes and vertical walls to be safely constructed. In some cases, the inclusions can also withstand bending or shear stresses, thus providing additional stability to the system.

At the time of this research, there were no uniform standards for these systems, and in fact, there were different design and construction criteria and procedures for each system. Moreover, each of these systems had a different performance record. Research under this project identified and evaluated various reinforcement methods such as tensile, compressive, and shear force resistance elements that are inserted into the soil mass to improve bearing capacity and/or settlement characteristics. The evaluations included all materials and methods to reinforce soil masses. Studies were undertaken to evaluate the basic mechanisms underlying each technique, and rational guidelines for design and construction of each technique were developed. Each technique was evaluated by reviewing the literature, and discussing the performance of particular case history examples with design and construction engineers, plus specialty contractors involved in using these innovative techniques.

Subsequent studies involved soil characterization and reinforcement material evaluations to determine appropriate parameters for design and construction control. Small-scale laboratory model and also centrifuge model studies were conducted for those techniques that required further refinement and verification. Full-scale field testing and construction monitoring studies were also done to validate some of the research findings from the initial investigations.

3.5.1 NCHRP Benchmark Study

The FHWA research program in soil reinforcement was based on the results of a major NCHRP study that performed an extensive literature review and evaluation of available systems and design methods (NCHRP Publication 290). That state-of-the-art report provided in-depth background on soil reinforcement for engineers seeking an understanding of this important, and at that time, new subject.

3.5.2 Reinforced Soil Structures

The NCHRP study was expanded by FHWA to examine the design, construction, and performance aspects of a selected few of the mechanically stabilized earth systems identified in Report 290 for use in retaining structures and excavation support systems. The main purpose was to develop guidelines for these systems to provide highway engineers with guidance for selection, design, and construction of the selected systems in a generic manner.

The study was performed by reviewing and evaluating several existing methods in terms of field experience, laboratory testing (including centrifuge studies), analytical studies, and a full-scale field evaluation program (figure 27). The results were then used to develop and substantiate the generic design procedures and other guidelines presented in the manual (32). Volume 2 contains a technical summary of the research supporting theory to verify the design theory in Volume 1, plus information on several proprietary reinforced soil systems (32).

Figure 27. Reinforced soil test wall.

The manual has become a valuable tool to assist highway engineers and others in determining the feasibility of using reinforced soil systems for walls and embankment slopes on a specific project, evaluating different alternative reinforcement systems, and performing preliminary design of simple systems. The manual also provides a basis for evaluation and preliminary design of new earth reinforcement systems that may be proposed in the future.

3.5.3 Reinforced Soil Foundations (RSF)

A staff study at TFHRC investigated the use of geosynthetic reinforcing elements beneath spread footings to create a composite material with improved performance characteristics to determine if this method of ground improvement is applicable to bridge support. Information was obtained on how to quantify the improvements and optimize the location of the reinforcement in the soil below the footing. The results of this study proposed an optimal size of an RSF using soil strain signatures and normalized settlement criteria. Model load test results on 34 footings describe the optimal depth and reinforcement layering within an RSF.

One of the first tests conducted was on a spread footing placed at the surface on an unreinforced compacted sand that was load tested to failure (figure 28). Both the footing and surrounding soil were fully instrumented to map the distribution of soil strain beneath the footing. The map was used to describe the complete mode of soil failure, and clearly defines the zone of maximum soil displacement. The identity of this zone within the engineered fill pin pointed where the geogrid should be placed for optimum reinforcement in the next series of tests.

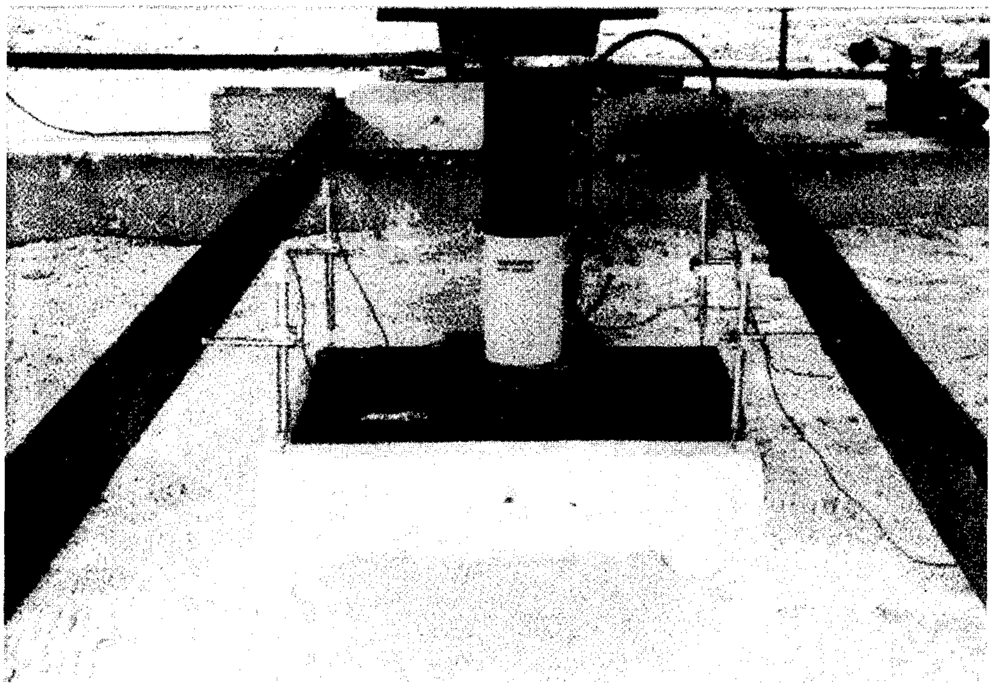

Figure 28. Spread footing load test on reinforced soil foundation.

The next series of tests was conducted to evaluate the relationships between the layering of the reinforcement to the width (B) of the spread footing. Two series of load tests were performed on four different sizes of square footings (0.3 m, 0.45 m, 0.6 m and 0.9 m) on the sand surface to measure the settlement(s) of the footing at various loads.

The next tests were performed to compare the performance of Reinforced Soil Foundations (RSF's) to the unreinforced footings with various embedment depths (D) to determine the best features of each approach to increase bearing capacity. For example, a spread footing embedded 0.5 B was compared with a one-layer RSF placed at 0.375B beneath the base of a surface footing. An embedded footing with a D/B of 1.0 was compared with a three- layer RSF placed at 0.25B, 0.5B and 0.75B below the surface footing. The test results were used to calculate bearing capacities at various D/B ratios.

Vertical displacements within the sand below the footings were measured by telltales located at various depths below the four corners of each footing. Horizontal strains were measured by inclinometers located at 0.25B and 1.0B outside the footing footprints.

Linear Variable Differential Transducers (LVDT's) were used to measure settlement at the top of each footing for each load increment that was measured by load cells between the footing and loading jacks. Footing settlement, vertical soil displacements below the footing, and horizontal displacements to the side of each footing were measured at each load increment.

As expected, the data show that soil deformation occurs first in the upper layer of sand just below the footing and propagates to deeper areas with increasing load, following a pattern that can be clearly seen in any standard soil mechanics text. What is not shown anywhere else besides these tests, is the well-defined strain signature that clearly shows that almost all soil deformation occurs within a zone of 0.5B beneath the footing, rather than 1.0 to 2.0B, as proposed by previous researchers.

Because the data show that the upper layer undergoes the highest strain during the early part of the load test, it is recommended to place a layer of reinforcement in this zone of initial strain, and a second layer in the lower zone of maximum strain. The telltale measurements clearly identified the higher zone to be at 0.125B, and the maximum zone at 0.375B. Placing a layer of reinforcement at these levels will significantly improve the load settlement performance of surface or shallow depth footings on sand. If only one layer is required, it should be placed at the point of maximum strain, which is approximately at the 0.375B level. It was also noted that, when the reinforcement was placed in the zone of maximum soil shear, it acted to significantly inhibit the development of a classical bearing capacity failure.

The zone of horizontal displacement is mostly within a distance of 0.5B beyond the edge of the spread footing. This means that the reinforcement doesn't need to extend more than 0.5B past the edge of the footing on all sides. The imprint area of the reinforcement is therefore required to be four times the size of the footing imprint.

In many tests comparing surface footings on sand to surface footings on an RSF, the ultimate bearing capacity of the RSF was twice the value of the conventional footing. The performance of an RSF was shown to be very comparable to the positive effects of footing embedment. The knowledge gained during these experiments was put to immediate use for design of the RSF to support the geosynthetic reinforced soil bridge pier described in section 3.5.4.1 of this chapter.

A review of the literature indicates that this study was the largest of its kind, both in terms of number of footing load tests performed and size of footings tested. The results clearly demonstrate that geosynthetic reinforcement can substantially increase the bearing capacity of shallow spread footings on sand and can reduce the amount of settlement, especially differential settlement of the four corners of footings. The footings resting on unreinforced sand settled unevenly, while those on reinforced foundations settled very evenly with no tipping of the corners. Additionally, the footings on a RSF were more likely to experience a gradual failure curve rather than a plunging failure (30).

3.5.4 Geosynthetic Reinforced Soil Structures

The use of geosynthetic grids and sheet materials to reinforce soil layers in walls, abutments, and piers to support highway structures has increased significantly in the 1990's due to cost advantages and freedom from worry about corrosion and durability issues. Similar to the rapid increase of other ground improvement technologies, expanded usage has preceded the development of rational technical guidelines and fostered significant debate over several technical issues, such as vertical spacing of reinforcement layers, connection issues, compaction details, facing cracks, soil fill specifications, seismic response, scour protection, pre-straining requirements, and optimal applications. It is also necessary to determine optimum base to height ratios, including appropriate limitations and design criteria, plus lateral load resistance factors.

FHWA developed an in-house staff project to answer these unanswered questions. The first phase of the study involved the construction of a full-scale bridge support pier out of polymer based fabric sheets, road base gravel, and regular home building cinder blocks (figure 29). The pier was constructed at the TFHRC campus to facilitate construction supervision and monitoring of the research testing. It was built on a reinforced soil foundation platform that was placed approximately one meter below natural grade.

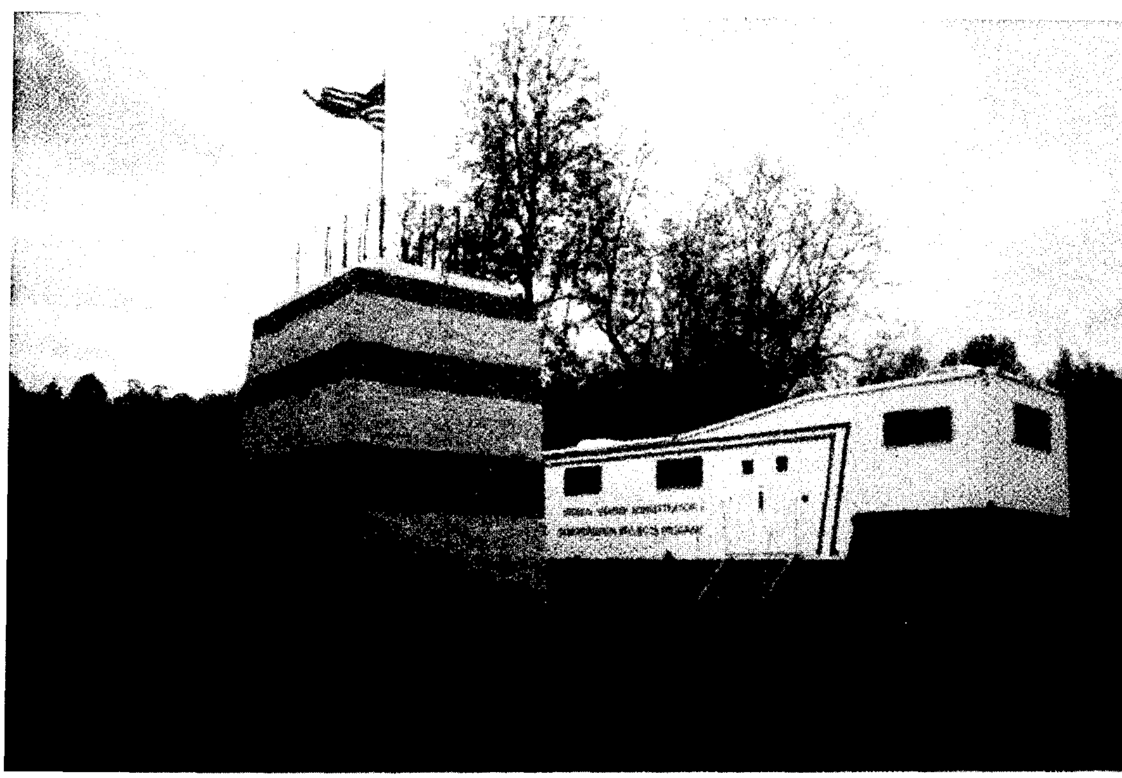

Figure 29. Geosynthetic reinforced soil support pier.

A series of model piers was also built and tested to supplement the results of the full-scale tests. These smaller piers were much faster to construct and easier to test to failure than the prototype, which permitted the researchers to vary different parameters to evaluate the effects of certain changes on overall performance. Another series of full-scale tests on the prototype and several larger full-scale structures is planned for the 1999 construction season.

3.5.4.1 Full-Scale Pier Project

The bridge support pier was built to a height of 5.4 m and was 3.6 m x 4.8 m at its base, with a slightly smaller top area due to an inward tapering effect for aesthetic purposes. The pier was fully instrumented to monitor load, vertical settlement, lateral deformation, and internal creep and strain in the reinforcing fabric.

A thin concrete leveling pad was used beneath the facing blocks to ensure a proper start and level rows of blocks throughout the entire height of the pier. Six concrete reaction pads were placed on top of the support base and inside the facing block perimeter. Four steel rods were anchored in each reaction pad. They were designed to be extended through the full height of the pier and attached to a similar set of six reaction pads to be placed at the top of the pier and matched to the bottom pads. The steel rods were isolated from the internal soil mass to preclude any vertical reinforcement contribution from the rods. The reaction pads and connecting steel rods were needed to apply squeezing loads for testing purposes, and were designed not to interfere with normal functioning of the pier.

A high-strength, woven polypropylene geosynthetic made by Amoco (#2044) was used to reinforce a well-graded gravel material that is routinely used beneath highway pavements in Virginia. The cinder blocks were dry stacked and served as a construction form as well as a facing block for the gravel during compaction operations. The fabric was placed at each layer of block and gravel, with no special connection features except to overlap the fabric between each layer of blocks. No gluing or pinning was used to secure the fabric to the blocks.

At the mid-height of construction, the top reaction pads were placed and reaction beams were attached to the steel rods to squeeze or pre-strain the composite soil mass using heavy duty loading jacks. Load cells, LVDT's on top and on the sides, and a laser measurement system were used to monitor stress and strain responses to the squeezing process. The pre-straining operation served to eliminate most of the expected post-construction settlements, and enhanced the composite nature of the reinforced soil mass because the key to the composite feature is the denseness of the soil and the bond connection between the fabric and the compacted soil.

The vertical spacing between reinforcement sheets plays a major role because the composite feature is greatly diminished when separation distances between reinforcement layers become too large. The optimum spacing issue was further studied under the model test investigation. The contribution of the facing blocks is also under investigation. In addition to the facing aesthetics, soil raveling and erosion control, and construction form work during compaction, there is a good possibility that the blocks make a significant contribution to the composite feature of the reinforced mass.

The size of the reaction pads and the number of steel rods were far greater than necessary to provide sufficient pre-straining during the construction process at the mid-point (or one-third point if deemed appropriate) and completion of the full-height pier. The extra reaction capacity was installed to provide sufficient capacity for research load testing purposes. No rods or pads would be needed if pre-straining was not considered important to ensure bearing capacity and settlement control. For this design, only about half the available capacity would have been required if load testing to failure was not in the plans, and pre-straining only was desired.

At full-height construction, the pier was again subjected to pre-straining. The same stress and strain type measurements were taken, plus creep and strain measurements were made on four layers of fabric installed in the top half of the pier. A total of 21 strain gauges was installed on each of the four layers. The measured strain along each fabric layer was uniform, indicating the load was applied evenly over the pier area.

The pier was later load tested to a much higher level than the pre-straining levels (but less than complete failure load) to determine near upper bounds on bearing capacity and settlement values for this particular composite mass. The loading was stopped when severe cracking, bulging, and displacement of the facing blocks occurred, but not before load and displacement measurements demonstrated how strong and capable this system is for support of heavy bridge loads without significant deformations resulting. Maximum loading conditions were not applied in order to preserve the structure for additional testing; however, total collapse failure loads were imposed on the smaller scale models discussed later.

The FHWA manual, *Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines,* recommends that bridge loads on this type of structure not exceed 200 kPa (2.1 tsf). At this loading level the performance of the pier was very good. Lateral deformation and vertical settlement were very small and no cracks or other signs of distress occurred in the blocks. Performance also remained good at much higher levels than the not to exceed limit specified in the manual.

The connection strength issue did not seem to be a problem in this situation. The connection consisted of a frictional bond between the blocks and the fabric, with no glue or fasteners used to enhance the connection. Results show that none was needed. The vertical squeezing forces that were applied to the soil and fabric mass seemed to cause a "drag" type of force to be applied to the blocks as the reinforced soil mass was forced to consolidate. Compression cracks occurred as the drag forces reached higher levels; however, the connection issue was not adversely affected.

The overall experiment was very successful and served to increase our knowledge of how this type of structure can best be utilized to provide safe and efficient support for highway bridges, especially in remote areas where concrete and steel are expensive to haul to the bridge site, and heavy equipment is hard to mobilize. This concept may also be a good alternative in seismic areas because each layer of gravel and reinforcement may serve as a force-dampening shock absorber between the earthquake-generated ground motions and the bridge superstructure (33).

3.5.4.2 Model Studies

At another site on the TFHRC campus, a series of smaller scale models of the prototype pier were built and tested to failure. The same type of block was used to build the models except that the fabric was not placed to overlap the blocks, and the blocks were removed before testing. A base height ratio of 0.5 was used to provide similitude with the prototype. The same gravel material was used; however, the same geosynthetic reinforcement material was used in only a few of the models at various vertical spacing distances to investigate the effect of distance on the composite mass performance under extreme loads. A lesser strength fabric was also tested at varying spacing distances (33).

3.5.5 Corrosion and Durability

One of the major design concerns for reinforced soil structures has been the corrosion or durability of the reinforcing elements in the soil/water environment in which they are placed. In the early days of building reinforced soil structures in the United States, the material of choice was almost exclusively metallic, either in strip or grid configuration. Galvanized steel worked best, and after a short trial period the use of aluminum and stainless steel was discontinued due to very poor performance. Concern about corrosion of the galvanized steel prompted some engineers to try geosynthetic polymer materials as a reinforcement alternative; however, similar durability concerns soon became apparent because of the lack of information on degradation factors, such as hydrolysis and oxidation phenomena, that might occur in the soil/air/water environment below ground.

To assist engineers in designing new projects and evaluating existing walls, FHWA performed a series of comprehensive research studies to investigate the corrosion potential of metallic reinforcing elements and polymer degradation as related to the design life of the reinforced soil structures. The durability research included an analysis of the principal aging factors to determine the extent of decomposition that typically occurs in a soil environment. Other topics, such as installation damage, biological and environmental attacks, and creep damage, were also investigated.

Two reports were issued that describe the corrosion process and provide guidance and criteria for evaluating potential corrosion losses when using coated or uncoated steel reinforcing elements. Remote electrochemical measurement equipment called a PR

Monitor was also developed to monitor corrosion potential and in-situ corrosion rates of base or galvanized steel reinforcements on both new construction or existing walls. The PR Monitor (figure 30) measures the polarization resistance (PR) of a corroding interface because the corrosion rate is inversely proportional to the PR (34,35).

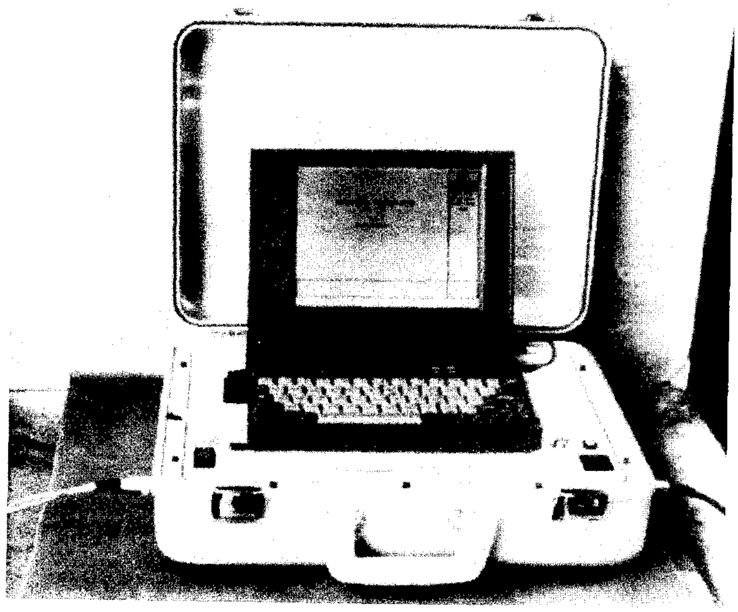

Figure 30. Polarization Resistance (PR) monitor for corrosion potential.

Several reports were also disseminated under the study, "Durability of Geosynthetics for Highway Applications", that describe the hydrolytic and oxidative degradation processes, installation damage patterns, and creep concerns of polymer reinforcements. These reports, plus others in the publishing process at the time of print for this summary report, provide guidelines and testing protocols for calculating the appropriate strength reduction factors for use in design life predictions (36,37,38). Some of the important findings are discussed next.

On the basis of the data thus far, it appears that most geosynthetic products have the durability needed for critical reinforcement applications, especially in relatively neutral soil environments. In severe environmental conditions, results indicate a fairly wide range of degradation rates. A test protocol for long-term durability performance testing of geosynthetics (i.e., oven aging and immersion testing) has been developed, along with an analytical model for service life prediction of geosynthetics.

Variations in the test protocols used to chemically characterize polymers, with specific reference to geosynthetics, which could significantly affect test results or make test results difficult to interpret, have been identified and corrections to the protocols were made. These protocol variations help to explain why comparison and use of data provided in the literature are difficult.

From the effort to better define the testing protocols, preliminary standardized test and QC/QA procedures to be applied industry-wide have been developed. This has set into motion the ability of the industry to perform the tests that will likely be recommended for future evaluation of geosynthetic durability, and the ability to develop a consensus on how those tests should be performed and quality control maintained.

The polymer and soil environmental factors that affect the geosynthetic degradation rate have been identified as well as tests that can be used to assess and quantify these factors. The study has also identified the issues that must be addressed to develop life prediction models for geosynthetics, especially with regard to relating the laboratory environment to the in-soil environment. A technology transfer report was developed by FHWA's Office of Technology Applications to assist practitioners in implementing the new guidelines (39).

A separate but parallel effort by Transportation Research Board (TRB) committee A2K07 has been initiated to develop the framework necessary for rapid implementation of the results of this study. This effort has also helped to identify just where the real needs in terms of geosynthetic durability knowledge are so that a coherent recommended practice to determine the long-term strength of geosynthetics can be developed.

The study has created an environment that has promoted improved communications within the industry, in particular their polymer experts and suppliers, and with the portion of the engineering community that routinely uses geosynthetics. This has allowed the geosynthetic industry to better understand the needs of those who use geosynthetics regarding durability issues, and has helped geosynthetic users to know what questions to ask and what can be realistically expected from the industry. A team spirit between the industry and geosynthetic users, which was not present before the study began, has begun to develop.

3.5.6 Permanent Ground Anchors (Tiebacks)

Permanent ground anchored wall systems, often called tieback walls, use tensile elements anchored in the ground to support earth retaining structures or stabilize landslides. These walls are built in excavated cuts from the top down. Other highway applications include bridge abutment underpinning when an end slope under an existing bridge is removed to permit widening of the roadway; and the strengthening of existing earth retention structures that have deteriorated because of corrosion or require additional support for increased loading situations.

Temporary ground anchors were the first system to be introduced in the United States to support excavations while the permanent facility was being constructed. Soon, however, these temporary measures gained wide acceptance because of economic and safety aspects, and they gradually became attractive as permanent solutions. The economy results from elimination of temporary support systems and reduced right-of-way considerations; safety is improved by eliminating cramped excavation work areas that are cluttered with delicate bracing.

Permanent ground anchors are relatively new geotechnical elements that were developed to a large extent by specialty contractors who had developed their own methods of design and installation. Many of these methods were proprietary or closely guarded family secrets. SHA design provisions were viewed by ground anchor contractors as unnecessarily conservative and restrictive, which increases construction costs.

At first there was much concern on the part of highway engineers because of a perceived lack of rational design procedures, construction methods, and documented performance experience. In response to this need, FHWA researchers initiated a contract research study to investigate this technology under experimental conditions to examine stresses and deformations occurring under typical loading conditions. Results were then used to develop a comprehensive manual of engineering guidelines and a computerized design procedure (40).

A series of four model test walls (2 m high and 5 m wide) were instrumented and tested to failure (figure 31) at the University of Illinois to verify and refine the preliminary guidelines established in the early stages of the study on the basis of a literature search and analytical trials. A full-scale wall (10 m high and 60 m long) was also built to further refine and validate the new guidelines. The full-scale wall (figure 32) was built at the NGES facility at Texas A&M University. One section of the wall had only one row of anchors with heavy soldier beams, and the other had two rows of anchors with smaller soldier beams. Pullout tests of full-scale, vertically installed ground anchors were also conducted in an adjacent area at the TAMU clay site (41).

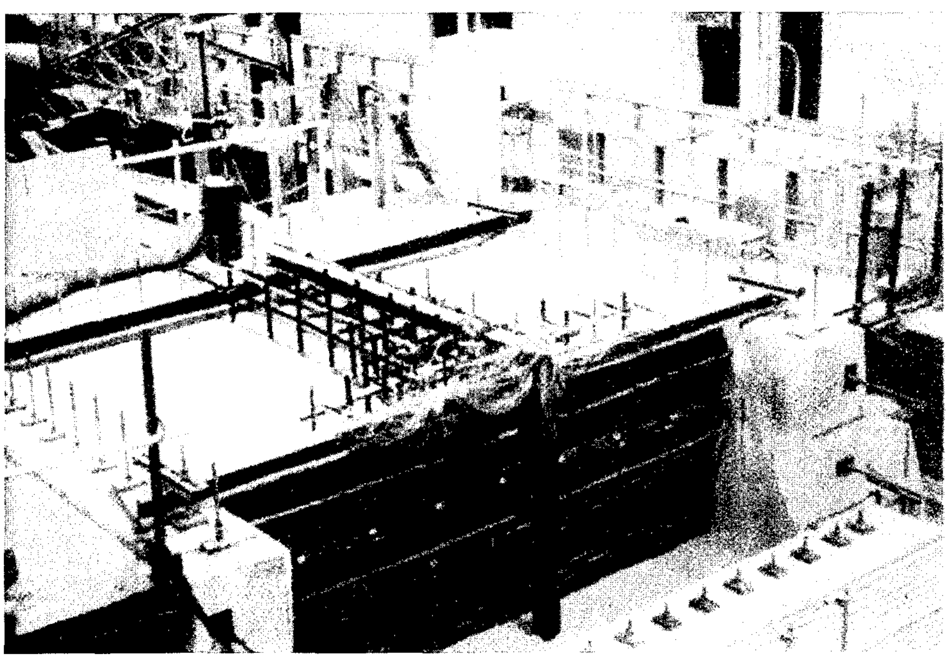

Figure 31. Large model ground anchor test wall.

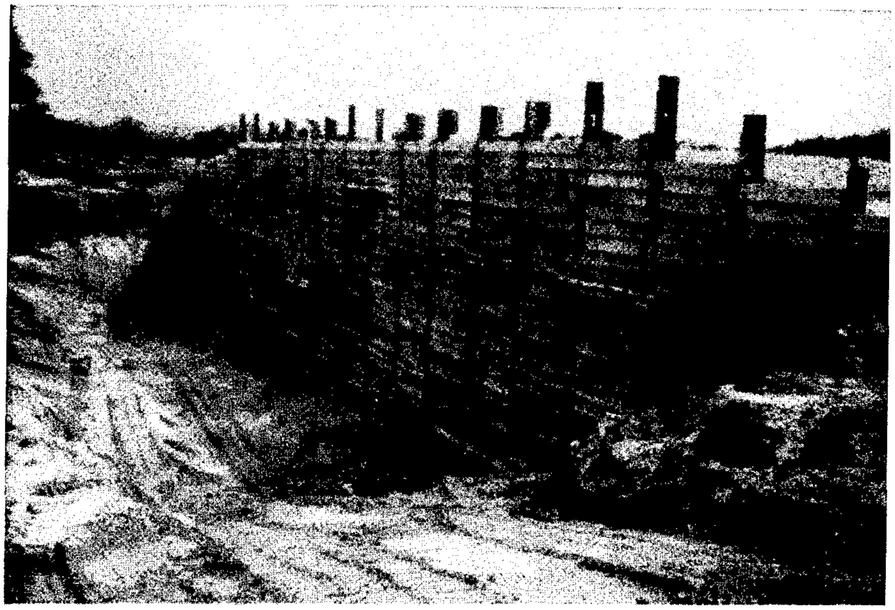

Figure 32. Full-scale ground anchor test wall at TAMU NGES.

3.5.7 Soil Nailing

Soil nailing is an earth retention system that combines short in-situ reinforcements and shotcrete to support excavations, hillside cuts, depressed cuts, and embankment steepening. Soil nailing structures are built from the top down in a minimum of space, without temporary support, without soldier beams, without disruption behind the wall, and less disruption to traffic and adjacent construction activities. Soil nailing structures can be built in cohesive and granular soils or in relatively heterogeneous soils with small, easily mobilized equipment, with less start-up time, and in remote sites. Soil nailing walls are often the most effective solution to the problems associated with emergency repairs, vertical cuts close to property lines, projects where drilling costs are high, and projects with limited access. When used in the proper application, a soil nail wall can be constructed faster and more economically than most other retaining wall systems.

An in-situ reinforcement technique that improves the soil's overall stability, soil nailing is constructed with steel reinforcing bars (soil nails) that are usually drilled and grouted into the ground. Sometimes, other metal tubes or rods are used instead of bars to resist tensile, compressive, and shear stresses. A relatively large number of soil nails are installed in a designed pattern that reinforces the earth into a stable block, which supports the unreinforced soil behind it in a way that is similar to that of a gravity wall. Soil nailing structures are designed to be both externally and internally stable. External stability requires that the structural mass be designed with an adequate factor of safety against sliding, overturning, and bearing failures.

To check a structure's internal stability, most engineers use a method of limit equilibrium analysis that computes the driving and resisting forces at the critical failure surface. To further the development and use of soil nailing, FHWA has instrumented many soil nailing structures, conducted extensive model testing, and thoroughly analyzed prototype walls. As a result, current designs are more economical and provide for better control of movement.

Construction of a vertical excavation begins with a shallow cut. The height of this cut is determined by the soil's ability to temporarily stand unsupported, normally about 2 m. The next step consists of shotcreting the cut and installing the soil nails. Once these steps are completed, another lift is constructed below the first, and the process is repeated until the desired level is reached. Drainage is provided to remove water from behind the shotcrete wall. When soil nailing projects are constructed as retaining walls, construction follows the same sequence, with the addition of better drainage details and possibly corrosion protection for the nails.

In nonaggressive ground environments, grout alone provides satisfactory corrosion protection. When used in more aggressive soils, the steel nail can be epoxy coated to increase its resistance to corrosion. In most soil nailing applications, the construction of a separate concrete face is reasonably economical, as well as aesthetically and structurally superior to the use of shotcrete facing.

Although soil nailing was imported to the United States from Europe with reasonably good engineering guidelines, there were some major questions concerning the general behavior mechanisms, failure modes, durability aspects, facing design, and seismic behavior. A series of research studies was initiated to develop comprehensive technical guidelines for using soil nailing techniques to stabilize highway slopes and excavations. The development of a computerized design program was also an important associated objective of this research.

Analytical studies and physical experiments were conducted to evaluate design parameters such as type of soil and noncompetent rock suitable for nailed reinforcement; type, size, and location of reinforcing nails; and design equations for checking stability, internal pullout resistance, and deformations. Durability aspects were also to be identified and procedures developed to provide assurances for corrosion protection and structural permanence. Laboratory tests were conducted to verify the choice of appropriate parameters for prediction and design. Field tests were then performed on full-scale structures to verify laboratory and analytical results (42). Figure 33 shows an instrumented nail being installed on a test wall at the Cumberland Gap tunnel project.

During the course of the soil nailing research project, a partnership with French researchers was developed to coordinate investigative efforts. The cooperative project was called "Clouterre", which is French for "soil nail." As part of the Clouterre agreement, FHWA agreed to focus major efforts on seismic behavior, field performance monitoring, development of a research quality data base, and facing design investigations. France placed most of its emphasis on the analysis of the engineering behavior of soil-nailed structures in different types of soils, including system behavior and

Figure 33. Installation of instrumented soil nail at Cumberland Gap site.

structural displacements. The French researchers were also responsible for making a critical assessment of available design methods and special loading conditions, such as frost effects and surcharge loadings, that occur at bridge abutments.

A study entitled "Seismic Analysis of Soil-Nailed Retaining Structures" was initiated under joint sponsorship with the National Science Foundation (NSF) to evaluate the response and possible failure mechanisms of soil-nailed walls under dynamic loads. A finite element analysis and evaluation of the dynamic loading behavior of these walls was performed using an integral approach consisting of post-earthquake observations, centrifuge testing, and numerical analysis. The researchers developed testing procedures to establish reliable design parameters for characterizing the dynamic soil-nail interaction and formulated an analysis procedure for the computation of dynamic loading effects on the location and magnitude of maximum nail forces.

A series of laboratory model tests and full-scale field tests was previously completed for FHWA to evaluate soil and reinforcement parameters that are involved in the design and construction procedures for soil nailing. Data analysis and evaluation of existing procedures were used to develop interim design and construction guidelines for using soil nailing techniques to stabilize soil cutslopes.

In a separate research study, FHWA funded a project for "Testing of Soil Nail Wall Facings" to determine ultimate and service capacities for developing an appropriate facing/connection design, especially in regions of high seismic activity. At the time of this research, the design methods for facings were quite conservative. Therefore, it was hoped that this research would allow thinner facings to be used, resulting in construction cost savings. Also at that time, there was not a consensus regarding which of the available design methods should be used, because none of the methods were found to directly apply to soil nail wall facings. The new procedures are described in the FHWA manual (43).

Another FHWA study investigated the use of soil nails for cohesive soil stabilization. A specialized direct shear apparatus was used to test specimens of the clay reinforced with small-diameter steel bars (nails) to examine the engineering effectiveness of using soil nails to stabilize excavations and slopes in clay soils. Proof tests were conducted initially using sand to verify the performance of the shear test apparatus, measurement instrumentation, and data acquisition system. Direct shear tests were then performed on unreinforced clay specimens to obtain reference data under constant strain rate loadings before the soil-nail reinforced tests were done. Stresses in the nails during soil shearing were measured to determine the nature of nail loading. Existing stability analysis methods for nail reinforced soil masses were verified and modified to account for the measured behavior.

A full-scale wall was constructed at the UMASS NGES facility in Amherst within the varved clay layers of soil in a remote section of the site. Two rows of nails were installed and readings were taken from the strain gauges and tip load cells on the nails, plus the vertical and horizontal inclinometers and piezometers in the soil behind the wall face. The wall was then induced to fail (figure 34) by excavating below the reinforced

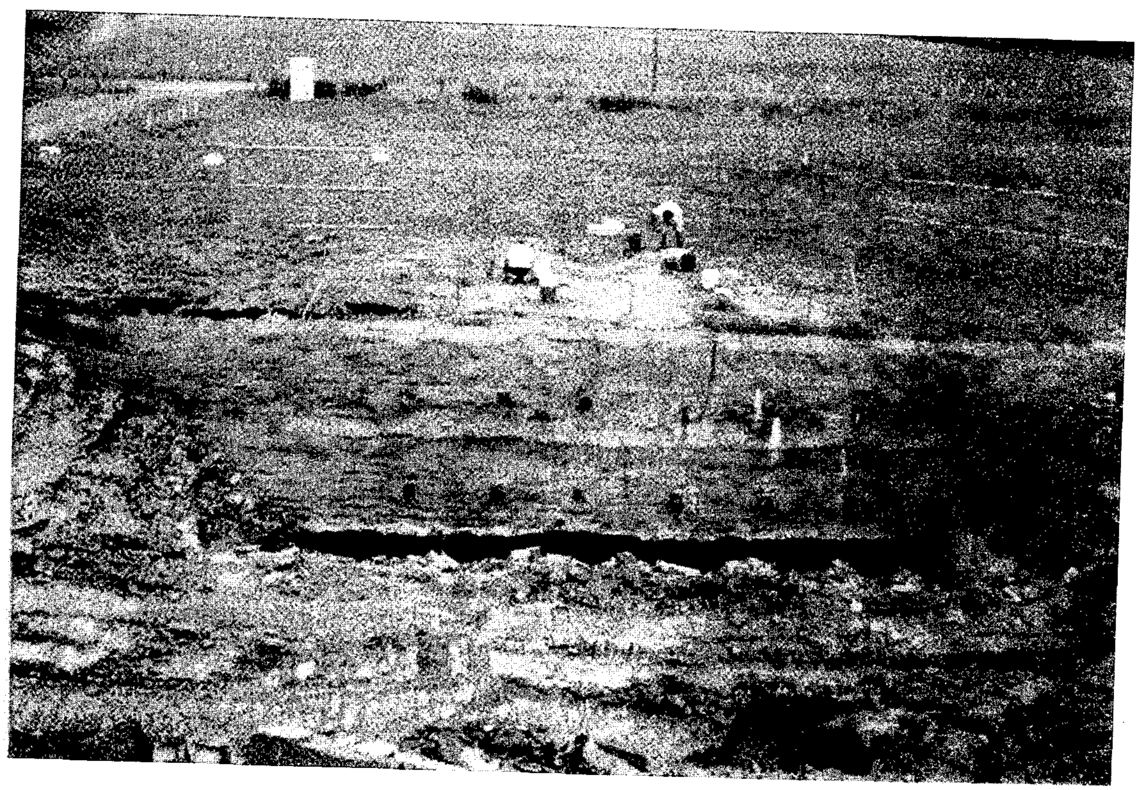

Figure 34. Failed soil nail wall due to undercutting.

portion of the wall to undercut its stability. Instrumentation readings were taken during the excavation operations, and at failure when the wall was undercut a total of 2.5 m below the reinforced face of the wall. The field work was funded by FHWA and ADSC.

FHWA and the Washington State Department of Transportation cooperatively funded a study to collect and develop a world-wide data base of instrumented soil nail wall projects. The study also involved using the data base to evaluate existing soil nailing design methods. The data collection and evaluation/validation of the available limit-equilibrium methods provided an improved understanding of the stress-deformation mechanisms in soil-nailed walls, which in turn led to the development of an improved and well-substantiated design procedure for soil-nailed walls.

3.6 Soil Treatment

The primary concern in soil support for structures is volume stability, strength and durability. However, adequate support is highly variable and is more case specific than site specific. In the proper state, virtually any soil type, except highly organic materials, may be adequate for foundation support. Conversely, any soil type, in its natural state, may be inadequate for foundation support. Adequate soil support depends more on the loadings and performance requirements than it does on the soil itself.

The history of soil treatment techniques can also be traced back to ancient times, like reinforcement technology. During the 1970's and 1980's, several promising technologies were imported from Europe along with the previously described reinforcement methods, except that they did not require the insertion of reinforcing elements into the soil mass. Four of these special methods were selected by FHWA for detailed study and evaluation to better understand the basic mechanisms underlying each technique; however, subsequent funding limitations caused the elimination of one of these technologies (grouting) from the overall program. Research studies were initiated and completed on dynamic compaction, prefabricated vertical drains, and stone columns.

3.6.1 Stone Columns

As in most new ground improvement techniques that were developed in foreign countries, experience has preceded the development of theory and comprehensive guidelines. Stone columns have been used since the 1950's as a technique for improving both cohesive soils and silty sands. Potential applications include (1) stabilizing foundation soils, (2) supporting structures, (3) landslide stabilization, and (4) reducing liquefaction potential of clean sands. The high potential for beneficial use in highway applications prompted a comprehensive investigation to determine how and why the system works so well, and to develop appropriate design and construction guidelines. The guidelines report describes construction, field inspection, and design aspects of stone columns. Also, several case histories are described. Bearing capacity, settlement, and stability design examples are given in the design appendices (44).

3.6.2 Dynamic Compaction

Dynamic compaction is also a very cost-effective soil treatment technique that can be used to improve poor subgrade support conditions at a roadway or bridge site. This is particularly true in or near urban areas where land with good support conditions has already been developed or set aside for commercial purposes other than highways. Much of the remaining space is undeveloped land because of poor soil conditions.

In many cases new roads and streets are forced to traverse old landfill deposits, strip mine spoil areas, or building rubble and construction debris deposits. Naturally occurring loose sands and collapsible soils such as loess can also present difficult construction problems for highway engineers. Dynamic compaction techniques have proven to be ideally suited to handle these problems where other techniques have failed. Another important application is for densifying loose sands to reduce liquefaction potential in high-risk seismic zones. Dynamic compaction techniques have been found to produce densification in natural and manmade deposits to depths varying from 3 to 12 m below grade.

Dynamic compaction is defined as the densification of loose soil deposits or miscellaneous fill materials by means of repeatedly raising and dropping a heavy weight from varying heights to impact the ground (figure 35). This process has also been called by other names, including impact densification, heavy tamping, dynamic consolidation, pounding, and dynamic precompression. The energy is generally applied in phases on a grid pattern over the entire loose or soft area using either single or multiple passes. Following each pass the craters are either leveled with a dozer or filled with granular fill material before the next pass of energy is applied.

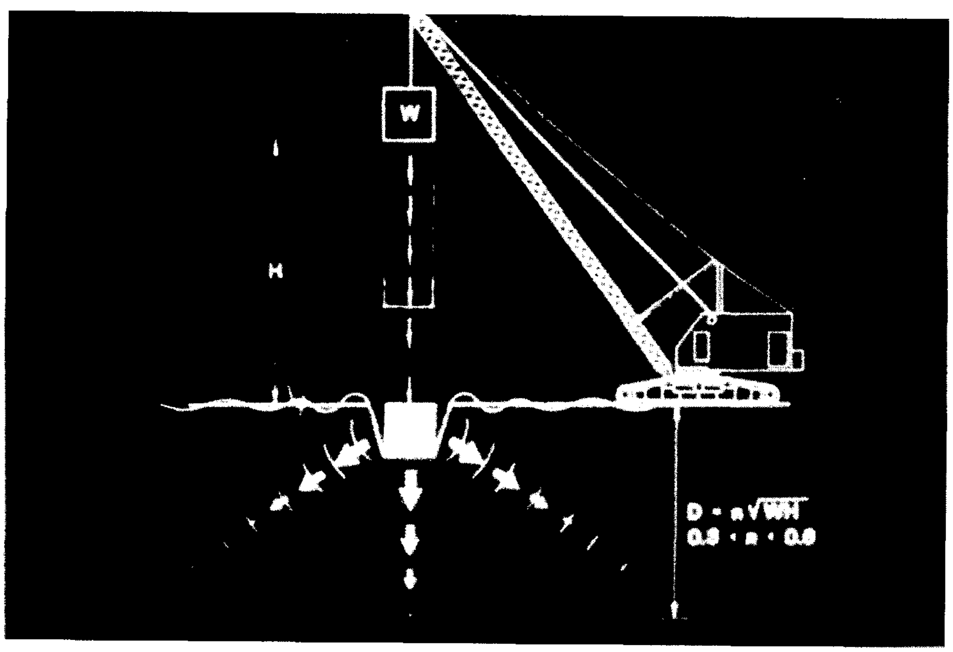

Figure 35. Schematic of dynamic compaction methodology.

All of the energy is applied from existing grade, and the degree of improvement is a function of the energy applied through the mass of the tamper, the drop height, the grid spacing, and the number of drops at each grid location. Lighter tampers and smaller drop heights result in shallower improvements. For greater depths and higher relative density improvements, heavier tampers and higher drop heights must be used.

When the technology was first imported from Europe, little was known about how to plan a project or complete a preliminary evaluation to determine if dynamic compaction is appropriate for the specific site and subsurface conditions. Design details and construction monitoring guidelines were nonexistent. There were no sample specifications to guide designers, and no procedures were available to measure the degree of improvement achieved with each pass. Not knowing when enough is enough can reduce the cost advantages rather quickly.

To gain more insight, FHWA initiated a contract research study to conduct tests and evaluation studies of the improvement mechanism to better understand how the technique worked. A series of field experiments was conducted to investigate soil and tamping parameters involved in the dynamic compaction process. Instrumentation was installed to monitor ground vibrations, horizontal and vertical displacements, pore pressures, acceleration and speed of the tamping weight, penetration of the weight into the ground, and degree of treatment achieved.

The results of the field tests were used to develop generic specifications and a manual that describes in detail all of the design and construction issues, plus all of the non-technical issues previously mentioned (45). The manual was recently updated by FHWA's Office of Technology Applications and reissued as Geotechnical Engineering Circular No. 1 to provide this new information to assist SHA's with a user-friendly engineering document. A slide tape show was also developed to provide a visual rendering of the manual for instructional purposes.

3.6.3 Prefabricated Vertical Drains

The need for proper drainage in highway projects is well established. Sand and /or gravel layers (or other geometric shapes) have been used for decades to provide the appropriate drainage vehicle. One of the most cost-effective methods of soft ground improvement is through drainage, especially the use of radial drainage and manmade vertical drains working in tandem. When heavy embankments are placed on soft depositional type soils, the loading will tend to squeeze the water out of the soil in a vertical upward direction to a drainage blanket placed at the bottom of the embankment, and possibly downward to a natural drainage layer (of sand) that might exist below the soft and low permeability layer that is being squeezed.

In a soil that has been deposited in layers in ancient times, the boundaries between layers tend to impede the water flow vertically. Therefore, the horizontal permeability is significantly faster, and can be as much as 10 times faster if there are intermittent granular layers in the deposited soil. By installing artificial vertical drains, the drainage path is greatly reduced and horizontal permeability will control the time of drainage.

When water is drained, the soil consolidates and gains strength, which increases its ability to safely carry more embankment loading, which will cause more consolidation and so forth. Very high embankments can thus be constructed in stages with time delays to allow for consolidation and strength gain.

Until recently, sand drains have traditionally been used for this purpose with success; there are, however, a number of practical constraints associated with installing sand drains, namely, the disturbance of soil (smear) around the sand drain, the need for a large quantity of water when jetting is used, the availability of quality sand to fill the drains, and the relatively high cost of installation.

Because of these disadvantages, engineers searched for a better way to create these artificial drainage paths that would be cheaper, faster, and environmentally less disruptive. The most popular alternative was called a "wick drain" and consisted of a prefabricated plastic band that had a geosynthetic filter fabric wrapped around a central plastic core that the water moved through after it was filtered through the wrapping (figure 36). Although these wick drains had many significant advantages over sand

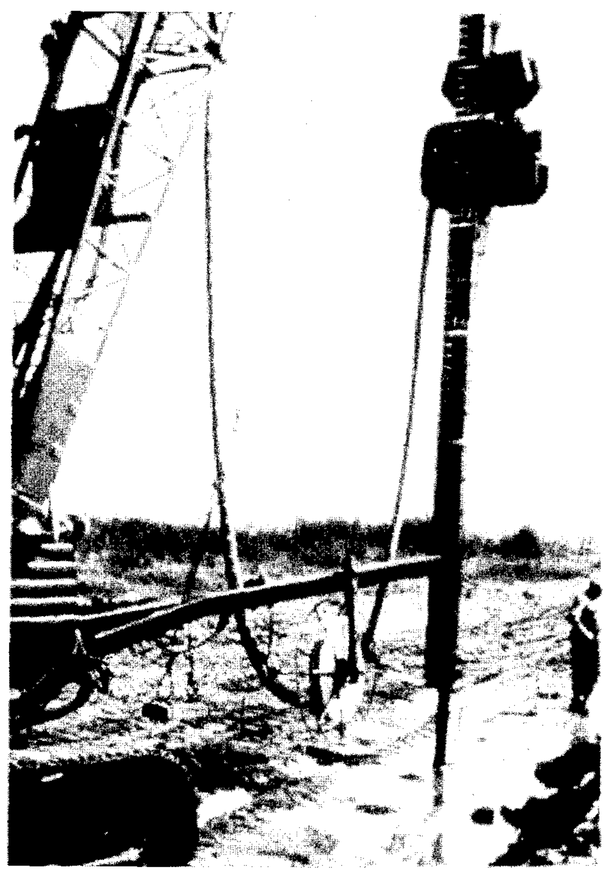

Figure 36. Wick drains being installed at an embankment on soft clay site.

drains, there were many unanswered questions regarding design assumptions, laboratory screening tests, quality control, installation methods, durability, and generic acceptance specifications.

Recognizing the huge potential of prefabricated vertical drains, industry responded with the development of a large number of different and mostly proprietary models; some good, others not so good. Engineers soon discovered the need for generic testing protocols to help them select and approve satisfactory drains.

A comprehensive FHWA research study was initiated to develop generic testing procedures and sample specifications, as well as complete descriptions and helpful guidance for design and construction. The study also included a parallel investigation of prefabricated drainage sheets and boards that were becoming popular for use behind retaining walls.

For more detailed descriptions of types and physical characteristics of these drainage materials, the best source is FHWA-RD-86-169 for wick drains, and FHWA-RD-86-171 for sheet drains (46,47). These reports also provide a discussion of design considerations, recommended design procedures, guideline specifications, and advice on construction installation, control, and performance evaluation.

3.7 Publications and Implementation Items

Research and development activities for ground improvement techniques were very successful. Numerous quality reports and manuals were generated from this project, which is by far the most comprehensive research investigation of this topic by any single organization in the world. Numerous technology transfer items were disseminated to accelerate the implementation of this new information to highway practitioners. Many changes were made to the AASHTO Specifications (see chapter 7) and several FHWA training courses and technical circulars were developed on the basis of the research results.

CHAPTER FOUR

SOIL AND ROCK BEHAVIOR PROJECT

Highway bridges and pavements are usually supported on whatever ground materials are located directly beneath or within easy access of the roadway right of way to avoid expensive haul distances. Consequently, highway engineers need methods for evaluating and upgrading available materials to properly support the pavement or bridge structure being designed.

During the height of the Interstate construction period, many difficult soil and site conditions caused highway engineers to search for better ways to eliminate or ameliorate these situations so that roads and bridges could be built in a safe and efficient manner. Many areas of the United States had common problems of unstable soils and poor compaction techniques; but some had regional concerns, such as frost action in the northern tier of States, and expansive soils in the south. Some areas even had problems with rock materials that seemed hard during excavation, but later would deteriorate or exhibit expansive soil behavior after the passage of time while inside an embankment fill structure.

The solution to these problems was universally recognized by FHWA and SHA's as a priority research need. Thousands of miles of highways were being constructed annually in areas where swelling soils, frost susceptible soils, deteriorating shales, hard to compact soils, and otherwise unstable soils were causing expensive damage to correct. Even a small reduction in the unit costs to repair these damages would result in annual savings of several million dollars.

4.1 Background

In the 1970's it was estimated that the annual cost of damage to highways and streets caused by expansive soils exceeded $1 billion. In addition, similar estimates were made concerning frost action and thaw weakening damage in northern states. At the same time, many States were spending millions to repair, rebuild, or replace highway embankments that were initially constructed as rock fills and later failed as though they had been built with soft clays. Still other SHA's were seeking solutions to the high cost of compacting weak soils or using chemical soil stabilizers to improve strength and/or reduce volume change tendencies.

The energy crisis was also causing prices of asphalt to skyrocket out of control. Many places were also concerned about the high utilization factors for quality granular materials, and efforts were needed to conserve limited sources of these materials. Research to increase the use of chemical compaction aids that would reduce the cost of compaction, and research to increase the effectiveness of existing soil stabilization systems featuring lime, cement, fly ash, and bitumens were given very high priority.

4.2 Objectives

The objectives were to develop methods for (1) predicting the performance of and (2) eliminating the engineering deficiencies of soil and rock materials used in earth structures, subgrades, base courses, and as support for highway structures.

4.3 Scope

Research efforts in this project were directed toward developing methods for predicting the volume stability of expansive and frost-susceptible materials and to provide methods for identification, characterization, and evaluation of materials that exhibit unaccountable instability or excessive compressibility when tested and handled by existing techniques. Research was conducted to provide physical and chemical treatment of soil materials to enhance their value and availability for engineering use. Special emphasis was placed on the development of methods for eliminating or relieving pavement distress due to excessive volume changes of expansive subgrades, inadequate strength or durability of subgrade or base components, and frost heave and subsequent weakness in foundation layers.

4.4 Project Description

The major research efforts were in five tasks:

1. Improved Technology for Expansive Clays and Shales - The research was directed toward providing an improved methodology for predicting expansive clay characteristics and conditions responsible for pavement distress and synthesizing remedial treatments that can be used for maintaining volume stability. The validity of design and construction procedures to prevent detrimental volume change of the soils was also examined.

2. Improved Compaction of Fine-Grained Soils by Chemical Treatment - Increasing the density of the soil mass generally provides improved strength and performance of the specific soil material. Detailed knowledge of the changes in soil structure or fabric changes caused by the compaction process, however, was conspicuously lacking. Earlier FHWA research had provided some insight into the soil fabric of compacted soils and into factors influencing the subsequent behavior of compacted soils. Research regarding the chemical substances (elements, ions, group and specific types of compounds) that might be added to soils to provide greater compactibility, and to make laboratory and field evaluations of selected compaction-aid chemicals was conducted under this task to provide solutions.

3. Increased Effectiveness of Existing Soil Stabilization Systems - This task was concerned with rendering current stabilization practices more effective, economical, and widely useful. Studies were conducted to identify and evaluate

trace additives for increasing the strength, durability, resistance to frost and moisture changes, and to extend the range of soil types appropriate for stabilization with a given stabilizer.

4. Development and Evaluation of Frost Heave Predictive Techniques - The research was done to evaluate the suitability of parameters such as heave pressure, permeability, and heave rate for predicting the frost susceptibility of subgrade soils and base course materials. After selecting the most appropriate parameters, and perfection of the apparatus and procedures for measuring them, criteria for predicting the frost heave susceptibility were developed and verified by field observations. In addition, research was conducted to characterize subgrade materials with respect to changes in strength during seasonal variation (frozen, thawing, and thawed periods).

5. Strength and Deformation Properties of Soil and Rock Materials - This task was concerned with: (1) providing a methodology for identifying and evaluating the performance of problem materials such as shales, organic soils, and sensitive soils; (2) developing techniques for preventing distress and failures of embankments, cut slopes, and foundations of problem materials; and (3) developing techniques for estimating and controlling hazardous rock fall problems.

The Soil and Rock Behavior Project was the initial project for FHWA in the geotechnical research arena. The following five sections of this chapter provide a summary of the major contributions of this project.

4.5 Expansive Clays and Shales

The first important decision in the design and construction sequence for a highway is the route selection. Route selection is often influenced by social, economic, environmental, and/or political considerations prevalent at the time of design. Often the geologic materials (and the associated problems) traversed by the selected route are not considered until the collection of parameters for the pavement design. For expansive soils, it is important to recognize the existence of the problem and have a qualitative indication of the extent of the potential swell problem as early in the design and construction sequence as possible.

Figure 37. Pavement damage due to expansive subgrade soils.

Volume change of expansive soil subgrades resulting from moisture variations frequently cause severe pavement damage (figure 37). Highways constructed in the Southwest, Western Mountain, Central Plains, and Southeast geographical areas are particularly susceptible to these types of damage. A survey of U.S. highway departments indicated that 36 States have expansive soils within their geographical jurisdiction. Expansive soils are so areally extensive within parts of the United States that alteration of the highway routes to avoid the material is virtually impossible.

Because of the billions of dollars of damage done in the United States to pavements and buildings each year, many requests for technical guidelines for expansive soils were generated by SHA's and building owners. Several workshops and technical conferences were held to discuss the problem and to develop a plan of action and list of research needs. It was determined at first that the procedures for the design and construction of pavements on expansive soils did not systematically consider the variety of factors and conditions that influence volume change, as evidenced by the continued occurrence of warped and cracked pavements in areas where expansive soils exist. Thus more accurate methods were needed for identifying, testing, and treating expansive clays to improve highway design, construction, and maintenance techniques.

It was also decided that a comprehensive study was needed to achieve the following goals: (1) the establishment of physiographic areas of similar natural sources and manifestations of swelling behavior, (2) the development of expedient procedures for identifying expansive clays, (3) the development of testing procedures for quantitatively (amount and rate of volume change) describing the behavior of expansive clays, (4) the development and evaluation of innovative technologies for prevention of detrimental swell under new and existing pavements, and (5) the development of recommended design criteria, construction procedures, and specifications for the economical construction of new pavements, and maintenance or reconstruction of existing pavements on expansive soils.

On the basis of these requests and a series of research recommendations developed by FHWA personnel, a contract research study was initiated. In the study, the distribution of potentially expansive soils was defined and their relative expansivity established to provide a summary of potential problem areas. Various methods for qualitative and quantitative evaluation of expansivity and pre- and post-construction methods to minimize the detrimental effects of subgrade volume change were also reviewed under the study. In addition, field sites were selected, samples taken, and field monitoring plans developed to evaluate selected methods for predicting expansivity .

The final reports summarize the major research results and present the details of the research efforts. Volume I presents the text and summary figures relevant to the discussion of the results of the research tasks. Volume II presents the laboratory data collected on samples from 22 field sampling sites and the monitoring data from 8 field test sections located in 5 different States (48).

Conclusions drawn from the research results provide better criteria for identifying and classifying potentially expansive soils; more accurate and reliable procedures for characterizing and predicting the behavior of expansive soils; guidelines for application of pre- and post-construction treatment alternatives for minimizing volume change of expansive soils; and practical design, construction, and maintenance recommendations for minimizing moisture infiltration into an expansive soil subgrade.

The results of the study that should be implemented are presented in a manual titled *Technical Guidelines for Expansive Soils in Highway Subgrades.* Technical guidelines are presented on the location of potentially expansive soil areas using occurrence and distribution maps, as well as alternative sources of information; field exploration and sampling of expansive soils; identification and classification of potentially expansive soils using index and soil suction properties; testing of expansive soils and prediction of anticipated volume change; selection of appropriate treatment alternatives; and presentation of design, construction, and maintenance recommendations for new and existing highways. Appendixes to the technical guidance report describe the soil suction test procedure, and include a standard procedure for odometer swell tests, a bibliography on treatment alternatives, and standards for field monitoring data.

When the research was completed, FHWA's Technology Transfer program funded an effort to implement the results. An executive summary report of the research reports was developed along with various training materials to be used at two training workshops. The executive summary report (49) was distributed at the workshops along with a participant's workbook and the technical guidelines manual (50).

4.6 Soil Compaction

Compacted soil is an essential element of highway construction. Soil density and moisture content is used almost exclusively by the highway industry to specify, estimate, measure, and control soil compaction. This practice was adopted many years ago because soil density and moisture content can be determined very easily via weight and volume measurements.

This doesn't mean that soil density and moisture content are the most desired engineering properties, because they are not as important to know as the soil modulus or stiffness characteristics. The latter properties were much more difficult to measure, so it became standard practice to measure the former indicators (density and moisture) in order to provide an indirect measurement of stiffness at a much reduced cost.

In addition to property measurement techniques, engineers and builders both were seeking some magical chemical to alter the soil properties to make it more readily compactible. Chemical compaction aids began to surface in large quantities purporting to be the ideal product to accomplish this highly desired objective, thus requiring an evaluation protocol to determine which, if any, of these products were legitimate sources of help with this problem.

4.6.1 FHWA Compaction Aids Research

A laboratory staff study on the evaluation of two proprietary materials as compaction aids was completed and a final report published. The testing program used to evaluate the materials was developed by FHWA and endorsed by the manufacturers prior to its initiation. It was concluded that neither product produced sufficient alteration of soil properties to be of any practical utility for acidic soils. Other researchers have concluded from similar, but broader, studies that these products may only be effective with neutral or alkaline soils.

A more extensive FHWA contract research study on "Chemical Compaction Aids for Fine-Grained Soils" was completed wherein the feasibility of improving the compaction characteristics of fine-grained soils by chemical treatment was determined for a number of chemicals and several proprietary products. The study was divided into three phases: (1) an office evaluation, (2) laboratory investigations, and (3) field evaluations of the more promising chemicals.

The results of this study indicate that the effectiveness of chemicals for improving compactibility cannot be generalized according to classes of chemicals and soil types because it is a function of many interrelated variables. The effectiveness of a given chemical must be evaluated with the soil to which it is to be applied. Laboratory techniques and evaluative procedures that appear suitable for predicting field performance of chemical compaction aids were developed to facilitate this "one-on-one" evaluative approach, which was partially validated by field studies in Iowa and New Mexico. Although several of the 20 chemicals evaluated in the study improved some of the engineering properties of a few soils, none of the benefits derived were generally or practically significant.

The research results are presented in a two-volume report *Chemical Compaction Aids for Fine-Grained Soils.* Volume I of this report includes an extensive review of appropriate subject literature and the laboratory moisture-density-strength study of 20 chemicals with 8 soils of varying origin and mineralogy. Also included is a theoretical discussion of possible mechanisms of chemical compaction aids, properties of the 26 soils used in the laboratory investigations, and data from supplemental tests designed to improve understanding of the influences of chemicals on fine-grained soils. Six chemicals were selected for the more extensive laboratory evaluations with 18 additional soils (51).

Volume II includes moisture-density-strength screening tests performed on several additional chemicals and an evaluation of the standard AASHTO T-99 moisture-density test results performed on soil specimens prepared under varying conditions of drying, pulverization, and re-use. Also presented are the results of a laboratory moisture-density-strength study of chemicals selected and evaluated through both qualitative and statistically related procedures, laboratory compaction growth, and 7-day moist cure results (51).
A discussion of the mechanisms of chemical compaction aids as evaluated through the assistance of infrared spectrography, vapor pressure osmometer, and zeta potential

tests is also included in Volume II. Based on the total study, an "ideal" compaction aid is described. Volume II also presents results of field trials conducted on a roadway embankment near Knoxville, Marion County, Iowa, and a soil-aggregate base near Villanueva, New Mexico (51).

4.6.2 Soil Stiffness Gauge (SSG)

As previously mentioned, soil stiffness information is more valuable to designers for evaluating subgrade support capacity than are density measurements; however, the difficulty and expense of obtaining quality stiffness data have traditionally caused engineers to rely on density tests to check quality assurance and control soil compaction. In the early 1990's, construction engineers began to search for something that was safer and more economical to use because accidents and production delays were increasing at an alarming rate. Current methods for testing soil compaction in the field are slow, labor intensive, unsafe, and of uncertain accuracy.

Because of the labor and time involved, construction sites are often under-sampled, causing some problems to go undetected, or providing data too late for cost-effective correction of problems. Sometimes the opposite is true, because some contractors frequently over-compact in order to ensure passage of acceptance tests and thereby avoid rework at a later date. Also, engineers tend to over-specify compaction requirements in order to allow for the significant variability in a noncontinuously monitored compaction process. Excessive over-compaction can have significant impact on site preparation costs.

The SSG (figure 38) measures the in-place stiffness of compacted soil at the rate of about one test per minute. The SSG weighs about 11.4 kg (25 lb), is 28 cm (11 in) in diameter, 25.4 cm (10 in) tall, and rests on the soil surface via a ring-shaped foot. The stiffness is the ratio of the force to displacement: K=P/d. The SSG produces soil stress and strain levels common for pavement, bedding, and foundation applications.

Figure 38. Soil Stiffness Gauge.

In addition to time and cost advantages, a portable compaction device that is quick and easy to use will save lives and reduce exposure to injuries by allowing the technician to make measurements at the rate of one in-place stiffness test per minute. Numerous deaths have been reported where technicians were preoccupied with performing a nuclear density test or other quality assurance method, and did not see or hear a heavy construction vehicle before it ran over them. In one incident, the U.S. Nuclear Regulatory Commission inspectors were called in because the gauge containing Cesium and Americium sources became exposed when the unit was crushed. The technician was killed. The paperwork and safety precautions are tedious enough under normal operations, but they are an order of magnitude higher when accidents occur. A non-nuclear method is in great demand.

In response to this need for a faster, cheaper, safer, and more accurate compaction device, the FHWA researchers joined with scientists from the U.S. Department of Defense's Advanced Research Programs Administration (ARPA) to cosponsor a study to investigate the possible use of military technology to solve this problem. As part of the defense reinvestment initiatives, and using funds from the Technology Reinvestment Project, ARPA authorized FHWA researchers to supervise the redesign of equipment that was built to locate buried land mines for armed forces personnel. The military device used acoustic/seismic detectors to locate the buried land mines, and included U.S. Navy sonar acoustics and electromagnetic shaker technology developed under another contract to DOD.

The prototype model was modified to make a soil stiffness gauge that is portable, lightweight, and safe to use. It rests on the soil surface via a ring-shaped foot and produces a vibrating force that is measured by sensors that record the force and displacement time history of the foot. It is a practical, dynamic equivalent to a plate load test. Figure 39 is a schematic of the SSG showing the major internal components, except for the D-cell batteries that power it.

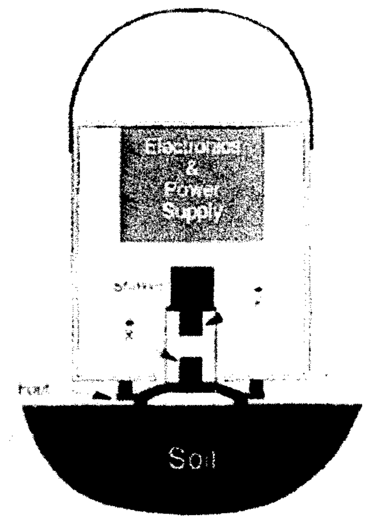

Figure 39. Schematic of SSG showing major internal components.

The device has been "Beta" tested by FHWA and several SHA's. Thousands of soil stiffness measurements have been successfully made at highway embankment and pipe backfill sites on sand, clay, and sandy loam soils. When converted to density values using correlation charts, these measurements are within plus or minus 5 percent of companion measurements made with a nuclear density gauge. Production devices are being made for further evaluation at sites representing a cross-section of U.S. applications and soils. Future models will include onboard moisture measurement instruments and a global positioning system (GPS).

4.7 Soil Stabilization

The concept of soil improvement or modification through stabilization with additives has been around for several thousand years. At least as early as 5000 years ago, soil was stabilized with lime or pozzolans. Although this process of improving the engineering properties of soils has been practiced for centuries, soil stabilization did not gain significant acceptance for highway construction in the United States until after World War II. Today, stabilization with lime, lime-fly ash, portland cement, and bituminous materials is very popular in some areas of the country.

One of the major concerns has been the shortage of conventional aggregates. The highway construction industry consumes about half of the annual production of aggregates. However, this traditional use of aggregates in pavement construction has resulted in acute shortages in those areas that normally have adequate supplies. Other areas of the country have never had good quality aggregates available locally. Metropolitan areas have also experienced shortages. The reasons include lack of the raw materials, environmental and zoning regulations that prohibit mining and production of aggregates, and land-use patterns that make aggregate deposits inaccessible. These factors, and others, combine to produce an escalation of aggregate cost, with a resultant increase in highway construction and maintenance costs. Consequently, there was a great need during the early stages of this research program to find more economical replacements for conventional aggregates. A natural result is that attention must be focused on substitute materials such as stabilized soils.

Another area of concern had been the energy crisis brought on by the temporary shortage of petroleum. It rapidly became a practice to consider the energy demands of a project as well as cost. In terms of highway construction materials, the trend was toward the use of materials that required less energy input in their production, handling, and placement. A study revealed that the energy requirements for producing the materials for various asphalts, crushed stone, and portland cement concrete pavements ranged from 30 to 96 percent of the total energy required for production, handling, and placing of various pavements. Since relatively small quantities of binders such as lime, cement, fly ash, and asphalt, could be used to improve pavement layers using stabilization technology, total energy demands may be reduced as well as costs.

The major objective of the soil stabilization research project was to develop information on materials that, when applied to soils of inadequate natural stability, would be capable of achieving stabilized soil subgrades and surfaces of sufficient strength to satisfy certain highway construction needs. It was also considered important to establish specific soil stabilization requirements to guide the development and evaluation phases of the soil stabilization research program. These requirements are expressed in terms of both the strength and thickness parameters of the stabilized-soil layer that will satisfy anticipated construction needs, and include consideration of certain limiting initial soil conditions that might be encountered in highway operations. Desirable maximum limits of curing time and quantity of stabilizer necessary to achieve the stabilization objectives were also needed.

4.7.1 Soil Stabilization Manual

A two-volume user's manual was developed for FHWA to provide guidance for pavement design, construction, and materials engineers responsible for soil stabilization operations associated with transportation systems. Volume I of the manual *Pavement Design and Construction Considerations* describes a method for selection of the type of stabilizers as well as pavement thickness design methods and construction information. Quality control, guide specifications, cost, and energy considerations are contained in the appendices (52).

Volume 2 of the manual *Mixture Design Considerations* was prepared for materials engineers. This volume describes methods for selection of the type and amount of stabilizers. Methods of estimating stabilizer contents are presented as well as detailed test methods, mixture design criteria, and typical mixture criteria (52).

The manual is directed to the engineer who is reasonably familiar with pavement technology, but who has limited experience with stabilized soil construction. Current technology of soil stabilization is presented in a complete but concise format such that the engineer can grasp the key elements and apply the information to specific needs. Suggested additional references are provided so that the reader may follow up on details of interest that are beyond the scope of this manual.

Basically, the manual was developed to provide guidance to design and construction engineers of highway agencies when using soil stabilization in lieu of high-quality aggregates for base and subbase layers in pavement structures. The manual illustrates techniques and advantages of using soil stabilization as a means of meeting shortages of local aggregate supplies and demonstrates the cost effectiveness of such utilization through examples.

Specifically, soil stabilization as addressed in the manual is limited to the following stabilizers: lime, lime-fly ash, portland cement, asphalt, and some combinations of these. The advantages of each stabilizer, mixture design procedures, characterization for structural design, and construction methods are covered for each stabilization method. In addition, a chapter is devoted to structural design utilizing stabilized materials in several pavement design methods, including AASHTO and elastic layered systems. Examples of specific situations are provided to illustrate the use of the manual as well as demonstrate how stabilized layers may be substituted for conventional granular materials.

4.7.2 Lime Stabilization Research

The results of an FHWA contract research study on the "Role of Magnesium in the Stabilization of Soils with Lime" indicated that, for all practical purposes, dolomitic or calcitic hydrated lime are equally effective for producing strength gain. However, calcitic lime was recommended for use with all soil types if reducing plasticity was the purpose of lime treatment.

The final report, *The Role of Magnesium Oxide in the Lime Stabilization*, is presented in three volumes (53). This report presents the results of a laboratory study to evaluate the relative effectiveness of calcitic and dolomitic lime for the stabilization of fine-grained U.S. soils. Evaluation of the relative effectiveness of lime, either obtained from commercial sources or manufactured in the laboratory, was based on the ability of the lime to reduce soil plasticity and increase its confined compressive strength.

Thirty-five clay soil samples, representative of major U.S. soil series, were treated with the various limes and were examined by x-ray diffraction, scanning electron microscopy, chemical analysis, petrography, and differential thermal tests to identify the specific soil or lime properties that govern the response of soil to lime treatment.

4.8 Frost Heave and Thaw Weakening Damage

The ravages of frost action on roads and streets is well documented by the news media each spring and by county and district maintenance engineers throughout the Northern States. For example, The Road Information Program (TRIP) estimates that more than $2 billion is required to rebuild the thousands of miles of pavement that are destroyed each winter in the United States. This expenditure is in addition to the cost of filling potholes and surfacing pavements with minor damage. According to TRIP, automobile repairs resulting from rough pavements and increased cost to transport goods because of detouring to avoid damaged roads should also be added to this cost to fully assess the impact of severe winter weather.

The problem of maintaining roadways and airfield pavements in areas of seasonal frost has long been a major concern to pavement design engineers. Although pavement designers have attempted to provide protection against the detrimental effects of frost action, severe winters have demonstrated that a basic and rational methodology for analyzing and designing pavement systems in cold regions did not exist during the early stages of this research project.

The seasonal variation in the serviceability of a pavement is very pronounced in areas subject to alternating freezing and thawing. The combination of freezing and thawing of pavement subgrades is commonly called frost action. Differential pavement surface heaving (poor rideability) frequently is the effect of freezing, and subsequent thawing may lead to a greatly reduced load-carrying capacity due to thaw weakening. Many potholes and other pavement breakups (distress) result from thaw weakening.

Some soils are more susceptible to frost action than others, and the amount of heave that occurs is not a good indication of how much strength loss will occur during the thaw period. It is also probable that a soil of lower frost susceptibility will experience greater heave than a soil of higher frost susceptibility if placed under more adverse temperature and water conditions. In fact, a highly frost-susceptible soil will not heave at all if either one of these two conditions (temperature and water) is missing. Conversely, clean granular materials not normally classified as frost susceptible will heave if the temperature and water conditions are sufficiently adverse.

4.8.1 Differential Heaving

Because the amount of heave is dependent on three conditions that can be quite variable—frost susceptibility of the soil, freezing temperatures, and access to groundwater—uniform heaving cannot be expected (figure 40). The differential heaving that results causes surface irregularities and general surface roughness in the form of bumps, waves, and distinctive cracking. Severe cases of differential heave will usually reduce traffic speeds significantly and may cause damage to vehicles or loss of control of the vehicle. The potential for abrupt differential heave at cut-to-fill transitions or culverts requires special design considerations.

Figure 40. Pavement damage due to frost heave.

The amount of heave that occurs is not entirely a result of the expansion of free water in the soil voids when freezing temperatures penetrate the subgrade soil mass. This can often be a small percentage of the total heave. In severe cases of heaving, the extent and rate of growth of ice lenses are determined by the soil's ability to draw water from below by capillarity and also by the rate and depth of penetration of the freezing temperatures. The formation of ice lenses responsible for heaving is governed by the interaction of heat and mass transfer (moisture movement) in porous soil media—a very complicated phenomenon. The growth of ice lenses also results in decreased soil density. After several cycles of freezing and thawing, the soil fabric can be adversely changed depending on the type of soil and the amount of ice lens buildup.

4.8.2 Thaw Weakening

Thaw weakening is considered by many to be the more critical manifestation of frost action. It is just as complicated as the heave problem and it is probably more difficult to evaluate or predict. This problem occurs when the ice lenses formed in the subgrade during freezing begin to thaw from the surface downward. This thawing results in melt water being trapped between the pavement and the still frozen portion of the subgrade, which, accompanied by loading of the soil in its loosened states, generates excess pore water pressure and a corresponding decrease in load-carrying capacity. The duration and frequency of load application (static versus dynamic) may also impact load-carrying capacity; that is, dynamic loading may be more destructive to soil structure, thereby reducing strength.

The increase in water content resulting from freezing and subsequent thawing is more detrimental for some soils than for others. The stability of fine-grained soils is more sensitive to changes in moisture content than is the stability of granular materials; that is, very slight increases in moisture content for silts and clays significantly decrease their stability while similar changes in water content do not affect the performance of granular materials. However, soil moisture content cannot be used as an indirect measure of thaw weakening because certain clay soils lose significant support capacity during thawing without significant increase in bulk moisture content. A different set of physical and environmental factors influence heave and cause subgrade weakening, thus requiring separate evaluations.

The frost action problem consists of a series of interdependent factors or parameters that vary over a wide range of values. Understanding the mechanism of frost action in soils requires a knowledge of soil behavior including soil physics. The frost susceptibility of soils is still a relatively unknown quantity; however, it is generally recognized that a soil is susceptible to frost action only if it contains fine particles. Most studies have shown that soils free of fines (particles smaller than the 200-mesh sieve) do not develop significant ice lens buildup or ice segregation. As a result, the engineering community has used various indirect measures or indicators based on particle-size distribution, pore-size distribution, grain shape, and plasticity characteristics. All of these contribute to frost susceptibility or ice lens buildup in varying degrees.

4.8.3 Coordinated Research Efforts

Due to the expense and large extent of evaluating all of the prior FHWA and SHA research studies on frost action, it was decided to develop a comprehensive research project that would utilize the combined resources of FHWA, the Federal Aviation Administration (FAA), and the Office of the Corps of Engineers (OCE) in the Department of Defense. A contract was signed with the OCE's Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, to evaluate, validate, and refine certain selected frost action techniques.

The CRREL study included an evaluation of the various devices for measuring frost susceptibility that were developed earlier by FHWA and the SHA's, and the development of full-scale field test sites to provide correlative data. The field data were also used to validate and refine a mathematical model and laboratory predictive techniques for assessing strength loss due to thaw weakening. Three test methods for predicting frost susceptibility were checked against the field test data for eight soils studied at the field test sites (54).

A computer model of frost leave and thaw weakening was developed from existing data obtained from earlier studies. It is a finite element model that couples heat and moisture transport in freezing soil water systems and provides quantitative predictions of the frost heave and thaw weakening a soil will experience under different moisture and temperature conditions (55).

A laboratory soil column device was designed and built by CRREL to nondestructively measure moisture content, density, and soil suction changes that occur during unidirectional freezing of the soil sample. A dual gamma energy source was used to simultaneously monitor the changes that occur as the soil sample was gradually frozen and thawed, without having to periodically stop a particular test to take a moisture and/ or density sample. The soil column results were used to refine the computer model while researchers waited for the measured results of the field test sites.

Another laboratory segment of the project involved repeated load triaxial compression tests on undisturbed samples of the test site soils. The samples were obtained by coring the frozen subgrade soils during the first winter cycle of the field test program. The samples remained frozen until tested and, upon completion of the repeated load tests, the samples were allowed to thaw and then retested in the same manner. The test loads were stopped before the samples failed so that they remained suitable for retesting. The next tests were run on the same samples at different stages of recovery from thaw weakening.

Thaw recovery was artificially produced by desaturating the thawed specimen to various partial saturation points. The CRREL researchers monitored moisture content, density, and stress state variables including moisture tension. The deformation moduli were expressed in terms of these variables. Various resilient moduli for the soils at several depths in each test section were analyzed to determine which values gave surface vertical displacements that matched the measured field values.

The CRREL researchers and the sponsors (FHWA, FAA, and OCE) selected two field test sites to verify the analytical and laboratory predictive techniques developed under this project: an off-road test site on highway department land at a district maintenance depot in Winchendon, Massachusetts, and an FAA site at the Albany County Airport.

To minimize site-associated difficulties, it was decided that a number of different soils would be studied under the same environmental conditions by importing selected problem soils to the Winchendon site and placing them in prepared trenches (cells). The Winchendon site was chosen because it has a high natural groundwater table, granular subsurface soil with a relatively high permeability, and a relatively deep frost penetration. Twelve different soils were obtained from various parts of Massachusetts and several neighboring States. Each soil was placed in a cell at two different water table elevations and capped with a thin bituminous surface course.

The data that was collected in the field tests are as follows:

- Precipitation
- Ambient temperature
- Depth of frost penetration
- Water content profile
- Moisture tension
- Frost heave
- Subsurface temperatures

In addition to the above data, Repeated Plate Bearing (RPB) tests were run by CRREL and FHWA during each seasonal variation to obtain appropriate pavement response data (deflections) under certain selected loads.

The Albany County Airport site involved the construction of an extension to an existing taxiway and an existing, but little-used, taxiway pavement that had experienced detrimental frost effects. The sampling and testing programs at the Albany site were very similar to those for the Winchendon site.

These carefully controlled and well-documented laboratory and field test studies provided a valuable data base that was used to develop new methods to solve the frost heave and thaw weakening problems. A comprehensive set of design and construction guidelines for pavements in seasonal frost areas was developed by the CRREL engineers with financial assistance provided by FHWA's Technology Transfer program (56).

4.9 Performance of Problem Ground Materials

During the most prolific construction years of the U.S. Interstate Highway System, many large highway embankment sections were built with shale materials taken from cut sections or borrow sources and deposited in the embankment prism as if they were rock materials that did not require thin lifts and compaction processing. In many situations, the shales were of a type that appeared to be as hard and durable as rock while contained in their natural environment, but were subject to large-scale deterioration pressures when exposed to oxygen and other factors while functioning as a fill material in a large highway construction project.

Some of the clay shales deteriorated so fast that they reverted back to a soft soil that caused the embankments to fail (figure 41), especially if they were placed on steep slope angles as most rock fills are constructed. During one period of the 1970's, many of these landslide-type failures occurred in several States, prompting an outcry for comprehensive research studies to determine causes and remedies for this problem scenario.

In response to these requests, FHWA researchers studied the work of previous investigators and developed a comprehensive research plan to study the shale deterioration problem. Initial findings determined that compacted shale embankment problems can generally be divided into two categories: (1) those involving settlement and possibly lateral movement and (2) those involving slope instability. Both problems arise in part from the fact that embankments are commonly constructed as rock fills with material placed in 0.3-m (3-ft) to 1.2-m (4-ft) lifts and compacted only by hauling and spreading equipment. This practice can result in large voids within the fill, which tend to collect material when the deterioration process begins. The introduction of water into the fill accelerates the deterioration process and causes a reduction in the void spaces, resulting in settlement within the fill. A reduction in shear strength also results from the deterioration process, causing slope failures to occur in some extreme cases.

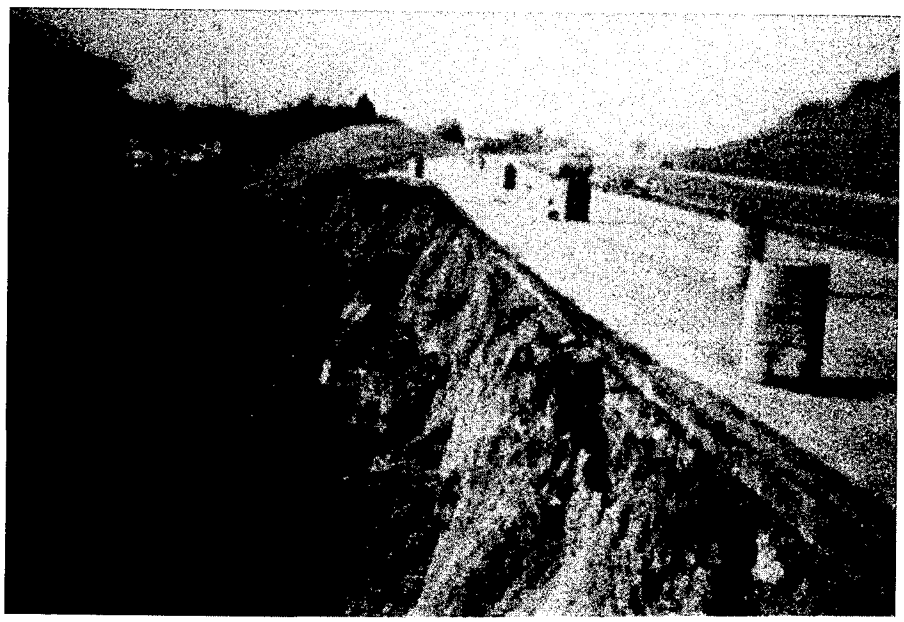

Figure 41. Shale embankment failure on I-64 in Indiana.

The obvious remedy for problems associated with shale materials is to mechanically process the materials during construction so that additional deterioration occurring during the service life of the embankment will not cause any significant embankment distress. The ease or difficulty of breaking down the shale material will determine the cost of the required processing. For example, a shale material that is mechanically hard when it comes out of the source area and nondurable (considerable slaking with time) is the most expensive shale material to use in an embankment because it is difficult to process to the point where subsequent deterioration will not cause excessive, nonuniform settlement and/or slope failure.

It is the consensus of engineers and researchers that the highway designer finds degradation and slaking to be the most important shale properties. Degradation is the reduction in particle size that results from construction processing, and slaking is the decomposition of the shale materials due to weathering within the new environment (embankment). In both cases, the amount of deterioration of fresh material (parent shale from the borrow or cut source) must be predictable to allow a proper design of the embankment. The degree of slaking that will occur after placement in the embankment will affect the geometry of the embankment and/or the amount of processing the shale will require during construction. The ease or difficulty of breaking down the shale material determines the cost of the required processing.

4.9.1 Shale Embankment Research

Based on the initial results, FHWA contracted to perform a comprehensive 4-year study to develop design and construction guidelines for using deteriorating shale in embankment fills. A separate contract was also issued to conduct several workshops in regions of high shale availability to teach SHA's and FHWA field personnel how to recognize shale deterioration problems and offer practical solutions. An executive summary report of the various research reports would be developed and distributed at the workshops to help field engineers implement the prominent findings of the research project. A participant's workbook was also to be developed and distributed along with the executive summary and a copy of the technical guidelines manual to be developed by the researchers.

The results of this study definitely indicate that compacted shale embankments can be designed and constructed economically to preclude subsidence and shear failures. The underlying cause of excessive settlement and slope failures in highway shale embankments appears to be deterioration or softening of certain shales with time after construction. The main difficulty is determining which shales can be placed as rock fill in thick lifts (0.6 m to 1 m (2 ft to 3 ft)), and which shales must be placed as soil and compacted in thin lifts (0.2 m to 0.3 m (8 in to 12 in).

The researchers developed procedures for anticipating the performance of shales in embankments from simple slaking indexes and delineated procedures for characterizing the shale materials, determining durability indexes, compaction tests including criteria for oversize shale gradations, and a simple test on compacted samples to assess expected compressibility of saturated shales for estimating long-term settlement potential.

The final report provides guidance on geological investigations, durability classification of shales, design features, and construction procedures unique to compacted shale embankments for highways. Guidance is also given on techniques for evaluating existing shale embankments and remedial treatment methods for distressed shale embankments. Index tests and classification criteria for determining shale durability, techniques for evaluating excavation characteristics, and alternative procedures for excavation, placement, and compaction of shales to achieve adequate stability and minimum settlement are described. The use of drainage measures, selective excavation, and placement of nondurable shales in thin lifts with procedural compaction provisions based on field test pads is emphasized (57,58).

4.9.2 Rockfall Hazard Mitigation

Public highway agencies are expected to provide a safe and efficient ride for its users. The traveling public not only expects it, they demand it. When serious consequences result from an unsafe situation, litigation is sure to follow. Rockfall is a common highway safety hazard in mountainous terrain (figure 42). The loss of life and property, serious injury, disruption of traffic, and expensive maintenance are major problems in many States. Costly litigation actions against States due to rockfall-caused accidents defer large sums from highway budgets that are needed for roads and bridges.

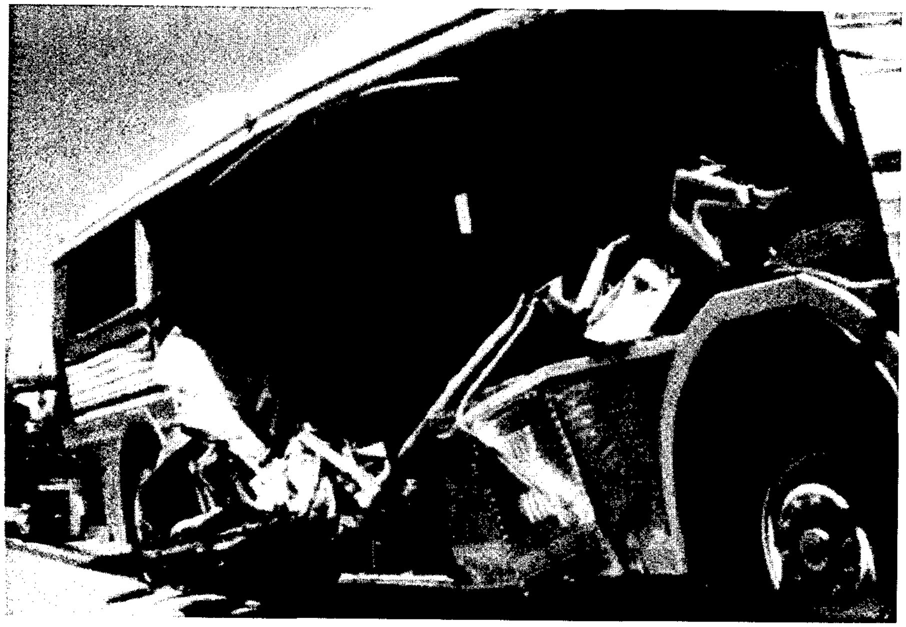

Figure 42. Bus badly damaged by large boulder at rockfall site.

Keeping roadways clear of rockfall debris is made more difficult in constricted transportation corridors where rock cuts are required. In some States rock slopes are rare but in more mountainous States, many miles of roadway pass through steep terrain where rock slopes adjacent to the highway are common. Some of these manmade slopes are very high. Many are situated near the base of rugged natural slopes that extend hundreds of meters further upslope.

There is an inherent rockfall potential at these sites. This potential is compounded by the way our highway systems have evolved over many years. In the past it was normal construction practice to use overly aggressive blasting and ripping techniques to construct rock slopes. Although this facilitated excavation, it frequently resulted in slopes more prone to rockfall problems. In some cases, uninformed designers were creating these unsafe rock slopes in order to satisfy architectural desires for a natural looking rock face. In addition, cut slopes are subjected to a broad range of climatic conditions that also affect the overall slope stability. Where these conditions exist, agencies are faced with the monumental task of reducing rockfall hazard.

It is estimated that a combined outlay of several hundred million dollars is spent each year to mitigate rockfall problems in this country. One recent incident occurred on July 1, 1997, on Interstate 40 in western North Carolina after a heavy rainfall caused a large rockfall to close all four lanes of the Interstate highway for over 4 months. Two cars were trapped and five people were injured. In addition, seven people were killed on the detour route in truck-related accidents that were attributed to the poor level of service provided by the lower standard highway route used as the detour facility. The rockfall slide area was approximately 100 m wide and contained more than 300,000 cubic meters of rock materials that had to be removed at a cost of more than $3 million.

An additional $1 million was spent to place a protective rock curtain over the cleared slope and construct a barrier wall at the toe of the slope to block further rockfall debris. The tourist industry claimed that it lost $40 to $50 million in business revenue during the shutdown period. A review of the remaining 32 km (20 miles) of this particularly dangerous highway section has resulted in an estimate of $40 million to correct the remaining potential rockfalll problems on this highway that was constructed in the early 1960's using construction blasting methods that blew the rock formations to unnecessarily high proportions.

The extreme danger to the traveling public and the significant economic impact of falling rocks on the roadway require an accurate assessment of rockfall probability and extent. In recognition of this problem, FHWA and several SHA's pooled their resources to initiate a program to develop a "proactive" system to improve an agency's ability to identify and respond to adverse rockfall situations. Prior to this cooperative approach, SHA's relied on a reactive system of identification and treatment to prioritize rockfall projects and allocate available repair funds. Experience has shown that a proactive system is more legally defensible than one that reacts to accident history and annual maintenance costs at a site to fix a problem situation.

In addition, it was discovered that a reactive system had several engineering deficiencies, and may not reflect the true potential for future rockfall events. The annual maintenance costs in a rockfall section generally represents the cost to clean out the catch ditch and to patrol the highway for rock debris on the roadway. However, if an adequately designed catch ditch performs well (no rock on the roadway) but needs regular cleaning, the maintenance cost may be high while the hazard to the motoring public is low. This would indicate that these two items are not sufficient by themselves to develop a rockfall priority list. In addition, this technique relies on information reported by highway maintenance crews, law enforcement personnel, the general public, emergency response personnel, etc. Such a diverse group is not adequately trained to systematically document or evaluate rockfall events.

The first step in developing a proactive system to address the rockfall problem was to develop a Rockfall Hazard Rating System that could be used by all agencies confronted with serious rockfall problems. Using resources from its own research budget and several SHA's including Arizona, California, Idaho, Massachusetts, New Hampshire, New

Mexico, Ohio, Oregon, Washington and Wyoming, FHWA arranged with the Oregon DOT (ODOT) to develop a generic Rockfall Hazard Rating System (RHRS).

The RHRS is a tool for managing rockfall sites along highway routes. The system contains six main features:

- A uniform method for slope inventory.
- A methodology for making a preliminary rating of all slopes in a jurisdiction.
- Guidelines for identifying all hazardous slopes and making a detailed rating of each.
- Guidelines for making design and repair cost estimates for the most serious sections.
- Project development.
- Annual review and update.

These features are discussed in detail in the research report and engineering manuals developed by ODOT for use in a series of workshops funded by FHWA's Office of Technology Applications (59, 60,61).

This new process developed by ODOT appropriately places the responsibility for slope evaluations and design concepts with properly trained and experienced staff. In Oregon's case, that responsibility rests with its staff of engineering geologists. Utilizing their expertise and judgment, they have demonstrated that reasonable and repeatable slope ratings can be achieved. In addition, appropriate state-of-the-art design concepts were advanced for project development consideration.

Experience with the RHRS has been very favorable. Courts have ruled that it is unreasonable to expect an agency to have at its disposal all the funds necessary to deal with all the rockfall safety related issues at once. It is necessary though, to have some kind of a proactive system in place that provides quality information to designers for project development and helps management make rational decisions on how to prioritize projects to best allocate scarce repair funds. The response by agency management has been one of relief and acceptance. Managers believe that public safety is now best being served and that greater legal protection is afforded the agency by having the RHRS in place in their State.

4.10 Publications and Implementation Items

Research and development activities for soil and rock behavior areas were very successful. Numerous quality reports were generated that give valuable guidance on how to treat various problem soil and rock materials, and new ideas and methodologies are documented in each report. Many technology transfer items were developed and disseminated to practicing engineers. Workshops and training courses were also conducted to enhance the implementation process.

CHAPTER FIVE

GEOTECHNICAL STAND-ALONE STUDIES

No less important than the categories of foundations, ground improvement, and soil behavior, a group of studies were conducted on individual topics that didn't fit under the three major projects of the geotechnology research program. For lack of an appropriate category title, these topics are herein referred to as stand-alone studies.

Rock mechanics and rock slope engineering were at one time considered for project status, but budget and staffing constraints reduced the amount of effort that could be expended in this area. This is not to take away from the importance of the research that was done, or the topics that didn't get initiated, but merely goes to show that there were a number of important issues to be addressed that didn't have an official home or umbrella to be placed under. It was decided to include rock fall and shale research under Task 5 of the Soil Behavior project and rename the project "Soil and Rock Behavior."

5.1 Background

Two good examples of stand-alone studies are the computer-aided design system for geotechnical engineering and the National Geotechnical Experimentation Sites program, which transcend all the boundaries of geotechnical engineering research and practice. As discussed in chapter one, these two current assets were missing during most of the program, and can be directly blamed for the slow advancement and difficulties that were faced in attempting to improve the state of the art in geotechnology. Now that these assets are firmly in place, advancements should come faster and easier.

The remaining topics also helped stretch the upper bounds of the present technology limits in their own right. Some of them contributed to more than one area of geotechnology, and a couple of them touched all the bases, not to the same extent as the NGES or the geotechnical databases, but important nonetheless.

5.2 Automated Geotechnical Information and Design System

FHWA recently initiated a major effort to develop an Automated Geotechnical Information and Design System (AGIDS) to integrate all of the FHWA research quality technical data bases, plus the information data bases in geotechnology into a comprehensive design aid system. AGIDS (figure 43) will allow geotechnical and structural engineers to quickly and economically obtain information and evaluate design alternatives from a centralized computer source of databases. These databases will be connected by developing commonality features and the design of a user interface application for performing cross queries, correlations, and engineering analyses.

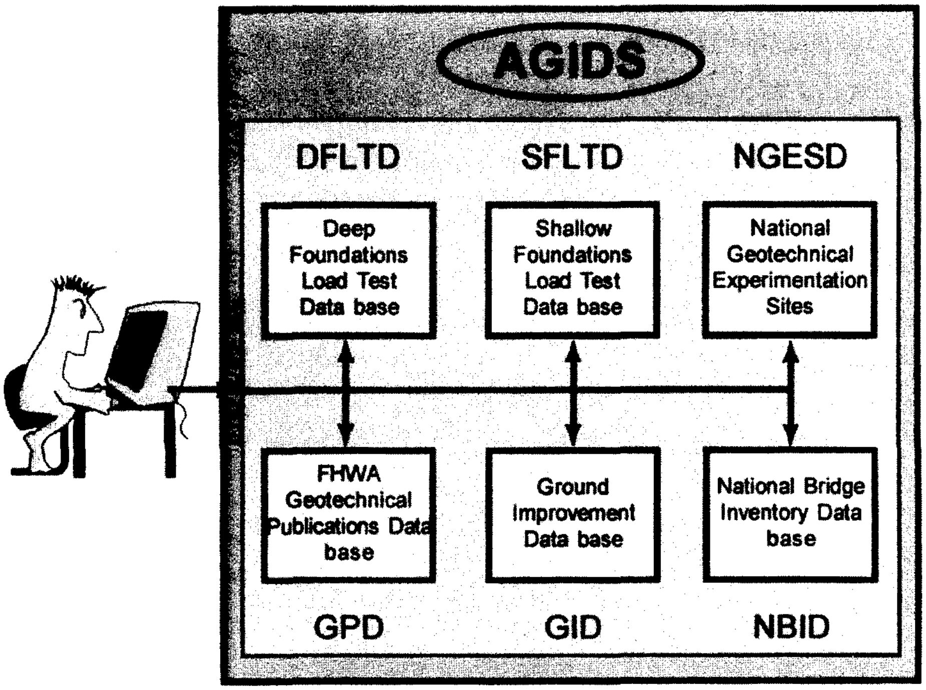

Figure 43. Automated Geotechnical Information and Design System.

Several of the data bases already contain modules for performing correlations, predictions, and analyses; however, they need to be linked through a multi-user workstation that contains an interactive system for automatically generating design solutions based on interactive user input. Such a system will take most of the guesswork out of geotechnical design, and replace it with an objective, quantitative system that supports sound management decisions.

A wealth of research-quality geotechnical data have been gathered from the literature, SHA files, other agencies, and foreign organizations for placement in a series of FHWA geotechnical data bases to increase the effectiveness of current and future research efforts to improve design and prediction methods. These tools are also an effective way for practitioners to improve their state of the practice on routine design work.

Each data base can be utilized as a stand-alone information source with its own information management and analysis modules, plus user interface applications. Each has a statistically meaningful source of high-quality data that can be used for the development and verification of new or improved analysis methods or simple design checks by providing a fast, convenient, and economical source of project specific or generic information for inclusion in reports in minutes instead of days or weeks. The data base also allows users to:

- obtain cost comparisons quickly for budget documents
- compare technical sufficiency and economic data on alternative designs
- locate existing site investigation data and historical load test data rapidly to assist in preparing plans
- compare various construction methods
- download data and perform comparative analyses for multiple design alternatives
- perform correlations between various geotechnical parameters
- obtain data to assist in design of instrumentation plans

Regardless of the project stage, the needed information can be obtained rapidly, reducing time and costs to formulate plans and evaluate design alternatives, which in turn will lead to reduced uncertainty in the project development phases. A more confident design process will reduce overall geotechnical and foundation costs. A detailed description of each of the data bases follows this section.

5.2.1 Deep Foundations Load Test Data Base

This data base provides a centrally located source of technical information on piles and drilled shafts, including soil data, load test results, instrumentation data, and driving records that can be used to verify and refine deep foundation theories. It can also be used to develop new theories or assist practitioners to perform routine design projects. In addition to basic search and retrieval functions, a correlations module and several static analysis programs have been incorporated into the data base to facilitate the performance of a comparative analysis.

Test data and well-defined soils information from thousands of pile and drilled shaft load tests have been collected and evaluated for inclusion in the data base. New data were also generated by making funds available for installing instrumentation and conducting load tests on active bridge construction projects at appropriate sites. The data base serves as a "standard" against which new and existing design procedures can be compared. Statistical correlations can be developed from the data base and used to develop new design aids (charts, curves, and tables) for pile and drilled shaft design procedures. The data base has been distributed for beta testing.

The data base was developed using SYBASE System 10 tools and resides on a UNIX platform on a RISC 6000 Geotech Server at FHWA's TFHRC. The data base operates in a Windows environment, and utilizes Menu bars, drop down lists, icons, and message boxes to make it more user-friendly. It also allows the user to directly print results to a local printer or be downloaded through a file transfer protocol and stored.

By entering the available choices in the menu, the user can obtain information on soils, piles, drilled shafts, instrumentation setup, construction method, driving records, and load test data. The user can also perform design predictions, analysis, and correlations, and obtain frequency distributions on the data available. From the statistics menu, the user can obtain data and statistical graphs from a selection of relationships, such as the number and types of deep foundations in a selected State, country, or in the entire data base. Statistical data can also be obtained for load tests, soil tests, and construction methods.

5.2.2 Shallow Foundations Data Base

The Shallow Foundations Data Base (SHALDB) is divided into two main parts: the user interface and the data base files. The user interface is a program that enables the user to easily add, access, and modify the data files that describe the many case histories stored in the data base. The data base files are grouped into five categories: general information, footing data, footing behavior, soil data, and settlement predictions.

The user-friendly program was written in Visual Basic and runs under Windows 3.1. The program is in three parts: maintenance, inquiry, and analysis. With the inquiry option, the user can select and view the footings from the data base that satisfy a set of criteria chosen by the user. The analysis option consists of making plots of one variable against another, such as predicted vs. measured behavior; or it can predict the settlement of footings on sand according to 13 different methods. There are more than 150 spread footing case histories in the data base for which either a load test was performed or the behavior was observed during and after construction. The data base will also provide a standard format for the reporting of new tests.

The SHALDB is a valuable tool that allows the user to observe the performance of actual case histories for spread footings of various sizes on sands with varying parameters under different loading conditions. This organized data base can be used to evaluate existing prediction methods or to develop and/or check a new method. It will also be useful to point out what kind of test information is missing from the data, and therefore what kind of tests need to be performed to fill the gaps. It will be useful to practitioners as well as other researchers (28).

5.2.3 Ground Improvement Data Base

FHWA recently joined forces with the International Center for Ground Improvement Technology in Brooklyn, New York, to develop an International Knowledge Data Base for Ground Improvement Technology (IKDGIT). The comprehensive, user-friendly data base provides access to experiences from many parts of the world specific to a selected technology, application, or location. It allows the user to retrieve information on possible technologies for a project under design by viewing similar case histories, problems encountered, possible remedial action schemes, comparative cost data, specifications and codes, and QA/QC. The engineer is able to supplement local experience with that of others with similar projects.

As discussed in chapter 3, ground improvement technologies have recently played a very important role in solving major geotechnical problems in highway construction and in other civil engineering fields as well. While recent research and development efforts have increased our knowledge base, many of the concepts have not been made fully accessible to many in the professional world. This requires a reliable, efficient, and interactive technology transfer process and geographical expansion of locally based experiences. The IKDGIT is a good tool that can be used to help expedite the technology transfer process.

The data base was formed in three parts. Part One is a compendium of national and international codes of practice. Part Two is a collection of monitored case histories that includes site observations, design methods, construction details, and performance monitoring data. Part Three contains information on instrumented structures plus data and analysis records on models and full-scale experimental studies.

The data base currently contains more than 200 documented records of ground improvement case histories from 15 countries. As with other technical data bases in the FHWA suite, the work is never finished. There is much more input expected from the participating countries in the near future that will increase the value of IKDGIT in its role as part of AGIDS.

5.2.4 Supplemental Data Bases

In addition to the three main data bases previously discussed, AGIDS will have access to the NGES and FHWA publications data bases to provide necessary technical and administrative information to assist engineers in planning, design, and construction of highway projects. The NGES data base is described in section 5.3 of this chapter. The FHWA publications data base is not described in this report; however, most of the references contained in that data base are listed in this report.

5.3 National Geotechnical Experimentation Sites (NGES)

A major focus of the FHWA geotechnology research program was the development of a designated system of national geotechnical experimentation sites to improve our ability to find and evaluate new techniques for constructing safer and more economical highways and bridges. With this objective in mind, FHWA teamed up with the National Science Foundation to establish such a system with a national management board and individual site managers. This section of the report describes the system that was developed to help investigators accelerate geotechnical research to solve many serious geotechnical engineering problems facing the highway community.

During the last two decades the geotechnical profession has witnessed major changes in the approach to site characterization and quantification of soil behavior. New in-situ testing methods and improved field instrumentation have provided valuable new tools to complement and/or create testing alternatives to laboratory procedures. These new techniques are leading to a better understanding of the static and dynamic properties of soils.

Although the evolution of new techniques has been relatively rapid, duplication of effort and lack of cooperative work among the various research groups has made progress slower and more costly than might otherwise have been possible. A lack of well-characterized, well-documented, reference sites has impeded the development and evaluation of new in-situ testing methods.

Such sites would allow ready comparison of new methods against known soil conditions and past testing programs. In the past, most researchers had to spend a considerable portion of their budget on creating a well-characterized site at which to conduct their studies. Unfortunately, in many cases, these previously studied sites are no longer available or are unknown to other researchers. As a result, the originators of a new method must perform their own extensive site investigation before reaching the initial objectives of the research. This increases the total project cost and wastes valuable time and effort.

Benefits from well-characterized and well-documented sites are not solely restricted to evaluation of new in-situ testing methods. A prime objective of geotechnical engineering is to predict the performance of constructed facilities—with or without soil and site improvement. The geotechnical profession needs to be able to evaluate its predictive capabilities by making comparisons with records of actual field performance. Thus, new geotechnical design and construction methods may be developed and tested at these sites, addressing not only the more conventional earthwork and design problems, but also environmental problems such as hazardous waste containment.

To quantify ground response and ground failure potential, geotechnical earthquake engineers badly needed sites that were well-characterized and permanently instrumented to record earthquakes. The development and verification of new tools to assess site-specific liquefaction potential, for example, require access to cohesionless soil sites where liquefaction has been observed during earthquakes and where soil characteristics are well-documented. Instrumentation of such sites could provide field records for the solution of several important problems, including the quantification of pore pressure response and deformations that develop during liquefaction. Analogous sites in clay deposits are also necessary to improve our understanding of how such deposits amplify detrimental earthquake motions.

A workshop was sponsored by NSF and FHWA at Orlando, Florida, in October 1991 to initiate the implementation of the NGES. Participants selected a small number of sites from a list of 40 candidate sites to form the core of the national system. The group selected the original 40 sites because they had reasonably good documentation of the soil conditions and previous experimentation results, a reasonable probability of continued access for at least 10 years, and a soil type of sufficient interest to geotechnical researchers. An initial screening prior to the workshop identified the nine most promising candidates for the designation of "national geotechnical experimentation site."

The evaluators decided that none of the sites met all of the criteria for selection and recommended establishing a national system of multiple sites according to a hierarchy of graded levels that could fluctuate as conditions changed. Texas A&M University and Treasure Island, California, the two sites that came closest to meeting all of the selection criteria, were named as Level I sites. Three sites—located at the University of Houston, Northwestern University, and the University of Massachusetts—were found to have some limitation that dropped them into Level II. The remaining four finalists were designated as Level III sites, and all others were grouped in Level IV. Each site will be reviewed periodically to determine if conditions warrant upgrading to a higher level. Loss of access or other negative circumstances may also result in downgrading a site.

The Orlando workshop participants also founded a System Management Board to set policies for the use and operation of the sites and to ensure continuity. They also established positions for a system director and for individual site managers at each of the top five sites—Levels I and II—that form the central core of the system. A draft plan and suggested budget for managing the system and funding improvements to the core sites were prepared for submission to FHWA and NSF. In 1997, it was decided to add a fourth Level II site to the NGES system. The site is located near Opelika, Alabama, on property owned by Auburn University. It has been officially designated as the Spring Villa NGES test facility.

Following the workshop, FHWA awarded a contract to develop a computerized central repository for all the data contained in the NGES catalog, plus any future data generated at the individual test sites. The cost of this project was shared by nine state departments of transportation—Iowa, Louisiana, Massachusetts, Minnesota, Nebraska, New York, Texas, Washington, and Wisconsin (62).

FHWA and NSF later awarded a large system-support contract in 1992 to provide for the overall management of the program and to operate and maintain a Central Data Repository (CDR). They awarded subcontracts to each of the five site managers and a part-time system director. The board approved improvements to each site on the basis of proposals submitted by the site managers.

The data base of the CDR includes graphs of representative profiles and typical plots of data for each site. Modem hookups provide remote access to allow users to review the quality and numerical details of the results. An electronic bulletin board provides late-breaking news about various sites and programs available within the system. The CDR is a user-friendly system shell with online computer search and data retrieval capabilities that enable geotechnical researchers to select the most appropriate site for their work. It can accommodate all essential information about each site, such as generalized soil conditions, listing of all available test data, site logistics and limitations, published references, and other site information (63).

The availability of a national system of geotechnical test sites that are already well-characterized and permanently instrumented will serve to accelerate innovative research on soil behavior and foundation engineering. Future research performed at these sites will be less individually oriented, with greater documentation maintained for the benefit of other investigators.

Researchers and practitioners can exchange information and ideas through the NGES system to focus their thought processes into more definable channels because they will be comparing theories and testing procedures against the same reality. This, in turn, should lead to better communication of the effects of geotechnical phenomena to the geotechnical community, thereby reducing the misunderstandings, inconsistencies, empiricism, and untested theories that pervade geotechnical practice today.

The NGES program will foster more cooperation between public agencies, universities, and private sector groups—something that has been missing from geotechnical engineering. In addition to providing a standardized base upon which to judge the results of new research, NGES will provide research sponsors like FHWA, NSF, and SHA's with more accountability than in the past, because investigators will know that others can come to the same site and repeat the experiment.

In summary, the development of well-characterized sites that are readily available to geotechnical engineering will encourage a variety of experimental activities, which will lead to techniques for constructing safer and more economical structures. As an additional benefit, these improvements will make U.S. geotechnical design and construction firms more competitive in the international arena. More information can be obtained from the references and/or the NGES web site at "htpp://www.unh.edu/NGES/index.html."

5.4 Evaluation and Improvement of Bridge Foundations

Various bridge components wear out or deteriorate faster than others. The deck, in general, deteriorates faster than the superstructure and the latter in turn deteriorates faster than the substructure, which includes the piers, abutments, and foundations. It is therefore not surprising that, in the majority of bridge rehabilitation jobs, the substructure usually can be salvaged with relatively minor or cosmetic repairs. Since the cost of the substructure represents a substantial portion of the overall cost of the bridge, evaluation of the condition of the existing substructure must be considered in any bridge rehabilitation or replacement project.

In certain instances, such as when a major change in the alignment is required to upgrade the existing structure or hydraulic requirements dictate the removal or relocation of the substructure components within the waterway, replacement of the substructure may be necessary. However, for widening, upgrading for increase in live loading, or replacement with a different type deck and/or superstructure, a thorough evaluation of the substructure (including the foundations) will be required. Correcting a deficiency to restore the integrity of an existing substructure or foundation may be many times more difficult and expensive than correcting a deficiency either in the deck or in the superstructure. Maintenance costs for a restored substructure may be higher than corresponding costs for a new substructure on a bridge replacement project.

5.4.1 FHWA Research Study

Because of potential savings, more than just cursory effort should be made to determine the feasibility of reusing existing substructures and foundations. At the beginning of the major emphasis period for the national bridge replacement program, it was discovered that rational guidelines for evaluating existing foundations did not exist, nor were there useful guides on how to make improvements to restore marginally acceptable foundations to an acceptable level of performance. In recognition of this need, FHWA initiated a contract research study to develop the engineering guidelines for making these evaluations, and to provide guidance for improving the soundness and bearing capacity of those units that needed upgrading to meet current standards.

It was first determined that there are many evaluation techniques and repair or construction methods that are applicable for the deck and the superstructure of existing bridges. The same thing, however, could not be said for the substructure, especially for those elements below the waterline or the ground line. The decision process for the repair or replacement of a bridge can be quite subjective. The purpose of the study, therefore, was to develop recommended guidelines for: (1) techniques for evaluating, and (2) design guides and construction methods for improving existing bridge substructures for replacement or rehabilitated bridges.

Part I of the guidelines report deals with deterioration of bridge substructures, effects of loading and unloading on the foundations, time effects on soil properties, and bearing capacity and settlement of foundations. Part II deals with current methods of inspection, substructure analysis, new methods for evaluating soundness and bearing capacity of foundations, and instrumenting foundations for future performance. Repair methods and techniques to increase the capacity of existing foundations by strengthening the foundation and/or soil and methods for reducing loads on the substructure are covered in Part III. Case histories of bridge substructures and recommendations for research in the subject area comprise Part IV of the report (64).

Valuable contributions were made by numerous materials experts in the concrete, steel, and timber industries pertaining to reuse and repair of bridge substructure elements.

Many bridge and staff engineers from the departments of transportation of California, Illinois, Massachusetts, New York, Pennsylvania, and Virginia also contributed valuable information on current practices in this topic area in their respective States that will help designers evaluate existing foundations for upgrade studies.

5.4.2 Unknown Bridge Foundations

During the 1980's numerous bridge collapses occurred due to scour failures of the foundation systems, causing significant injuries, loss of life, and property damage. These events prompted the U.S. Congress to revise the National Bridge Inspection Standards to include an item (#113) on Scour Critical Bridges, which requires that all bridges be evaluated for their vulnerability to scour damage. The FHWA Technical Advisory on "Evaluating Scour at Bridges," October 21, 1991, is the implementing document. FHWA Hydraulic Engineering Circular #18 recommends a process to perform the scour evaluations to determine the vulnerability of existing bridges to scour-induced collapse.

The process described in HEC-18 requires that specific knowledge of foundation type, size, and depth be available to make the evaluations. SHA's have plans and records on their bridge foundations for most bridges on the Federal-aid system, except some of the older bridges and many of the off-system bridges. A survey was completed in 1990 that included a preliminary assessment of all bridges in categories of low scour risk, scour susceptible, or with unknown foundations. It was recommended that a strategy be developed to help manage the risk of not knowing the type, size, depth, configuration, or condition of a bridge foundation. It was also necessary to develop procedures for SHA's to use in ascertaining these unknown characteristics.

In 1991, FHWA contracted to develop the required strategy and procedures. The study began by developing a statistical profile from the FHWA and SHA data bases to define the extent and severity of the problem. Next, a risk-based strategy was developed to assess and manage the risk of not knowing the foundation particulars and help SHA's determine which bridges most urgently need these data for scour evaluations. Finally, a method guide is presented in the final report that describes measures that can be used to determine foundation characteristics such as type, size, depth, and service condition.

The guidelines cover deterioration of bridge substructures, effects of loading and unloading on the foundations, time-effects on soil properties, current methods of inspection, and substructure analysis. Repair methods and techniques to increase the capacity of existing foundations by strengthening the foundation and/or soil, methods for reducing loads on the substructure, new methods for evaluating soundness and bearing capacity of foundations, and instrumenting foundations for future performance are also covered in the report (65).

5.5 Geotechnical Risk and Reliability

Most engineers design under the condition of uncertainty with regard to material properties, service requirements, and engineering models to name just a few. Geotechnical engineers have a very pronounced problem with uncertainty because of the highly variable nature of soil and rock properties. In the past, geotechnical engineers have dealt with the high level of uncertainty by conservatively assigning or specifying much larger capacities than the projected demand. This ratio of capacity to predicted demand is the classical safety factor approach, which requires significant experience levels to be done right.

Risk-based design can be used to reduce some of the conservatism inherent in the factor of safety approach by attempting to quantify these uncertainties and deal with them in a more rational manner. Uncertainties in the data need to be identified and then quantified with statistical methods that are easy to use. Mathematical modeling techniques can be used to estimate the effect of these quantified uncertainties on performance predictions. This will result in a quantified measure of confidence that the engineered structure will perform adequately.

A reliability index can be calculated to give a measure of the relative error contained in a prediction of performance behavior with respect to the margin of safety desired in a particular structure. Although geotechnical engineers routinely design for a "probability of failure," it is much more prudent to use the term "reliability index" or "geotechnical reliability assessment," especially in a court of law where an aggressive attorney would have a career day in front of a lay jury.

To assist highway engineers to make better geotechnical predictions of performance, FHWA contracted to evaluate the state of the art and develop a Geotechnical Risk Analysis User's Guide. A report was prepared that surveys the available literature at that time and presents a large bibliography of references to explain the information contained in the guidelines manual. The manual shows how to quantify uncertainties and adjust design conservatism accordingly in a simple-to-use approach. Design problems from engineering practice are presented to illustrate the approach (66,67).

5.6 In-Situ Soil Testing

In-situ soil testing is an important method for determining geotechnical design parameters, especially for hard-to-sample soils needed for laboratory testing. Most of the current techniques in use were developed in the United States and Europe without FHWA funding; however, a few guidelines type manuals were developed by FHWA as user-friendly informational documents for U.S. highway engineer practitioners (68,69,70). In some other separate instances, FHWA spent considerable resources developing special in-situ tools to obtain soil design parameters. These efforts are described in the following sections.

5.6.1 Stepped Bladed Vane

Lateral soil pressure is an important element in soil mechanics theory and practice, but it is very sensitive to disturbance and difficult to measure. A step-tapered blade was developed to compensate for disturbance by measuring soil and pore-water pressures on three thicknesses of blades, and extrapolating for the hypothetical soil pressure at zero blade thickness. The three-bladed vane (figure 44) contains nine teflon-diaphragm pneumatic stress cells to measure soil pressure. The equipment has been shown to provide reproducible, reliable, and economic measurements of lateral stress in sands, silts, and clays.

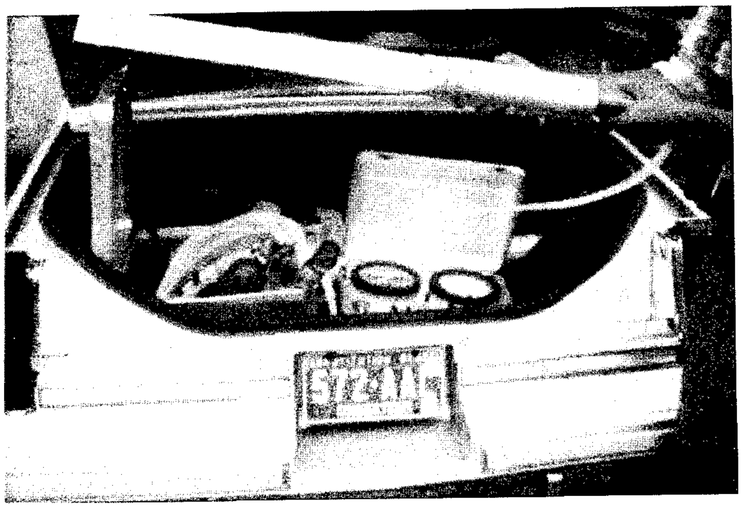

Figure 44. Close-up view of step bladed vane.

The device measures quickly, accurately, and inexpensively the total and effective lateral stress in soils, which is a property that is fundamental to virtually all soil mechanics, including foundation-bearing capacity, pressure on retaining walls, and slope stability. The device and test procedures were used in a number of case histories where the design predictions were compared with measured performance. A detailed description of the equipment and sample design problems can be found in the final report (71).

5.6.2 Simplified Torsional Cylindrical Impulse Shear Test

This device was developed in 1994 for FHWA to predict the behavior of soil deposits during earthquakes. It provides detailed information for soil deposits on in-situ nonlinear shear stress vs. strain characteristics that is needed for commonly used computer analysis procedures for earthquake engineering. Predictions can be made for large ground motions and soil liquefaction that may occur during future earthquakes to prevent the source of immense losses such as those of past earthquakes.

The impulse shear test device addresses the major problem of obtaining the required information without disturbing in-situ conditions excessively. Disturbances can create considerable uncertainty in behavior predictions, which can lead to costly over-design or worse – unconservative designs that fail in seismically active areas. Improving our ability to estimate the soil characteristics of interest will allow us to realize more fully the potential of dynamic geotechnical computer analysis procedures used, for example, by the California Department of Transportation. This will lead to more effective earthquake engineering and, in turn, to greater safety, economy, and reliability in the earthquake-resistant design of highway structures.

The device consists of a single cylinder with a diameter of 7 cm located at the end of a probe that penetrates the soil below the base of a borehole. An impulsive torque is applied to the cylinder by an excitation system to induce shear stresses and strains in the surrounding soil. The applied torque and resulting rotation are measured by sensors mounted in an instrumented head attached to the top of the cylinder. Figure 45 shows the device being lowered into a soil borehole at a seismic site on the Treasure Island NGES.

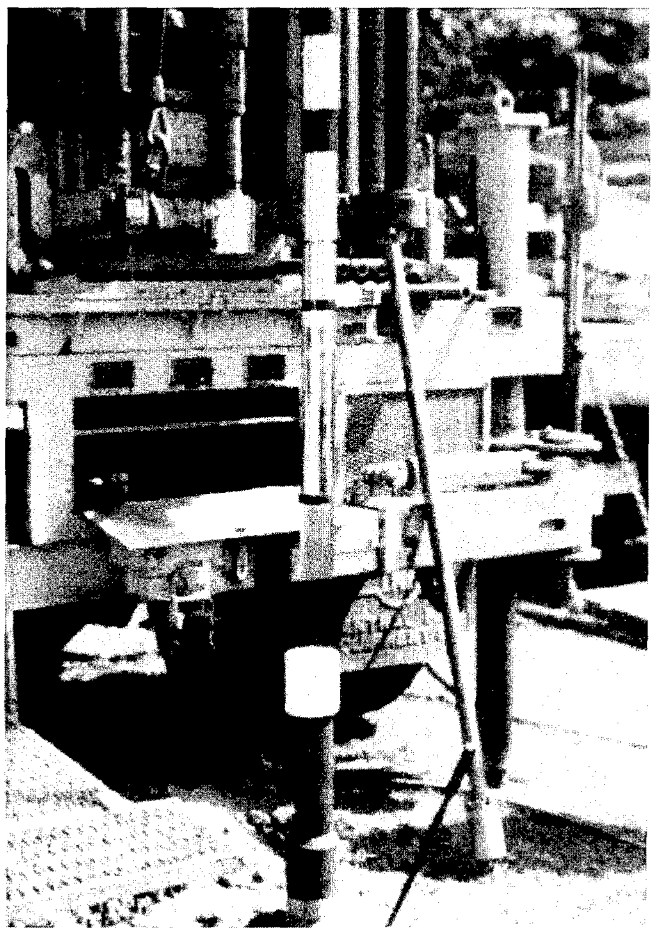

Figure 45. Torsional impulse shear test to obtain earthquake engineering soil parameters at Treasure Island.

The device has been tested at several NGES facilities and at TFHRC to establish the operability of the testing system and to develop test procedures. It was found to be a promising technique from a technical and practical standpoint. Current efforts are attempting to improve the existing prototype with respect to efficiency, usability, economy, and reliability.

5.6.3 Controlled Source Spectral Analysis of Surface Waves (CSSASW)

In addition to the two previous methods, which involve the insertion of a probe into the underlying soil, FHWA also funded a study to investigate the use of CSSASW techniques for nonintrusive shear wave velocity profiling of soils with high liquefaction potential. The results were compared with the results of direct measurements made at a test site with extensive subsurface data and seismic instrumentation. FHWA has also evaluated this technique for determining the thickness or depth of unknown bridge abutments and foundation systems.

The CSSASW system is a rapid and cost-effective technique that can accurately determine the apparent dispersion of Rayleigh surface waves at a site, which can be correlated with shear velocity profiles to produce essential data to analyze site response during earthquake loading. This is especially important in hard-to-sample soils. The device (Figure 46) uses a powerful electromagnetic vibration source powered by a generator and two data receivers that pick up the soil vibrations generated by the exciter. The Rayleigh waves are measured by the two vertically oriented accelerometers positioned at a known distance from the exciter.

Figure 46. Controlled source spectral analysis of surface waves (CSSASW) testing at Treasure Island.

5.6.4 Multiple Deployment Model Pile

The installation of full-scale test piles to obtain pile design parameters during the design phase is sometimes used on large projects to save money on construction costs by reducing the conservatism that generally occurs due to unknown or unsure conditions.

Conservatism leads to higher safety factors, which means higher costs. Full-scale test piles are an expensive and inconvenient way to obtain the desired information. Geotechnical engineers have long searched for an accurate model pile test that can properly simulate the field behavior of full-scale piles.

Many model piles have been developed during this quest. Examples include the In-Situ Model Pile (IMP) developed at Oxford University, the MIT Piezo Lateral Stress Cell (PLSC), the Norwegian Geotechnical Institute (NGI) model pile, and many others that are available, but none of which are quite up to par for highway bridge standards. These model piles are calibrated tools that are equipped with instrumentation to monitor the pile-soil interaction during pile driving, soil setup with time, and subsequent loading to failure. This behavior is measured by strain gauges, load cells, and pore pressure transducers attached to the model pile. Some also have accelerometers and displacement transducers.

FHWA recently sponsored the development of the Multiple Development Model Pile (MDMP) for use as an in-situ soil testing device for site investigations to obtain essential pile design parameters. The main purpose of the MDMP is to duplicate the driving and after driving conditions that full-scale piles experience. The instrumentation must therefore be rugged enough to withstand driving stresses and maintain the required standard of accuracy. Restrike of the model piles in clay soils can be used to assess load transfer during pore pressure dissipation with time; thus, the pile's capacity gain from "setup or freeze" can be accurately quantified.

The MDMP was successfully used at two sites in Newbury, Massachusetts, on a SHA bridge construction project. The results compared very well with full-scale data from instrumented pile load tests to failure. The model results show that the MDMP is capable of providing very accurate soil-structure interaction relations during static load testing. These findings were used to predict the time-dependent behavior of the full-scale instrumented piles, and to reevaluate the pile capacity gain phenomenon. These results helped to explain some unanswered questions and facilitated the development of new procedures that incorporate pile capacity gain in design and construction.

5.7 Seismic Design of Highway Bridge Foundations

In a recent letter from Mr. James Roberts, Chief Engineer of Caltrans, to the FHWA, special emphasis was made on the need for additional research on the seismic behavior of foundation soils during major earthquakes. An excerpt from this letter follows:

> "It has often been said that the October, 1989 Loma Prieta earthquake in California was the Geotechnical Engineer's earthquake because of the major impact the deep soft soils had on the bridge and roadway damage. This was the United States warning to pay more attention to the importance of soil-structure interaction and the disastrous effects of not properly designing structures constructed over these types of foundation materials. We had a warning from the

damage patterns in the 1985 Mexico City earthquake and the geotechnical engineers began to alert the structural engineering community about the importance of geotechnical input to structure design. The recent Kobe earthquake reinforced the importance of foundation response to the seismic performance of structures."

The loss of life and extensive property damage suffered during recent earthquakes in California (Figure 47) and some foreign countries have emphasized the need for research to provide improved procedures and specifications for constructing highways and bridges with better earthquake resistance. FHWA increased its Seismic Research Program to evaluate the seismic vulnerability of bridges, tunnels, retaining structures, slopes, and embankments shortly after the Loma Prieta and Northridge earthquakes in the early 1990's. Much of this research is being conducted by the National Center for Earthquake Engineering Research (NCEER) in cooperation with other agencies participating in the Federally-sponsored National Earthquake Hazards Reduction Program.

Figure 47. Liquefaction damage due to Loma Prieta earthquake.

NCEER is presently conducting two separate FHWA-sponsored contracts. One contract is focused on the seismic vulnerability of new highway construction, and the other is concerned with the seismic vulnerability analysis and retrofitting of existing highway structures. Revised seismic design and construction guidelines will be developed through a synthesis of existing knowledge and the development of new information from analytical and experimental research activities being conducted under the NCEER and other FHWA projects.

CHAPTER SIX

ASSOCIATED GEOTECHNICAL RESEARCH AND TECHNOLOGY PROGRAMS

In the beginning, the Geotechnology Research Program was assigned to the Federally Coordinated Program (FCP) of Research and Development for FHWA. The FCP was the brainchild of FHWA's Director of Research, Dr. Charles Scheffey, in the early 1970's. He was very fond of reminding everyone that it was a "federally coordinated" program, not a "coordinated federal" program. FCP program managers were not expected to supervise and direct non-FHWA research programs, but they were expected to play a leadership role in coordinating these other research programs from Federal, State, and private sector organizations conducting research in their respective areas.

During the 1970's and 1980's, a number of agencies and outside organizations were actively engaged in geotechnical engineering research. FHWA played an active role in encouraging coordination and partnering with these other organizations, especially in the beginning when there wasn't an "umbrella" type organization to provide central leadership. This function was later taken over by the Geotechnical (GT) Board of the National Academy of Sciences shortly after it was established in the middle 1980's. This seemed to work very well for a few years until the Board was de-commissioned in the early 1990's during an economy drive to consolidate programs.

As a result of losing the Geotechnical Board, which was very popular in the GT community, a group of leading geo-engineers came together at a workshop in May 1994 to focus on the problems associated with the loss of the GT Board and other setbacks, both recent and potential future losses. One of the positive outcomes of the workshop was the agreement to establish a nongovernment umbrella organization called the Geo Council.

The Geo Council was established by a group of national experts in early 1995 to be an independent organization to fill the void left by the GT Board. The objective is to expand the sphere of geotechnical influence by creating a unified base of geo-professionals from the Federal, local, academic, and private sectors of the geotechnical community. The former executive director of the GT Board, Mr. Peter Smealie, was elected as Executive Director of the Geo Council to serve for an indefinite term period. The Council serves to further the general interests of geotechnology that are common to most, if not all, the separate organizations that comprise the membership. It is an organization of organizations that does not compete with the specific goals of its individual members, such as the ADSC, Deep Foundation Institute (DFI), United States University Council of Geotechnical Engineering Researchers (USUCGER), ASCE's Geo-Institute, Association of Soil and Foundations Engineers (ASFE), and several others with common interests. The Geo Council recently took control of the NGES program to further serve the GT community.

The Geo Council serves as a forum for exchanging ideas and information among geo-engineering associations and professions, construction organizations, and government agencies. It also seeks to ensure that geotechnologies are able to play their proper role in addressing national needs such as mineral and energy exploration and production, civil infrastructure, national security, and environmental quality.

The Geo Council

- documents the importance of geo-engineering to our future.
- encourages the transfer of new technologies between technical disciplines and into standard industry practice.
- identifies and removes barriers to the advancement of geo-engineering theory and practice.
- promotes excellence in geotechnology education and research.

The formation of the Geo Council is of great importance because many of our most pressing national issues relate in some way to geotechnologies and the work done under the auspices of council members.

For instance, geotechnologies are literally the underpinnings of our daily lives, dealing with the foundations upon which all buildings and bridges sit, the tunnels our subways run through, the sewers and water systems that run underground, and almost everything that comprises our national infrastructure.

Geotechnologies contribute to managing hazardous and radioactive waste, which are often stored underground. They help us gain energy independence and predict and mitigate natural disasters like earthquakes, volcanoes, and landslides.

Geotechnologies also help ensure national security by developing ways to create underground defense facilities capable of surviving nuclear and high-explosive attacks.

And geotechnologies are key factors in exploring our remaining frontiers on earth, such as the polar regions and the ocean floor, and they will certainly be a part of our exploration of the universe beyond Earth itself.

The Geo Council and the former GT Board have been very valuable partners to FHWA's GT research program. They have served as advisors in the development (and re-direction when necessary) of the overall program plan, and helped to disseminate important research findings.

Other valuable partners have included National Highway Institute (NHI), Transportation Research Board (TRB), National Cooperative Highway Research Program (NCHRP), Highway Innovative Technology Evaluation Center (HITEC), National Science Foundation (NSF), American Society for Testing and Materials (ASTM), American Society of Civil

Engineers (ASCE), and the U.S. Army Waterways Experiment Station. Highlights of the activities of these partners and a few others are now presented to document some of their contributions.

6.1 National Highway Institute (NHI)

For the past 25 years, through its NHI, the FHWA has developed and presented to the SHA's technical training that is not readily available from other sources and which these agencies would not ordinarily develop for themselves. Numerous geotechnical courses (1 to 5 days) are offered nationally through the NHI primarily to the States. In each fiscal year, hundreds of these short courses are presented to thousands of participants.

State and local government personnel and private sector personnel are charged a fee for NHI's short courses; the fees for State and local personnel are half the cost of instruction, while private sector personnel pay full fees. State and local agencies pay fees ranging from a total of $1,000 for a 1-day course to $4,000 for 4- to 5-day courses. The $1,000 fees cover 30 to 40 students. FHWA geotechnical personnel assist in the instructional duties for these courses.

A considerable portion of the NHI State Program budget is spent to offer very comprehensive, graduate level curricula needed by mid-level highway engineers and managers to supplement their previous academic studies. One of these courses is the Geotechnical Engineering course. This comprehensive graduate level course is for 4 weeks and is aimed at the top two or three people in highway departments who will serve as the State's geotechnical specialists.

The course is divided into 11 training modules, each of which can be offered as a stand-alone NHI course, or several modules can be grouped together to address specific training needs. A state-of-the-art manual, which will serve for later use as a practical reference, was developed for each module. Instructors for each module are recognized experts in each topic area.

6.2 FHWA Office of International Programs

The GT team is working through FHWA's Office of International Programs to expand its program of interaction internationally. The agency has formalized its scanning process for finding transportation technology that can aid the United States in improving the durability of its infrastructure and the safety and operation of its facilities. As the international network expands, the agency will increase the number of focused technical trips abroad to facilitate the exchange of technology in various geotechnical topics. The FHWA geotechnical specialists will continue their strong participation in committees and task forces of the Organisation for Economic Co-operation and Development (OECD) and of the Permanent International Association of Road Congresses (PIARC). Formal geotechnical research coordination agreements have been established in France and Japan and are pending in other countries.

6.3 Transportation Research Board (TRB)

The Transportation Research Board (TRB), a unit of the National Research Council, supports research efforts concerning the nature and performance of transportation systems, disseminates research information, and encourages the application and implementation of appropriate research findings. The continual interaction between geotechnical specialists occurs through a variety of forums and media:

- TRB Annual Meeting – Annually many FHWA geotechnical personnel participate among the international public and private sector registrants at the TRB's annual meeting. Participation includes attendance at numerous technical and specialty workshops and TRB technical committee meetings. The FHWA also hosts exhibits that display the latest technology and provides literature and publications to participants.

- FHWA GT personnel interact with TRB professionals through daily committee and panel contacts, facilitating a continuing forum of exchange of technical program information to keep the TRB up-to-date on FHWA geotechnical research areas.

- The FHWA continues to contribute publications to the TRB-managed Transportation Research Information Service (TRIS) data base.

6.4 National Cooperative Highway Research Program (NCHRP)

The National Cooperative Highway Research Program is a unique contract research effort designed to pool state funds into a national program that can respond quickly and efficiently to the needs of the State highway and transportation departments and provide an effective attack on the pressing problems in any area. The NCHRP is a program of applied, rather than basic, research and as such is totally committed to providing practical solutions at least cost. As solutions become available, every effort is made to help the administrators and engineers put them to early use. Although the Transportation Research Board administers the NCHRP, the content of the Program and the rules and regulations that guide it are solely the prerogative of the American Association of State Highway and Transportation Officials (AASHTO) and its member departments.

FHWA works as a partner organization of TRB and AASHTO as the principal participants in the NCHRP program operation. Each partner carries out clearly defined, mutually supportive roles. A large number of quality research projects in the geotechnical area have been successfully completed in the past 25 years. These studies were coordinated with the FHWA program described in the main body of this report, and they served to enhance the overall success of both programs.

6.5 American Association of State Highway and Transportation Officials (AASHTO)

The FHWA and the American Association of State Highway and Transportation Officials (AASHTO) have had a long relationship, covering much of this century. Through the AASHTO, standards and specifications are reviewed and approved by the States and subsequently adopted by the FHWA for use on Federal-aid highway projects. Consequently, since the States are responsible for the planning, design, and construction of highways nationally, the AASHTO is critical to the adoption and use of new highway geotechnology among the member states.

In the overall design of the FHWA technology transfer program, FHWA's technical program officials and field offices are enlisted in the outreach process to ensure that new technology and innovations get into the hands of the users as quickly as possible. Geotechnical staffers often serve as project managers for on-site geotechnology demonstrations, bringing their expertise along with them and gaining an opportunity to further expand their expertise by interacting with other experts in the field.

The Transportation Equity Act for the 21st Century (TEA-21), which was signed into law in June 1998, increases research investment to a record level; and marks the beginning of a new era in which decision making power moves closer to the State and local officials who best understand the research needs of their localities. AASHTO is now empowered to develop national research programs through its Standing Committee on Research (SCOR) in cooperation with FHWA and all of the heads of the state highway agencies. Decisions will now be made by those closest to the action, who know the short-term problems, the long-term needs, and the importance of public opinion.

The role of AASHTO is more important than ever, because it is very difficult to get the individual parties to accept a long-term research agenda. Through its various committees, such as SCOR, it will have a much more significant voice. AASHTO and FHWA will provide the essential leadership to assemble the necessary stakeholders to develop a national research agenda, coordinate technology transfer functions, and measure the results of these activities that deliver products to meet the needs of the travelling public.

TEA-21 provides more money for research and implementation activities than ever before, however, it also changes the distribution system. There is now more money going to the States, and less money going to FHWA. The States will now play a much greater role in developing a national research program. AASHTO will provide leadership and help to minimize duplication of efforts and delays that might occur because so many different entities must agree on a national agenda.

6.6 The Highway Innovative Technology Evaluation Center (HITEC)

The Highway Innovative Technology Evaluation Center (HITEC) is a nationally recognized service center and clearinghouse for implementing highway innovation, one that serves as a focal point for the collaborative evaluation of innovative technologies (new products) and helps to expedite their transfer into practice. HITEC evaluates products for which recognized standards or specifications do not exist.

The HITEC process accommodates both "high-tech" and 'low-tech" products, intended for use in any aspect of the highway community, including design, construction, operation, or maintenance. HITEC has established a close working relationship with many highway-related organizations, including AASHTO, ASCE, FHWA and TRB. These groups, along with the individual State, county, and municipal agencies, provide HITEC with a broad and diverse pool of expertise to draw upon in the formation of its Technical Evaluation Panels. FHWA GT specialists are an important part of the expertise pool.

6.7 Electric Power Research Institute (EPRI)

During the late 1970's, the Electric Power Research Institute (EPRI) initiated a major geotechnical research program in response to industry requests for improved analysis and design capabilities for the foundations of electrical transmission line structures. The initial objective and scope of this project was to focus on static axial loading of drilled shaft foundations. Subsequently, the project was expanded to include other loading modes such as lateral, torsional, bending moment, cyclic, and combined loadings.

The bulk of this research was conducted at Cornell University under the supervision of Professor Fred Kulhawy as the Principal Investigator. More than 30 reports were prepared and disseminated to help EPRI designers select methods most appropriate to their specific geotechnical needs. The Cornell work resolved many uncertainties in the electric power industry's understanding of foundation engineering for transmission line structures. Benefits from this research program were also applied to highway structure foundations and vice versa through a coordinated exchange program among EPRI, Cornell and FHWA. Details and a complete listing of all reports can be found in *Summary of Transmission Line Structure Foundation Research,* EPRI Report No. TR-105206, September 1995.

CHAPTER SEVEN

TECHNOLOGY TRANSFER

Technology transfer is the process of moving the results of research and development from the laboratory into practice. FHWA has long been recognized as one of the world leaders in highway engineering technology and has always been very open and generous in sharing its knowledge and expertise with others. The FHWA's current emphasis on implementation activities continues an evolution that began before the turn of the 20th century when its predecessor, the Office of Road Inquiry (ORI) was established. Research and technology transfer were two of the principal missions of the ORI and are, in fact, the oldest continuous FHWA activities.

Since the days of the ORI, the need for technology transfer in the highway program has become even more established. The FHWA Geotechnology Program has been cited by FHWA's top management as a model for others to follow. The current program reflects the philosophies of the older programs that pioneered these activities, and utilizes some of the newer and more sophisticated ideas for marketing new technology into the 21st century.

The FHWA's technology transfer mission is to ensure the timely identification and assessment of innovative research results, technology, and products, as well as the application of those that are determined to be of potential benefit to the highway community. These technologies and products are developed, implemented, and promoted with the FHWA's partners in State and local agencies, private industry, universities, and others in the national and international highway communities.

It is clear that technology transfer has always been an integral part of the FHWA mission. Recently, the highway network in the United States has experienced numerous changes. The traffic on our highways has grown to the point that many of them routinely are congested. At the same time, the Interstate Highway System is virtually complete, and new highways are only infrequently being built, while many existing miles are wearing out. One answer to these concerns is introducing new technologies to the reconstruction, rehabilitation, and resurfacing of existing highways as well as to the construction of new highways. The Nation is faced with doing a better job with the highways that it has.

While the FHWA has a strong and growing technology transfer program across the United States, the success of the program is dependent on other public and private organizations advancing the agency's efforts further in the highway community. The FHWA technology transfer process actually begins during the research and development stages when researchers begin to think about how and where their new technology will be phased into practice. A technology transfer specialist is brought in to thoroughly assess the research and development efforts to help devise an implementation strategy to get the research and development to the appropriate users.

In the case of existing technology that is developed by sources outside FHWA, the researchers become involved either in the identification process or later in the test and evaluation process. They also stay involved during the implementation and marketing stages to assist with any technical problems that may arise. A key step in the whole process is the identification of new and innovative technologies that have high potential for successful application in the United States highway program.

In addition to the normal avenues for discovery, the FHWA uses a "scouting" and "scanning" approach to technology discovery. Scouting is a military term that refers to the activities of a person or small group that goes on ahead of the main body to evaluate future prospects and gather information that will be useful for down the road decision making. Whenever our researchers and technology transfer specialists are visiting other domestic or foreign places of interest, they keep their ears and eyes open to learn about new technology that might be of interest and useful for possible application in the FHWA Geotechnology Program.

When an interesting new technology is discovered by one of our "scouts," a small group of experts is formed to conduct a "scanning" review. They begin by making an office engineering review and developing a plan to visit several organizations in one or more countries to gather detailed information. Sometimes, as part of these reviews and discussion, research and technology transfer partnerships are developed to further benefit the FHWA and its partner of choice.

In the case of new foreign technology that looks very promising, a plan of testing and evaluation will be developed to investigate the behavior and cost-effectiveness of these new techniques, materials, and/or equipment products. While these evaluations are going on, an implementation and marketing plan is also being developed. In some cases it may be necessary to conduct further field trials of these ideas, methods, practices, or products beyond the research testing and evaluation phase, in which case they are turned over to a special "Experimental Projects Program" for evaluation. This program is designed to encourage the construction of particularly promising experimental features to determine if they can be adopted for standard use in highway construction.

7.1 Demonstration Projects Program

Probably the most effective means of technology transfer is to conduct an actual demonstration of how the results of research can be applied to an actual operational situation. In most cases the field engineers do not have the time and resources to properly analyze useful research and translate it into operation. Demonstration projects allow researchers and technology transfer specialists to better communicate with those engaged in field projects. An official Demonstration Projects Program was established by FHWA in 1969 to promote and accelerate the widespread adoption and use of practical highway research results and their application to innovative engineering and construction practices.

7.2 Problems

The rapid development and increased use of special geotechnical techniques has not occurred without problems and setbacks. Also, the acceptance rate has not been uniform throughout the U.S. highway industry. Some agencies have been slow to adopt some or even any of the new methods, and some methods are very popular in some areas, but not in others. Although many reasons are given by agencies for their reluctance to accept the new technologies, the following are the most frequently cited:

- Lack of awareness
- Lack of performance history
- Proprietary aspects
- Lack of design aids
- Technical concerns
- Perceived risk associated with something new
- Traditional conservatism

A significant number of engineers are still not aware that some of these techniques exist. The lag time between the emergence of a new technology and its introduction into a certain geographical area varies, but on average it is too long. There has been some improvement since the 1980's, but it must continue to improve in the current decade. The lack of adequate performance history has generated some reluctance in some highway engineers who usually tend to be conservative when it comes to using new products or techniques. Not many practitioners are quick to volunteer to be "pioneers" in the use of untested or unproven technology. Most would rather wait to see how things work out somewhere else. Of course, some tend to wait much longer than necessary.

In some foreign areas where the project "owner" is getting a long-term guarantee from the contractor, the demand for historical performance data is reduced. Historically in the U.S. highway industry, the owner assumes all risk once the project is accepted (shortly after construction is completed), as opposed to European practice where the contractor can be held accountable for the length of the guarantee period. Some U.S. agencies are testing this European practice to see how it works in their domain.

Another cause of implementation delays is that a few of these techniques have patents or other proprietary restrictions associated with their use. These proprietary controls can reduce the attractiveness of the techniques to some highway designers and, in some cases, become contractually awkward.

Still another cause of delay is the lack of suitable design aids. It is one thing to be aware that these methods exist, but quite another to be adequately informed about their proper use. Many situations have occurred where new techniques have been introduced to the profession without making available adequate design aids and construction guidelines.

Unless the practitioners can see that user-friendly design tools are available, some will naturally shy away from using the new technology. Research and technology transfer efforts play an important role in reducing this reluctance on the part of the practitioners.

And finally, one of the biggest challenges facing the technology transfer program and implementation activities for geotechnical and ground treatment techniques is the elimination of various technical concerns expressed by the practitioners. For example, many are still concerned about the effect of corrosion on the design life of reinforced soil structures that use metallic materials as the reinforcing elements. By the same token, the durability of geosynthetic reinforcement material needs to be examined in greater detail. The lack of reliable quality control procedures for many ground treatment methods has discouraged their use in many cases. And overly restrictive environmental criteria have sometimes influenced decisions not to select particular ground treatment methods.

The lack of early consideration by the practitioners in the design process also makes a big difference. Too often these techniques are only considered as a last resort, which places them at a distinct competitive disadvantage.

7.3 Solutions

In an attempt to deal with these problems, the FHWA has developed a team approach utilizing personnel and resources from the Research, Development, and Technology Transfer programs to tackle these issues. Research has provided answers for developing improved methods and devices that practitioners can use to solve their problems. A series of demonstration projects have been established to show how the technology works. Technical experts from FHWA's Operations offices are also very involved in this team approach and are available to provide technical assistance to the practitioners during the design and/or construction phases of any project. Funding is also made available to instruct, monitor, and report the results of new experimental features that are incorporated into the highway project. High-speed electronic communication and Internet availability of the FHWA technology information is also important to the implementation efforts.

Education and training are also an important part of this effort. Workshops and courses are developed and sponsored by FHWA's National Highway Institute (NHI) to teach practitioners how to use the technology. Instructor's handbooks and student workbooks have been prepared to aid the educators in conducting the training sessions. Slides, view-graphs, videotapes, and other training aids have also been developed for use in the courses. The FHWA geotechnical team of practitioners, researchers, and implementors provide expert guidance to the NHI staff members during development and conduct of these courses.

The main elements of the solution process can thus be summarized as follows:

- Research and development
- Demonstration programs
- Experimental projects
- Workshop/seminars
- Operations surveillance
- NHI courses

7.4 Observations

In a multilevel government, a network encompassing Federal, State, and local government; universities; private industry; and highway organizations is critical to the speed of delivery and adoption of new technology. Technology transfer requires a structured program with champions from throughout the highway community who will convey the technology in innovative ways.

There must also be a simple vision that everyone can relate to and support; the new technology must make sense to the users and have a favorable cost-benefit. It also takes follow-up efforts to ensure that the technology progresses to all appropriate users, that those users have all the information they need to implement the technology, and that the technology is applied and becomes a part of the state of the practice. Additionally, the State must be permitted to be flexible and innovative; if users of the technology are not stifled, they will probably change what you give them into something better.

Technology transfer is just as important today as it was 100 years ago. The problems are just as real, and the need for solutions is just as pressing. Today, the technology is micropiles, geosynthetics, soil nailing, deep soil mixing, and other innovations we must have for the 21st century.

7.5 Examples of Success

The most direct and effective measure of success of any research effort is the application of research results in practice. During the past 10 to 15 years, the results of FHWA research in geotechnical areas have been incorporated into highway practice by the development of specifications and guidelines for the design of foundations, retaining walls, buried structures, and ground improvement techniques. The following brief summary will serve to highlight some of these contributions that have had a major impact on improving the state of the practice as well as the state of the art.

NCHRP Project 12-35; "Recommended Specifications for the Design of Foundations, Retaining Walls and Substructures" was initiated in 1989 with the intent of developing recommended revisions for sections 4, 5, and 7 of the AASHTO Bridge Specifications. The topical areas addressed during the project included spread footing, driven pile, and drilled shaft foundations (Section 4); gravity, semi-gravity, cantilevered, and anchored retaining walls, and mechanically-stabilized earth (MSE) and modular (or bin) wall systems (Section 5); and piers and abutments (Section 7). Project tasks included: (1) a data and literature search; (2) evaluating the information and preparing an outline for the recommended specifications; (3) submitting an Interim Report for comment by the review panel; (4) preparing the recommended specifications and commentary incorporating review comments; (5) identifying other articles of the Specifications affected by the proposed revisions; and (6) preparing a Final Report. The Final Report was submitted in 1990 and the recommended revisions were published as the 1991 Interims to the AASHTO Bridge Specifications.

The work completed for NCHRP 12-35 represents a significant testimonial to the value of FHWA's geotechnical research program. At the time this work began, the AASHTO Specifications did not contain any articles or provisions for drilled shaft foundations, tolerable movements of bridges, or for retaining walls other than gravity walls. In fact, the provisions for retaining wall design were limited to a single page of the Specifications. As a result, whereas some portions of the work entailed only minor revision of the existing articles, others required substantial effort, including development of entirely new articles. The following sections highlight the application of this work, with emphasis on the contributions made by FHWA geotechnical research.

7.5.1 Foundations

Revisions and additions to the provisions for the design of spread footings incorporate the results of Gifford, et al. (1987), Moulton, et al. (1985), Moulton (1986), and Lam and Martin (1986) (27,3,4,72). Gifford, et al. (1986) was directed toward documenting the settlement performance of bridge abutments and piers supported on spread footings founded on sand and using the data acquired to evaluate the accuracy of various published methods for estimating settlement of footings on granular soils (Article 4.4.7.2.2 Elastic Settlement). Moulton, et. al. (1985) and Moulton (1986) were referenced in Article 4.4.7.2.5 to provide guidance for estimating tolerable movements of simple- and continuous-span bridges when this type of information is not available from the bridge designer. Lam and Martin (1986), which describes procedures for developing ground and seismic parameters and for evaluating ground stability, is referenced in Article 4.4.10 for the design of footings subjected to dynamic and seismic loading.

Since the provisions for the AASHTO Specifications were relatively complete and well established for driven piles, the work consisted mostly of adding articles to incorporate recent analytical and technological developments. Principally, this consisted of research related to the design of laterally loaded piles (Reese, 1984), allowable stresses in piles during driving and under service loads (Davisson, et al., 1983), and the use of wave equation analysis (e.g., Goble, et al., 1986) to evaluate pile driveability (22, 11,12). Recommendations by Davisson, et al. (1983) to qualify allowable stresses under service loads based on the pile damage potential from subsurface conditions expected during driving were incorporated in the development of Article 4.5.7.3. Article 4.5.11 incorporates recommended maximum allowable driving stresses for steel and concrete piles recommended by Davisson, et al. (1983). Wave equation analysis (e.g., Goble, et al., 1986), which is used to model the soil-pile-hammer system, is included as Article 4.5.9 of the Specifications as a complement to the use of dynamic monitoring (Article 4.5.10) used to evaluate pile structural integrity, stress levels, pile and drive system performance, and pile capacity.

Because the design of drilled shafts was not addressed in previous editions of the AASHTO Specifications, all current provisions were developed as part of NCHRP 12-35. As a result, a substantial portion of the drilled shaft provisions incorporate design recommendations presented by O'Neill (73). This study resulted in the development of a manual describing design methods and construction procedures for drilled shaft foundations. In addition, reference is made in the articles to other FHWA-sponsored research, including Reese (74). Article 4.6.5.1 is a series of provisions for the geotechnical design of axially loaded drilled shafts in soil. The provisions are based on design procedures presented by Reese and O'Neill (1988), which incorporate the results of full-scale load tests on instrumented drilled shaft foundations. Provisions for considering the effects of group action (Article 4.6.5.2.4) and vertical ground movement (Article 4.6.5.2.5), such as from negative loading and expansive soil, were also developed from procedures presented in O'Neill (73) and Reese (74). Design for lateral loading is addressed in Article 4.6.5.6 and incorporates the results of Reese (74) as described previously, which can be used to evaluate the effects of shafts extending through sloping ground.

7.5.2 Retaining Walls

As mentioned previously, the content of the previous edition of the AASHTO Specifications only addressed the structural design of gravity and semi-gravity retaining walls. Accordingly, the current AASHTO Specifications required development of entirely new provisions to supplement previous provisions, and to address the design of cantilevered and anchored retaining walls, and MSE and modular wall systems. Discussion below is limited to FHWA-sponsored research for anchored and MSE retaining walls.

The results of FHWA-sponsored research to develop design and construction guidelines (Christopher, et al., 1990) for MSE walls and the durability and corrosion behavior of reinforcements in these walls (Elias, 1990), were used to develop selected design provisions for the current AASHTO Specifications. Important additional guidance for the design of these walls was obtained from the results of NCHRP 24-2 (Mitchell and Villet, 1987). Christopher, et al. (1990) was used in developing provisions for proportioning wall structure dimensions for external stability (Article 5.8.1), the internal stability of inextensible and extensible reinforcements (Article 5.8.4.2), and the design for seismic loading (Article 5.8.10). Design life criteria presented in Elias (1990) were used in developing provisions for estimating corrosion losses for coated and uncoated steel reinforcements (Article 5.8.6.1), and for determining aging and construction damage losses for polymeric reinforcements (Article 5.8.6.2) (32,42).

In addition to the research references cited herein, supplemental information was obtained from the review of numerous other reports which present the results of various FHWA geotechnical research efforts. According to the author of the NCHRP 12-35 report, the results of FHWA-sponsored geotechnical research efforts were a very important component in the development of the revised specifications and guidelines. The most significant contributions were in the areas of spread footings, driven piles, and drilled shaft foundations, and anchored and MSE walls; areas that have received considerable attention during the past decade.

7.6 More Examples of Success

In addition to the incorporation of research results into practice, another measure of success is the cost-savings that can be attributed to the use of new and innovative geotechnical technologies. Such data are not easy to gather for a national perspective; however, a few States and some regions have made nominal efforts to quantify these savings.

In 1985, a special 1-day session titled "Cost Savings Through Geotechnology Transfer" was held in conjunction with the Northwest Geotechnical Workshop in Valdez, Alaska. The purpose of the session was to provide documented feedback on the "payoff" of FHWA geotechnology research and implementation efforts. The 10 northwestern States that normally participate in the yearly workshop were each asked to provide a minimum of 3 case history cost-saving examples. Forty-three cost-saving examples were presented with a combined savings totaling $76 million. Many of these examples involved ground treatment technologies that had been introduced to the region during the previous 5 years. These examples are a small random sampling that did not represent the full measure of cost-savings attributable to the FHWA efforts. However, it does give an indication of the significant "payoff" that is being realized.

In recent correspondence (1994) between the Secretary of the Washington State DOT and the FHWA, the Washington DOT engineers estimated that highway construction savings from the FHWA's Durability of Geosynthetics study could be on the order of $70 million per year nationwide, which translated to $1 million to $2 million per year in savings for the State of Washington alone, based on current program levels. Considering that the current total cost of this research project is only $1.3 million, this appears to be a very profitable investment of research funds.

In another letter to FHWA from the Colorado Transportation Institute, it was noted that earth reinforcement technologies are a good example of actual and potential cost-savings that have resulted from FHWA research and implementation efforts. On the basis of their experience, they have conservatively estimated that State DOT's can save approximately $700 million annually with full implementation.

In a feature article in the December/January 1992 issue of the Association of Drilled Shafts Contractors (ADSC) magazine called *Foundation Drilling*, the editor, Scot Litke, credited FHWA research with valuable contributions to improving the state of the practice and saving money. Mr. Litke is also the Executive Director of ADSC. The following excerpts from this article amplify these credits.

> "The latest in a series of Federal Highway Administration drilled shaft research projects has just been announced. The area of investigation is a direct outgrowth of the agency's Research Review Board process. This evaluation arm of the FHWA includes prominent representatives from the field of deep foundations engineering and construction. The ADSC is represented by ADSC Director Bud Stebbins, Chairman of the Association's Research Committee, and by the ADSC Executive Director. The Review Board recommends and evaluates proposed areas of foundation research that will be considered by the FHWA and the transportation industry. The FHWA is the funding agent.
>
> As an agency the FHWA continues to demonstrate an extremely high level of "inconclusiveness." This is to say the agency actively seeks the recommendations of those engineers and contractors who ultimately will undertake the projects either partially or fully funded by the agency. Rather than set itself outside of the mainstream of highway construction, the FHWA gets right in the middle, and that applies to its activities in all aspects of highway design and construction, from basic materials testing, to sophisticated design modeling. The FHWA's commitment to technology transfer (education) is a model for all government agencies to follow.
>
> Much of what has come before has been reported in *Foundation Drilling* magazine. As more data on current projects becomes available it will be thoroughly reported. Now we move to a new area of investigation, that of Load Transfer on drilled foundations and earth retention systems. In these two areas, the level of cooperation has been remarkable, the end result of which is a more cost effective product for the taxpayer.
>
> Once again, the FHWA has demonstrated its forward thinking modus operandi. The ADSC is pleased to be a fully contributing partner to FHWA research projects."

The "Research Review Board" referenced by Mr. Litke in the article is the "Geotechnology Research Specialty Committee" established by the FHWA program manager to assist in the decision-making process and planning for research programs. In addition to foundation specialists from industry, the committee also had representatives from FHWA field offices, SHA's, ASCE, TRB and NSF.

In a November 20, 1996, letter from Mr. Litke, he quoted specific cost savings attributable to an FHWA research study, plus references to other successful studies funded by FHWA. The letter is re-printed herein.

> "I am writing in reference to a research project entitled, "The Effects of Free Fall Concrete in Drilled Shafts," funded, in part, by the FHWA Geotechnical Research Division. ADSC: The International Association of Foundation Drilling was the co-funder of the project. Once the research was completed, the ADSC's Technical Library Service published a full report, which was then circulated widely to the Bridge and Geotechnical Divisions of State Departments of Transportation and FHWA Regional Offices throughout the United States.
>
> In the three years since the report was published, we have determined that, in almost every case, specifications relative to the free fall method of concrete placement for drilled shaft construction were changed significantly. Our follow-up analysis has found that this much more economical method of concrete placement has resulted in savings to State Departments of Transportation bridge projects in excess of $500,000.
>
> During the past ten years, there have been a number of other research projects for which the ADSC and the FHWA have been the participating funding organizations. Included in this long list are projects focused on Non-Destructive Evaluation; Development of a National Load Test Data Base; Load Transfer in Intermediate Soils; Mathematical Characterization of Anomalies in Drilled Shaft Construction; Load Transfer Mechanisms in Soils; and a host of other studies that have had direct impact on developing more reliable and cost-effective drilled foundation systems. The end result is literally millions of dollars in construction cost savings.
>
> In that the ADSC's research mandate is to only fund projects that have the potential of directly cutting construction costs, the Association appreciates having the FHWA as a co-funding partner. The ultimate beneficiary of this important work is the American public.
>
> We look forward to a continued, mutually-beneficial relationship."

In 1995, a series of letters were written to the Federal Highway Administrator, Mr. Rodney Slater, expressing concern over significant budget cuts and perceived downsizing of the Geotechnical Research Program. In addition to urging renewed emphasis on this area, these letters contained very flattering testimonials about the benefits received from previous FHWA efforts. These accolades came from other government agencies, private research institutes, academia, SHA's and the private sector, in an effort to show their appreciation for the contributions made by FHWA to improve geotechnical engineering for highways, other transportation modes, and the Nation's entire infrastructure program.

Brief excerpts are presented from a few of these letters to illustrate the broad support and respect for this program. They can be considered as one more measure of success.

Ms. Laurinda Bedingfield, Commissioner of the Massachusetts Highway Department, said:

> "During the past year, the Massachusetts Highway Department supported geotechnical research programs in the order of 13.5% of our total research investment. While each state has its own special problems, the research on the Federal level is influenced by a national need and, as a result, has a much greater impact and is more cost effective. The ongoing Central Artery/Third Harbor Tunnel Project in Massachusetts is a prime example of the critical importance of geotechnical engineering in transportation projects, and of the contribution of a Federal research program in that area."

Mr. James E. Roberts, Director of Engineering Services and Chief Structural Engineer for the California Department of Transportation, said:

> "A strong FHWA leadership role in geotechnical research is essential in supporting the design of effective Federal and State Highway programs. FHWA geotechnical research has resulted in the successful development and improved application of micropiles, soil nailing, reinforced soils, geosynthetics, pile groups, and spread footing foundations. These technologies have had a favorable effect on engineering design and construction practice with large cost savings.
>
> I am obviously interested in the FHWA geotechnical research program for selfish reasons. However, the cost avoidance in future damage repair is many times the current cost of properly engineered structure and embankment design. That design must be supported by geotechnical engineering resulting from research. The savings are universal throughout the United States."

Professor Frank Townsend, University of Florida, and President of the U. S. Universities Council of Geotechnical Engineering Research, which represents more than 100 universities said:

> "The FHWA's Geotechnical Research Program has been the premier organization in introducing new developments and technologies in the United States. As such it has impacted the U.S. engineering and construction industry far beyond the transportation sector."

Dr. Robert M. Koerner, Director of the Geosynthetic Research Institute, said:

> "Please be advised that I consider FHWA's Geotechnical Research Program the most innovative and rewarding program to taxpayers of all federal programs that I know of. This is based on my 30 years of research and development interfacing with virtually every branch of government; federal, state, and local. The feedback and accountability of infusing new and economical concepts and ideas into the transportation sector is exemplary. This FHWA program should actually be "show-cased" to others as being the way to conduct research for other agencies to follow."

Professor Paul Mayne of Georgia Tech said:

> "The innovative and progressive research directed by the Geotechnical Program at TFHRC has been an important contribution to our nation's infrastructure...Before entering Academia, I worked as a professional engineer for 11 years. I can personally vouch that the FHWA GT Program has funded and engaged in research of direct practical and economical benefits to the U.S. Public...Now as an educator, I find the efforts and accomplishments of this program to be valuable assets for teaching and education of our new and upcoming civil engineers . . . In closing I consider the FHWA GT program to be one of the most outstanding research organizations in the U.S."

Dr. Frazier Parker, Director of the Alabama Highway Research Center, said:

> "FHWA Geotechnical Research has played an essential role in funding innovative and important geotechnical research. This research has greatly influenced highway design and construction practice in the U.S. and the world, and it would be a blow to good engineering if the geotechnical research effort were diminished."

Dr. Ara Arman, Vice President of Woodward-Clyde Consultants, Inc., said:

> "The Geotechnical Division of the Turner-Fairbanks laboratory has been well recognized, nationally and internationally, as being a major force and resource in the development of practical, readily applicable geotechnical research. Their work has, throughout the years been translated into untold millions of dollars in savings in design and construction. As you are aware foundations and geotechnical portions of transportation facilities are often the most costly items. There are many examples that one can show where not only large amounts of tax dollars were saved because of the innovations introduced by FHWA but a number of new businesses and permanent jobs were created."

Dr. William Marcuson, Director of the Geotechnical Lab at WES, said:

> " I believe FHWA has made the Geotechnical Engineering Program an international program. Additionally, I believe the accomplishments of this program have been substantial and are producing a positive image of your organization in the engineering community."

Professor Dov Leschinsky, University of Delaware, said:

> "I have witnessed the development of new earth structures that cost less than half of the price of their conventional equivalents, and have a life expectancy twice as long (e.g., reinforced earth retaining walls and slopes). Surely such innovative structures save the tax payers billions of dollars when implemented by the various state DOTs. However, state DOTs, and many federal agencies (e.g., EPA, USCOE, USDA) will not implement new technologies without the "stamp of approval" of the FHWA's Geotechnical Engineering Research Center. Simply put, the reputation of this center with regard to engineering thoroughness makes it easier for the public to accept new technologies."

Professor Fred Kulhawy of Cornell University said:

> "Under FHWA's capable leadership, much truly innovative basic and applied research has been done to benefit the entire transportation industry. I am not speaking about incremental technology improvements, I am speaking about entirely new technologies being developed and applied. These types of developments have been revolutionizing the entire construction industry. And, I might add, have led to the types of transportation facilities that have performed remarkably well during the recent California and Japanese earthquakes. The Geotechnical Program has been one of FHWA's most effective for a very long time."

Dr. Mehmet Tumay, Director, Louisiana Transportation Research Center and former Director of the National Science Foundation Geotechnical Program, said:

> "Our own center counts the geotechnical area as one of its strengths; however, the direction, technical expertise and sponsorship of the FHWA Geotechnical Program remains a key ingredient to our success. This program has been a model, mover, shaker and a team player."

Dr. Herbert H. Richardson, Director of the Texas Transportation Institute, said:

> "It is your Geotechnical Engineering Program which is largely responsible for the break through on the wave equation and pile driving analysis in the mid-seventies. In the eighties, it is your Geotechnical Engineering Program and

vision which are largely responsible for the increased use of shallow foundations for bridges at very large savings to the taxpayers. In the nineties, it is your Geotechnical Engineering Program being a true international leader with partnerships in China, Europe, and South America."

Dr. Ralph Trapani, President of the Colorado Transportation Institute, said:

"I respectfully ask that you review the contributions from the geotechnical research programs administered over the past several years, and in the context of their overall importance to our national transportation program."

Mr. Scot Litke, Executive Director of ADSC, said:

"The FHWA's Geotechnical Research Program has been a very effective partner in fostering advances in drilled foundation and anchored earth retention design and construction practice. These changes have resulted in literally billions of dollars in savings in the construction of the nation's highway bridges. Private industry has been a co-founder of virtually all of the drilled foundation research and development activities supported by FHWA's Geotechnical Research Program. Without the assistance provided by the Program very little of the cost-saving advances could have occurred.

Professor Don DeGroot of the University of Massachusetts said:

"I could cite many examples of innovative and important developments that have resulted from FHWA sponsored research, but I will limit my comments to just one; a comprehensive case study conducted on the behavior of spread footings on sands. The project represents one of the best case studies ever conducted in our profession and will have a significant impact on the way we design foundations for transportation facilities. In fact, it is already being used by the Massachusetts Highway Department to evaluate their design methodologies. If it were not for FHWA's efforts, both financial and motivational, our practice would not have the benefit of the valuable information that this study generated."

Other letters of testimonial are also on file. From these letters and other reports and documents, it is clear that the FHWA program for research and technology transfer of geotechnical engineering is a vital service to improving highway design and construction, with valuable spin-off to other disciplines of civil engineering and infrastructure renewal. Although much has been accomplished, there is much more that needs to be done. With the recent establishment of the National Geotechnical Experimentation Sites, plus a group of research quality data bases, FHWA is now positioned to make even greater advances in geotechnology that will save many millions of dollars on future highway projects.

CHAPTER EIGHT

CONCLUSIONS

Every work of humans is constructed on, in, or with ground materials. Highway facilities certainly fall within these bounds. Even intelligent highway vehicle systems must have a sound foundation support system. Some exceptions are those things that fly, drift in space, float or fall down, and even these must start or end with some contact with the ground. Knowledge of the science, art, and technology of these materials (geotechnology) is necessary to enhance and exploit these resources.

To orient the general civil engineer and lay reader of this report, significant background discussions and explanations of the objectives and scope of the various geotechnical research projects and studies were presented at the beginning of each chapter. These discussions were followed by a review of the performance of each study and a delineation of significant results. The report is sprinkled with a number of success stories to demonstrate the value of the research efforts and to justify the significant expenditures of highway user tax funds. Chapter 7 attempts to show that the research and development products are not gathering dust on the shelves in the libraries of the world, but rather they are used often and productively. Numerous testimonials are immodestly delineated to demonstrate the acceptance of these products into the highway and civil engineering mainstream.

Geotechnology and geotechnical engineering are used almost interchangeably throughout the report. These terms are used to imply a wide range of technical disciplines that contribute to the understanding of soil and rock behavior, and are defined as the field of professional practice and research that draws heavily on the principles of soil and rock mechanics, foundation engineering, and engineering geology. These disciplines involve the study of highway structural foundations, tunnels, earth retaining structures, cut slopes, and pavement subgrades. The research reported in this document involves the application of geotechnology in site characterizations, design, construction, and performance monitoring and assessment.

At the same time that the science, art, and engineering principles of geotechnology have been extensively improved due to the quarter century of work reported herein, the public demands placed on this profession have increased significantly. The ability to design and build larger structures has brought heavier loads that must be supported by ground materials. Expectations on performance have also gone up, and the public will no longer tolerate failures or gross over-design to mask knowledge gaps and uncertainties. The decrease in available quality construction sites compounds the demand for bigger and better infrastructure facilities. Sites with poor or marginal geotechnical features can no longer be avoided because the options in site selection are fewer and further between. Underground options are sometimes the only choice at hand for extending or improving urban infrastructure facilities.

Expanding or upgrading urban highways in crowded environments has significant potential to influence adjacent structures. The prediction and control of ground movements from highway construction operations such as open-cut excavations, tunneling, dewatering, and vibrations from pile driving and blasting operations is becoming more and more important. The Boston Central Artery and Third Harbor Tunnel project is a good example of both a geotechnical nightmare and a researcher's dream because of the fascinating geotechnical problems and challenges. Some of the advancements reported in the earlier chapters of this report were developed by studying some of the Boston problems in the early phases of design and construction, and the later phases will certainly benefit from this new knowledge.

The author is sure that there will be some readers who will ask why it is still necessary to continue geotechnical research programs because it seems to them that we have done all there is to do. Why continue to do the "same old, same old" for the sake of just doing more. At the risk of dignifying this shallow thinking, the author suggests that these people reread the report and reflect on the many problems that continue to stymie the efficient and safe construction of this nation's transportation system over, through, and within heterogeneous ground materials.

These problems have not been approached with sufficient resources in the past, and will continue to grow and compound with increasing demands of a mobile and highly technically oriented society. Thoughts of reducing or downsizing geotechnical research efforts need to be reversed and expanded to properly address these urgent problems. Geotechnical engineering can and should play a major role in assessing the effects of construction on other structures adjoining the highway, by providing rational tools and methods for selecting the appropriate construction methods, predicting the ground movements, designing protective measures, and developing remedial correction schemes. If allowed, geotechnology will play a critical role in the construction, renovation, and upkeep of our Nation's highway system.

APPENDIX A

FUTURE GEOTECHNOLOGY RESEARCH PROGRAM

BACKGROUND:

During the 1970's, a series of FHWA studies determined that various segments within the field of highway geotechnology needed significant improvement in design and construction applications. This was especially important considering that bridge foundations, retaining wall systems, embankments, and cut-slope operations account for well over 50 percent of the total cost of most highway projects. It was therefore imperative that accurate and rational guidelines be developed for geotechnical-related design and construction applications to ensure safe and efficient highway structures. Also, at this time, there was a significant influx of innovative geotechnical methods to retain earth masses and/or improve ground materials to withstand heavy loads.

As a result of these discoveries, FHWA expanded the Geotechnical Research Program to address many of these needs. The program was divided into three main projects: Soil Behavior, Foundations, and Ground Improvement. This program, as described in the body of this report, was completed in 1998; and a new program to study innovative foundations and excavation support systems was established. The new program places more emphasis on the development of innovative methods to support bridge foundations and earth retention systems.

In the *National Geotechnical Engineering Improvement Program* report prepared for The Office of Engineering, the authors developed a list of research needs that relate mostly to foundations, earth retention, and excavation problems that were identified by their customers in a recent national survey. The results of the survey and a state-of-the-practice assessment by FHWA clearly shows that research is needed to develop technical guidance for some of the new technologies that have recently emerged from foreign sources or other building disciplines.

OBJECTIVES:

The objectives of this research are the development of new and/or improved support systems for bridge foundations and deep excavations for highway construction projects.

SCOPE:

The scope of this research includes analytical studies, laboratory testing, and field monitoring of construction sites in order to develop, refine, and validate new or improved designs. It includes research into a wide range of materials properties, instrumentation techniques, monitoring methods, analytical techniques, performance assessment, and design principles in much the same way as the predecessor program.

The research program will be set up to focus on two main projects: foundations and excavation support systems. The foundations project will cover innovative load testing systems, load and resistance factor design, piles, drilled shafts and spread footings, plus some innovative uses of geosynthetic reinforcing materials that are combined with modular building blocks to form bridge support piers and abutments. The excavations project will look at new and innovative methods to build earth retention systems from the top down, plus other innovative ways to support and retain soil and rock masses.

APPROACH:

The major research efforts in the foundations project are included in four tasks:

1. Inovative Load Testing Systems - In the FHWA *National Geotechnical Engineering Improvement Report*, it was noted that there was a large increase in the number of highway agencies that are using innovative load test systems for bridge foundations. The reasons for the increase are economy and reduced time for load testing as was demonstrated in previous FHWA research studies. However, several methods need documentation for standardized test procedures or for the interpretation of the data produced by the test. The Office of Engineering will use this information to develop a Geotechnical Engineering Circular to provide FHWA-recommended procedures for these innovative load testing systems, such as the Statnamic rapid load test, the Osterberg load cell, and several dynamic load test systems. Comparative analysis studies will correlate results from these tests with results from conventional static load tests from the FHWA load test data base developed under previous research studies.

2. Load and Resistance Factor Design (LRFD) - According to the Office of Engineering's national report, the FHWA geotechnical research data bases are key links in their work to implement LRFD nationally. Recent efforts by them and the National Highway Institute to train engineers and implement LRFD procedures for foundations have disclosed that adequate resistance factors are not available to make an orderly transition to LRFD methods. The authors of the report suggest that the resistance factors can be developed from one segment of the FHWA research data bases and then verified with data from other segments of the data bases. In addition to using the data base to verify the reliability of the various factors and computational procedures, theoretical correlations of existing procedures with the research quality databases will be required to convince customers of the reliability of the new LRFD procedures.

3. Micropile Technology - The Office of Engineering has requested that recently completed research efforts in this area be expanded to investigate use in seismic retrofit situations and for slope stabilization purposes. According to its survey, the popularity of micropiles is increasing, with more proprietary systems being developed for both foundations and earth retention. In addition, three recent failures of micropile systems on design- build projects have caused concern among the

FHWA engineers, their partners, and customers about current design practice. Both vertical (compression and tension) and lateral resistance (structurally and geotechnically) of micropile systems must be investigated before FHWA launches Demonstration Project 116 on micropile technology.

4. Automated Geotechnical Information and Design Aid System - A comprehensive effort is required to integrate all of the FHWA research-quality data bases and recently developed design improvements into a comprehensive design aid system to allow bridge engineers to quickly and economically obtain information and evaluate design alternatives from a centrally located computer source. The approach to be taken will involve development of commonality features and the design of a user interface application for performing cross queries, correlations, and engineering analyses. Several of the data bases already contain modules for performing correlations, predictions, and analyses, but they need to be linked through a multi-user workstation that contains an interactive system for automatically generating design solutions based on interactive user input. Such a system will take most of the guesswork out of geotechnical design and replace it with an objective, quantitative system that supports sound management decisions.

The major research efforts in the Excavation Support Systems project are included in three tasks:

1. Soil Mixing - The process of deep and shallow soil mixing with cement and lime additives is increasing at a rapid rate, especially in large urban areas near large bodies of water containing very soft soil deposits. The two largest highway construction projects in the United States (Boston Central Artery and the I-15 corridor in Salt Lake City) are employing different types of soil mixing to stabilize critical ground conditions. These soil-mix designs were introduced into these projects through value engineering or design-build contracting approaches. At present, neither FHWA nor AASHTO have any published design guidance for these techniques, which originated in other countries.

   Research will develop soil-mix design criteria and construction quality control procedures to permit rational use by FHWA customers. Some preliminary research by FHWA has clearly shown that these methods have significant potential to reduce costs and time delays if rational guidance for strength, deformation, and durability concerns can be developed.

2. Top-Down Construction Techniques - The use of soil nailing, ground anchor tiebacks, and other top-down construction techniques, such as slurry walls, continue to be a very popular way to support deep excavations, especially since FHWA research results have been disseminated through implementation manuals, training courses, and other technology transfer functions. Further refinements to optimize their usage are needed in the form of increased knowledge of the load transfer mechanism between the reinforcing elements and various soil types or ground

treatments. Corrosion and durability aspects are also in need of study. Most of the prior research involved granular materials to take advantage of the soil's frictional strength along the reinforcing element's surface area to resist deformations that could damage the structure. Recent FHWA research efforts have clearly shown that clay soils can also be reinforced with nails and other inclusions.

3. Geosynthetic Reinforcement Applications - Recent FHWA research results have demonstrated that geosynthetic materials can be economically combined with modular blocks and granular soil materials to provide foundation support for bridges and excavation support for roadways. Initial studies of this technology have resulted in questions related to mobilization of the resistance in the composite mass structure. Other design issues include the vertical spacing distances between the geosynthetic reinforcing sheets and the connection methods between the reinforcing elements and the facing blocks.

SUMMARY:

The future R&D program described in this appendix will provide new knowledge and technology to help ensure the safety and reliability of the Nation's highway bridges and retaining wall systems that are exposed to such dangers as floods, earthquakes, and strong winds. The new knowledge will also help to reduce the amount of over-conservative design that often results from fear due to a lack of knowledge in how to properly design for certain contingencies. It would not be prudent to have large quantities of "buried treasures" beneath some bridges and earth retention systems in order to be sure that these structures are safe and reliable in times of crisis. We must also be sure that these systems are efficiently designed. Experience and previous research results have demonstrated that this new program can provide the opportunity to develop these innovative capabilities for improving the safety, reliability, and efficiency of these critical national assets.

APPENDIX B

TUNNELING GEOTECHNOLOGY

In the early 1970's, the U.S. Department of Transportation (DOT) initiated a major research program in tunneling that was divided among four DOT agencies. Most of the technical aspects were divided between the Federal Railroad Administration (FRA) and FHWA. Improved tunnel linings and excavation techniques were the responsibility of FRA; FHWA handled site investigation, tunnel instrumentation, cut-and-cover tunneling, and ground movement and prediction control. Justification for the research program was based on projected demands for transportation tunnels increasing from two to three times during the 1970's and doubling again in the 1980's and 1990's, for a total of almost $30 billion by the end of the century. It was also estimated that 50 percent of all highway tunnels would be built in an urban environment by cut-and-cover techniques. Research aimed at improving the design and construction of tunnels could reduce costs by at least 30 percent.

Overruns in cost and time were common in highway tunnel construction projects during the 1970's, mainly because of unforeseen ground conditions due to inadequate site investigations. Most of the FHWA research effort was concentrated on improving our knowledge of predicting and controlling these problems, which were obviously geotechnical in nature. The project was concluded in 1983 and a summary report was distributed in January 1985 (FHWA-RD-85-016).

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

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

The report fully documents major research advances, significant design and analysis improvements, and substantially new recommendations in areas ranging from analytical modeling to soil property evaluation. The summary report also gives a comprehensive listing of the major reports that resulted from each study, some of which were and still are benchmark references for geotechnical and structural engineers today. This summary report on the U.S. DOT Tunneling Project is a must-read and must-have document for a transportation engineer's personal library.

APPENDIX C

GEOTECHNICAL (GT) FACILITIES AT TFHRC

The Geotechnical Laboratory at the TFHRC includes soil mechanics, soil behavior, and foundations testing facilities. The primary functions of the laboratory are to determine mechanical properties of ground materials and to evaluate soil-structure interaction for bridge foundations and retaining walls. In addition, the laboratory can perform rock mechanics, geophysical, and in-situ testing of various ground materials.

The GT laboratory facilities are capable of conducting all of the standard tests for characterizing ground materials. In addition, model tests of piles, drilled shafts, spread footings, and reinforced soil retaining systems can be conducted in large laboratory tanks and test pits. Automatic pile drivers, an overhead crane, and load testing reaction frames are available to conduct evaluations of load/settlement relationships of instrumented foundation systems.

The indoor facility houses a below grade, 2-m cubical test pit, plus several 1.5-m-diameter by 1.5-m-deep steel tanks for testing smaller scale models in both sand and clay. Loading is provided by a 16,250-kg reaction frame and a specially designed jacking system that allows for the precise measurement of extremely small loads in both compression and tension (extraction tests). An overhead, 5-ton capacity crane is available for loading and unloading equipment and materials in the sunken pit and test tanks. A small model automatic pile driver is also available to drive 250-mm- to 1-m-long model piles into sand or clay test tanks or pits. The driving weights can be varied in small increments and adjustments can be made in the number of blows per minute.

The GT outdoor facility (figure 48) consists of two, 7.0 x 5.5 x 6.0 m test pits with concrete walls and drilled shafts anchored in bedrock for reaction loads up to 255,000 kg. The pits are filled with sand or clay to support either shallow or deep foundation systems for the experimental test programs. In one corner of each pit is a sump pump that is used to control the water level. The pits are served by a test control building that houses the data acquisition system, the load testing equipment, and a larger model pile driving rig (figure 49) that operates much the same as a prototype pile driver by releasing heavy weights from a certain height to free fall and develop up to 2,000 ft-lbs of driving energy (maximum 500-lb weight falling a maximum of 4 ft (1.3 m) to top of pile).

A recent acquisition includes a 4 MN Statnamic device with a catch mechanism, which was the first American-owned Statnamic device. The first project was a series of load tests on model groups of piles at TFHRC (figure 50). The second project was a group load test of stone columns in cooperation with the Hayward Baker Co. and the University of South Florida. The third project was a series of lateral and vertical load tests on drilled shafts at the Auburn University, NGES facility. A total of 10 axial and 4 vertical Statnamic tests were performed at Auburn. The results will be compared with static testing at the site.

Figure 48. Tour group at the GT outdoor facility.

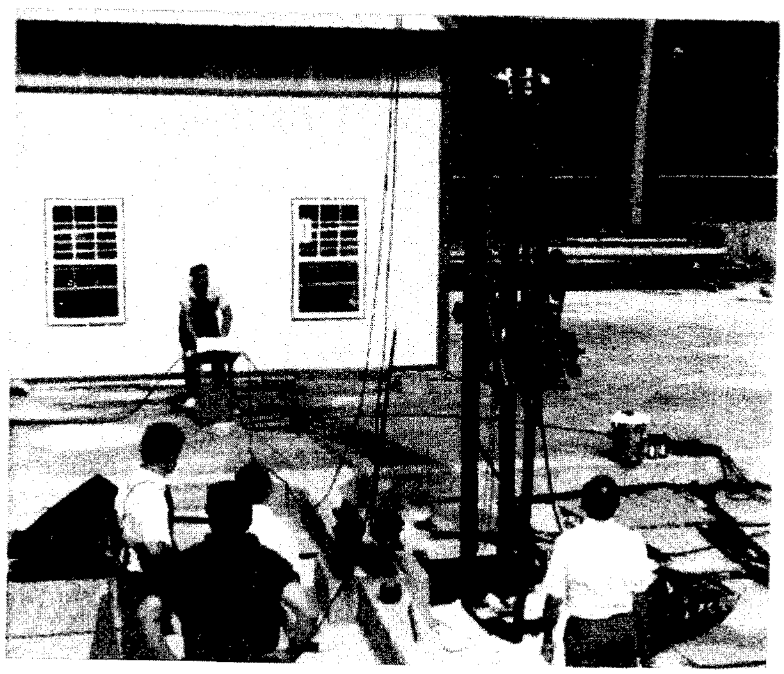

Figure 49. Pile driving of model piles at TFHRC.

The GT outdoor facility also includes a mobile pile testing tractor and trailer that was originally developed for the FHWA Demonstration Projects Division under Demonstration Project No. 66 on Pile Foundations. At the conclusion of the project, the trailer was

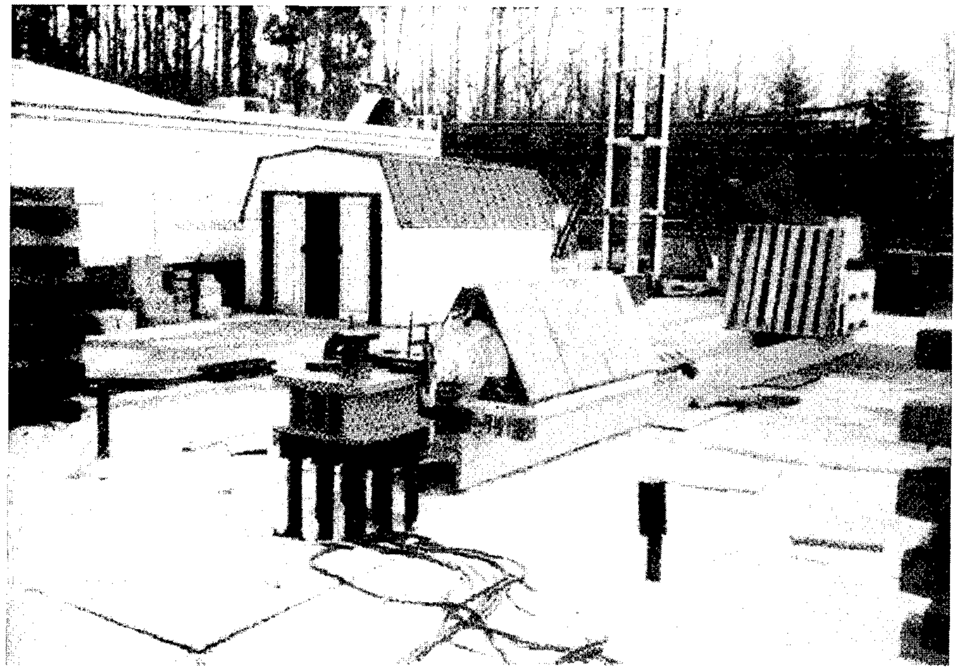

Figure 50. Lateral statnamic load test on model pile group at TFHRC.

transferred to the Geotechnical Research Unit at TFHRC. The trailer includes a large, 1,000-ton (890-MN) load frame with air compressor, generator, four 300-ton jacks, load cells, LVDT's, and instrumentation readout devices. The reaction system must be provided at the test site. The FHWA trailer comes with four high-strength (A514) plates to provide connection between the load frame and the anchorage system.

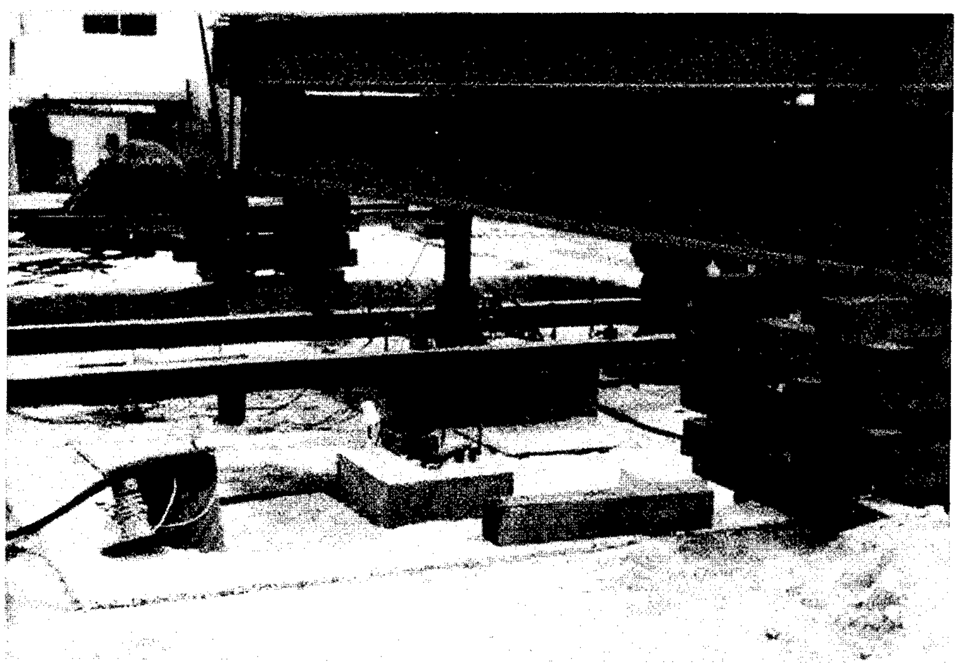

Figure 51. Spread footing load test.

Researchers from the GT laboratory perform comprehensive load-testing studies on deep and shallow foundation systems (figures 51 and 52) to observe performance and to obtain load settlement behavioral data for analytical studies to improve foundation design procedures. Data are stored in recently developed geotechnical data bases for future analysis by staff using a number of new computer modeling techniques. The data bases will provide a valuable standard against which new and existing design procedures can be compared.

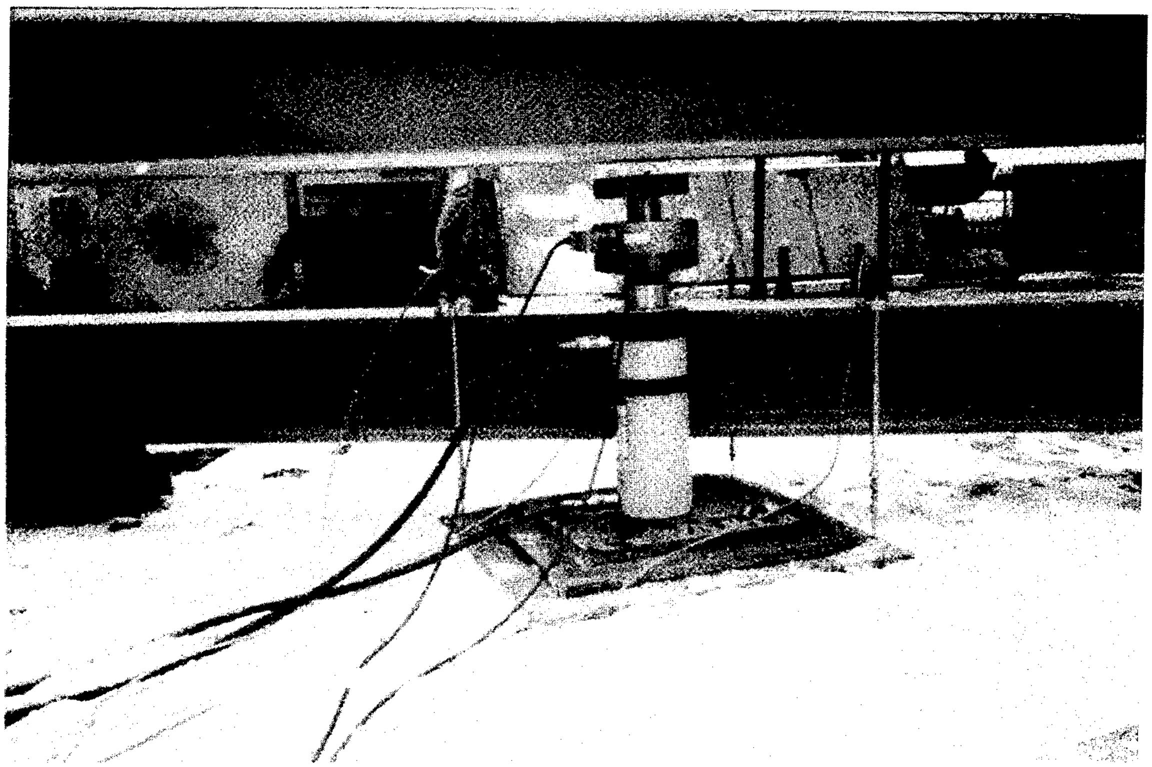

Figure 52. Plate load test.

APPENDIX D

PROGRAM AWARDS

During the course of this research program, the geotechnical staff members have received numerous awards from both within and outside FHWA. These awards can be thought of as another measure of success for the overall program. Listed below are two non-FHWA and TFHRC awards that are particularly noteworthy, plus two in-house awards.

ASCE Laurie Prize:

On October 21, 1991, the author of this report received the 1991 James Laurie Prize. Mr. DiMillio was cited for his work in advancing the art and science of highway geotechnical research, including work in the areas of soil mechanics, soil behavior, foundation engineering, slope stability, and ground improvement.

The ASCE James Laurie Prize was established by the Society in 1912 and is named in honor of the first ASCE President. Beginning in 1966, the prize has been given annually to an ASCE member who has made a definite contribution to the advancement of transportation engineering, either in research, planning, design, or construction, these contributions being made either in the form of papers or other written presentations, or through notable performance or specific actions that have served to advance transportation engineering.

California Geotechnical Award:

An FHWA geotechnical engineering research project received the 1989 California Geotechnical Association's Outstanding Project Award during a ceremony held on January 10, 1990, in San Francisco. Accepting for FHWA was Mr. Carl Ealy, Project Manager for the TFHRC study. The project involved a pile load test program to determine the driveability, load capacity, load/settlement, and load-transfer behavior of five different types of full-scale, instrumented piles and a load test to failure of a full-scale pile group of five closed-ended steel pipe piles (see Section 2.7.2).

Outstanding Technical Accomplishment Award:

Each year the TFHRC presents the FHWA Research and Development Award for Outstanding Technical Accomplishment to a member of the staff who has written an outstanding paper or report on an in-house project of superior quality. In 1994, Carl Ealy (figure 50) won this award for his report on "The Development of FHWA's Deep Foundation Load Test Data Base" (see Section 5.2.1). In 1996, Mike Adams won the Honorable Mention Award for his report on "Geosynthetic Reinforced Soil Bridge Pier," which is described in detail in section 3.5.4 of this report.

Figure 53. Presentation of TFHRC Outstanding Technical Accomplishment award.

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