Soil Improvement and Foundation Remediation
with Emphasis on Seismic Hazards

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and
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A report of a workshop

sponsored by the
National Science Foundation

and held at the
University of Washington
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Note

This report presents a compilation of the discussions of the participants in a National Science Foundation workshop, along with supporting background information. As such, it reflects the views of the authors, which are not necessarily those of the National Science Foundation or the University of Washington. No endorsements of any product or process described in the report is intended.

Front cover: Slope failure along Union Pacific railroad right-of-way in 1949 Olympia, Washington earthquake (photo by G.W. Thorsen).

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Summary

On August 19-21, 1991 a workshop sponsored by the National Science Foundation on Soil Improvement and Foundation Remediation with Emphasis on Seismic Hazards was held at the University of Washington in Seattle. The objective of the workshop was to provide a forum for the exchange of information and experience among experts with a wide variety of viewpoints and perspectives on soil improvement and foundation remediation as well as geotechnical earthquake engineering. Invited participants included consulting geotechnical and structural engineers, specialty contractors, engineers representing all levels of government, and academic researchers.

The specific goals of the workshop were (1) to summarize the current state of knowledge concerning soil improvement and its applicability to foundation remediation for various geotechnical hazards, especially those which are earthquake-induced; (2) to identify current research needs in these areas; and (3) to recommend future directions for research on soil and foundation remediation. This report is a written record of the workshop deliberations and its attempt to meet these goals.

The report begins with an introduction providing some background and organizational details of the workshop. Chapter 2 is an overview of the seismic hazards of liquefaction, ground shaking, and foundation, slope and retaining structure failures, along with a brief discussion of soil improvement and foundation remediation techniques for mitigation of these hazards.

Chapter 3 describes all the common soil improvement and foundation remediation techniques in terms of their current practice and illustrated by case histories, historical use, observed effectiveness, and current levels of confidence in their results. Included are (1) densification techniques (dynamic compaction, vibro compaction and vibro replacement, compaction grouting, blasting, and compaction piles); (2) drainage techniques (interception, pore pressure control, dewatering, and acceleration of consolidation); (3) physical and chemical modification techniques (grouting, soil mixing); (4) inclusion techniques (soil nailing, metallic and geosynthetic reinforcement, piles, and stone columns); and (5) structural foundation remediation techniques.

Verification of the effectiveness of soil improvement and foundation remediation techniques is addressed in Chapter 4. Included is a discussion of geophysical testing techniques which hold considerable promise in this area of verification. Research needs are described and prioritized in Chapter 5. Chapter 6 gives some suggestions as to how future research in soil improvement and foundation remediation might be directed and improved.

Probably the most important product of the workshop is a prioritized list of specific research needs for densification, drainage, physical and chemical modification, inclusions, and foundation remediation techniques. This list was carefully developed by an inter-

disciplinary group of experts with a broad range of experience and perspective.

There are tremendous benefits to increasing industry-university cooperative research on soil improvement and foundation remediation techniques, and such cooperation should be strongly encouraged. The developing National Test Sites program for Geotechnical Experimentation appears to provide an excellent framework for sharing research costs and results in this area.

The results of future research on soil improvement and foundation remediation techniques will lead to their more widespread acceptance in practice, and to their more reliable and economical use. §

Acknowledgments

This workshop was made possible by grant BCS-9107767 from the U.S. National Science Foundation, Siting and Geotechnical Systems/Earthquake Hazard Mitigation Program, Dr. Clifford J. Astill, Director, and the Geomechanical, Geotechnical, and Geo-Environmental Systems Program, Dr. Mehmet T. Tumay, Director. This support is gratefully acknowledged. We especially appreciate the encouragement and ideas provided by Drs. Astill and Tumay, both while we were planning the workshop and at the workshop itself.

The Organizing Committee consisted of Dean G. W. Clough (Virginia Polytechnic Institute), Mr. Edward D. Graf (Grouting Consultant), Dr. Richard H. Ledbetter (USAE Waterways Experiment Station), Mr. Joseph P. Welsh (Hayward Baker Co.), and ourselves. This committee selected the workshop participants and assisted in the initial planning. In addition, Ledbetter and Welsh did double duty as Discussion Group Leaders, for which we are grateful. We also thank the other Discussion Group Leaders for not only summarizing all the participants' reports, but also for ably leading their respective discussion groups.

A number of UW staff and graduate students assisted with various aspects of the workshop. Ms. Ellen Barker of Engineering Continuing Education and Dr. Ron Bucknam of the Department of Civil Engineering took care of many of the local arrangements. Our secretaries, Ms. Carole McCutcheon and Ms. Gretchen Carlson provided their usual competent help before, during, and after the workshop. Ms. Carlson also prepared the text of the final report. Our graduate students, Amy Beitel, Mathew Craig, Sujan Punyamurthula, Bonnie Savage, Nadarajah Sivaneswaran, Kandiah Sribalaskandarajah, Wen-Sen Tsai, and Jerry Wu served as discussion group reporters, secretaries, copiers and runners. Ms. Mary Marrah and Mr. Ron Porter of the Washington State Transportation Center took care of the final graphics, cover design, and printing of the report.

Mr. Juan Baez, Dr. Rudy Bonaparte, Prof. Roy Borden, Mr. Rich Faris, Dr. Gus Franklin, Prof. George Gazetas, Mr. Ed Graf, Dr. Richard Ledbetter, and Prof. Geoff Martin provided helpful comments on a draft of the report. Profs. Dick Woods and Jean Benoit kindly wrote sections of Chapters 4 and 6.

We thank all these persons for their contributions to this report and to the success of the workshop.

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1. Introduction

1.1 General

Over the past 25 years, the field of soil improvement has developed tremendously. This development has resulted from an improved understanding of geotechnical hazards and the factors that control them, the economic benefit of the development of sites with marginal to poor soil conditions, and from the use of innovative construction techniques developed primarily by specialty contractors. Most of the recent developments have been applied to foundation soils and sites prior to new construction, although a few traditional procedures (e.g., grouting) have a long history as a post-construction site and foundation remediation technique. While remediation of existing structures, particularly with respect to seismic hazards, has received considerable attention in recent years, foundation remediation has been comparatively neglected. It is possible that some of the recently developed soil improvement techniques might, with appropriate research and development, also be suitable for remediation of existing foundations. With this in mind, the summer of 1991 appeared to be an opportune time for a careful examination and evaluation of soil improvement and foundation remediation techniques to set the stage for efficient and productive future research in the area.

On August 19-21, 1991 a workshop on Soil Improvement and Foundation Remediation with Emphasis on Seismic Hazards was held on the University of Washington campus in Seattle, Washington. The workshop was sponsored by the National Science Foundation with support from both the Siting and Geotechnical Systems program, Dr. Clifford J. Astill, Director, and the Geomechanics, Geotechnical and Geo-environmental program, Dr. Mehmet T. Tumay, Director. The workshop was attended by 35 engineers from the United States, Canada, and Japan. A roster of workshop participants can be found in Appendix A.

1.2 Background

Geotechnical hazards represent continuing threats to the performance of many types of structures and facilities. Certain hazards, such as expansive soils, act slowly and insidiously without recognition by the general public or policymakers, but cause tremendous localized economic losses year after year. Other hazards, such as earthquakes, act very quickly and dramatically causing highly publicized economic loss and loss of life or injury. Advances in the characterization of such hazards have allowed them to be identified and to be generally dealt with in a rational manner. In many instances, logistical or economic factors may require that the soil or foundation conditions at the site be improved to ensure satisfactory foundation performance.

Certain sites possess geographic location or other characteristics that significantly increase their economic value, even though subsurface conditions may be

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such that their proposed development is difficult and costly. The natur the geotechnical hazards is often rela the type of the proposed developm For example, port facilities are often sup ed on loose, saturated, cohesionless alluvial and fluvial soil deposits that may be subject to liquefaction. In such cases, soil improvement, foundation remediation or both are required to ensure satisfactory performance. Whether we are considering residential or industrial building sites or dam sites, the natural process of development tends to utilize the most easily developed sites first. Thus, as the 21st century approaches, geotechnical engineers are more and more frequently being challenged to develop poor and marginal sites. Since this trend can only be expected to increase, the need for improved methods of soil and foundation improvement is urgent. This need is especially urgent for existing structures founded on poor soils in hazardous locations. As knowledge of geotechnical and structural earthquake engineering has increased in recent years, so have the standards of performance. Adding to this are the increased expectations of the general public to be risk-free.

In contrast with many other aspects of geotechnical engineering, soil improvement techniques have developed largely due to the initiative and imagination of contractors. A relatively small number of specialty contractors have promoted many of the techniques now commonly used for soil and site improvement. While these techniques have proven to be very effective, most have been developed by empirical trial and error testing, and the mechanisms by which they work are not clearly understood by all practicing engineers. Thus their selection, design and utilization may not be the most efficient or economical for the soils or structure under consideration. Research in this area, especially applied to remediation of existing structure foundation is clearly required.

No National Science Foundation workshops had previously been held in the United States or Canada on the specific topic of soil improvement and foundation remediation. Workshops on related topics have been held on siting and geotechnical systems (Illinois Institute of Technology, 1986), dam failures (Purdue University, 1988), national geotechnical test sites (University of New Hampshire, 1989), and site characterization (University of California at Davis, 1990). Related conferences include the Symposium on Soil Improvement — A Ten Year Update held at the ASCE Convention in Atlantic City in 1987, several on geosynthetics, the ASCE Foundations Congress at Northwestern University in 1989, and the ASCE specialty conference on Grouting, Soil Improvement, and Geosynthetics in New Orleans in 1992.

1.3 Objectives

The scope of the Workshop on Soil Improvement and Foundation Remediation with Emphasis on Seismic Hazards was quite broad. Because experience with non-seismic hazards and their related mitigation techniques is so extensive, the treatment of seismic hazards and the foundation soil remediation techniques available to mitigate them was emphasized. Issues were addressed from the standpoint of the hazards themselves, available mitigation techniques of all types, the hazards for which they are applicable, and the likely feasible mitigation measures.

The objective of the workshop was to provide a forum for the exchange of knowledge and experience among experts with a wide variety of viewpoints and perspectives on soil improvement and foundation remediation as well as geotechnical earthquake engineering. The specific goals of the workshop were (1) to summarize the current state of knowledge concerning soil improvement and its applicability to foundation remediation for various geotechnical hazards, especially those which are earthquake-induced, (2) to identify and evaluate current research needs and opportunities in these areas, and (3) to recommend future directions for research on soil and foundation remediation.

1.4 Workshop Organization

Because of the interdisciplinary nature of the topic, the workshop participants invitation list was designed to provide a broad range of experience and perspective. Invitations were divided nearly evenly among academic researchers, government agency engineers, contractors, and consulting engineers.

Because of the breadth of the topics to be considered and the diversity of backgrounds and interests of the invited participants, the workshop was organized in a way to encourage productive interaction and active participation among all attendees.

Discussion groups were formed to address both hazards (static and seismic) and soil improvement and foundation remediation techniques. Discussion leaders, each of whom was a recognized authority in the topic of that group, were assigned to each discussion group. Each participant sat on one hazards discussion group and one techniques discussion group. The participants were shifted around in the hazards and techniques discussion groups, i.e., members of a particular hazard discussion group were distributed among all of the techniques discussion groups and vice versa. This format allowed each participant to interact with as many other participants as possible.

The makeup of the various discussion groups was as shown below.

Prior to the workshop, each participant was asked to prepare a brief (2-3 page double spaced) report on the application of a particular class of techniques to a particular class of hazards. These reports were to discuss the current state of knowledge regarding the applicability of the technique to the hazard (including both advantages and limitations), and methods for verification of improvement or remediation effectiveness. The reports were also to list, where possible, examples (referenced case histories) of good and/or poor performance of the technique to the hazard, and to discuss research needs and opportunities. These short reports were assembled and summarized by the discussion group leaders with the summaries and individual reports made available to all participants for review at the time of workshop registration. They provided a good starting point for discussions in the discussion groups and for the written reports produced by each discussion group.

Hazards Discussion Groups	**Liquefaction**	**Ground Shaking**	**Foundation Failure**	**Slope/Ret. Structures**
	Martin*	Ledbetter*	Woods*	Bonaparte*
	Baez	Abghari	Darragh	Collin
	Denby	Anderson	Faught	Faris
	Finn	Koga	Gazetas	Forrest
	Kilian	Lum	Ho	Holtz
	Yang		Taylor	Ng
	Stevens		Mayne	Wightman
			Franklin	
	* Discussion group leader		Graf	
			Manning	

Techniques Discussion Groups	**Densification**	**Drainage**	**Phys/Chem Mod.**	**Inclusions**	**Foundation Rem.**
	Welsh*	Holtz*	Borden*	Finn*	Franklin*
	Mayne	Baez	Abghari	Collin	Anderson
	Stevens	Bonaparte	Faris	Denby	Darragh
	Wightman	Ho	Faught	Forrest	Kilian
		Koga	Yang	Gazetas	Ng
		Benoît	Graf	Lum	
	* Discussion group leader		Woods	Manning	
				Taylor	

Workshop Schedule

Date	Time			Activity
Mon., August 19	7:30	-	8:00	Registration
	8:00	-	8:20	Welcoming remarks and workshop introduction
	8:20	-	9:00	Overview of seismic hazards — Prof. S. Kramer
	9:00	-	9:30	Overview of dynamic foundation response — Prof. G. Gazetas
	9:30	-	9:45	National geotechnical test sites program — Prof. J. Benoit
	9:45	-	10:00	Break
	10:00	-	12:00	Hazards discussion groups meetings
	12:00	-	1:00	Lunch
	1:00	-	1:30	Hazards discussion groups meetings
	1:30	-	2:45	Plenary session — hazards discussion groups reports
	2:45	-	3:00	Break
	3:00	-	5:00	Techniques discussion groups meetings
Tues., August 20	8:00	-	9:45	Techniques discussion groups meetings
	9:45	-	10:00	Break
	10:00	-	12:00	Plenary session — techniques discussion groups reports
	12:00	-	1:00	Lunch
	1:00	-	2:45	Hazards discussion groups written report preparation
	2:45	-	3:00	Break
	3:00	-	5:00	Techniques discussion groups written report preparation
Wed., August 21	8:00	-	9:45	Techniques discussion groups written report preparation
	9:45	-	10:00	Break
	10:00	-	11:50	Plenary session — general discussion
	11:50	-	12:00	Closing remarks and adjournment

The workshop schedule was broken into a series of sessions that took place over a 2.5 day period. The workshop schedule was as shown above.

The purpose of the hazards discussions was to set the stage for productive discussions of soil improvement and foundation remediation techniques. Consequently, more workshop time was devoted to the techniques discussions than to the hazards discussions.

1.5 Organization of Report

This report summarizes the current state of practice in soil improvement and foundation remediation for seismic hazards, and presents the discussions and conclusions of the various discussion groups. It relies heavily on written reports prepared during the workshop by each of the discussion groups, but is not simply a compilation of those reports. Draft copies were reviewed and edited by the members of the organizing committee and each of the discussion group leaders prior to publication. Some sections of the report were also reviewed by various members of the discussion groups.

Chapter 2 presents an overview of seismic hazards and their causes, and discusses the requirements of soil improvement and foundation remediation techniques for mitigation of these hazards. Chapter 3 describes current soil improvement and foundation remediation techniques in terms of their historical use and effectiveness, and the existing levels of confidence in their results. The issue of verification of the effectiveness of soil improvement and foundation remediation techniques is addressed in Chapter 4. Research needs are described and prioritized in Chapter 5, and future directions for research in soil improvement and foundation remediation are discussed in Chapter 6. A summary and the conclusions of the workshop are presented in Chapter 7.§

2. Overview of Seismic Hazards

2.1 Introduction

A great number of geotechnical hazards have been associated with seismic activity. These hazards have historically resulted in considerable geotechnical damage, but have also strongly influenced other types of damage such as collapse of buildings, bridges, and dams, destruction of lifelines, and initiation of fires. These hazards may be broadly divided into those primarily associated with ground shaking and those associated with soil deformation. However, for purposes of workshop organization, hazards were considered to be those associated with liquefaction, ground shaking, foundation failure, and slope and retaining structure failure.

In order for soil improvement or foundation remediation techniques to mitigate these hazards, their causes must first be understood. Some hazards may be attributed to a single cause, others may have several potential causes. In some cases, the causes of the hazard are relatively straightforward, in others the cause may be unclear. Further research into the causes of various geotechnical seismic hazards is in progress and the results of that research will undoubtedly influence the practice of soil improvement and foundation remediation. This chapter presents an overview of seismic hazards with examples of their effects, and discusses their causes as currently understood by the geotechnical engineering profession.

2.2 Ground Shaking

Ground shaking hazards may be described as those that lead to the excessive response of soils and structures to earthquake motions. Ground shaking effects are implicit in all geotechnical seismic hazards since it is the shaking that leads to the development of the hazards. Ground shaking characteristics can be broadly divided into three categories — ground motion amplitude, frequency content, and duration of strong ground shaking — and the related hazards can be interpreted in terms of these categories.

1. *Excessive ground motion amplitude*

Amplitude can be expressed in terms of acceleration, velocity, or displacement. Large ground motion amplitudes can lead to damage to various types of structures located on or within a soil deposit. Large forces may be induced in relatively stiff (low natural period) structures by high acceleration amplitudes, while damage to more flexible (higher natural period) structures may be less influenced by acceleration amplitude than by velocity or even displacement amplitude.

While ground motions are typically described at a single point, they actually vary both vertically and horizontally. Structures of long horizontal extent, such as bridges or dams, or structures that extend over considerable ranges of depth, such as shafts or piles, may be subjected to differential ground motions. The differential motions, whether caused by travelling wave effects or material and geometric heterogeneity, can induce response that is different from that predicted with the common assumption of coherent ground motion.

Ground shaking can also lead to permanent deformations of slopes, retaining structures, foundations, etc.; however, these hazards will be discussed in other sections of this report.

2. *Unfavorable frequency content of the ground motion*

The dynamic response of structures, whether building- or bridge-type structures or geotechnical structures such as slopes, retaining walls and dams, is influenced by the frequency content of the imposed loading. The geometry and material properties of a soil deposit combine to form a "filter" to incoming seismic waves that can allow some frequencies to be amplified while others are attenuated. The process is often complicated, but the effects of soil conditions on the frequency content of ground motion are now fairly well established.

3. *Excessive duration of strong ground motion*

The duration of strong ground shaking is most strongly influenced by earthquake magnitude, however, it has also been shown to be influenced by local soil conditions (Chang and Krinitszky, 1977). Certain types of structures, and certain types of soil deposits, accumulate damage with increasing number of cycles or stress reversals. In such cases, the duration of strong ground motion can become very important.

2.2.1 Examples

The influence of local soil conditions on levels of ground shaking has been illustrated on many occasions. The report of the 1906 San Francisco earthquake (Wood, 1908) stated that the observed level of damage was primarily associated with the underlying geologic conditions. In the 1957 San Francisco (Idriss and Seed, 1968), illustrated in Figure 2.1, and 1967 Caracas earthquakes (Seed and Alonso, 1974), strong motion instruments recorded significant differences in ground motion amplitude and frequency content for sites on rock and/or shallow, stiff soil deposits than for sites on thick deposits of soft soil. In 1985, a large earthquake off the Pacific coast of Mexico induced modest accelerations in hard soils in and below Mexico City, some 350 km away. In the parts of Mexico City where the hard soil was overlain by 35 to 40 m of soft clay, however, ground surface accelerations were nearly five times higher, and structures with natural periods equal to the predominant period of the soft clay (and with typical damping characteristics) were subjected to horizontal accelerations approaching 1 g, as shown in Figure 2.2. In the 1989 Loma Prieta earthquake in the San Francisco Bay area, ground motions at soft soil sites, where considerable damage to bridges and viaducts was observed, were significantly greater than those recorded at rock and stiff soil sites (Figure 2.3).

The term "soil amplification" has been coined to describe the filtering that seismic waves undergo as they pass through the soil. On the other hand, soil filtering might also depress those harmonic components of the incident seismic wave whose frequencies substantially exceed the natural frequencies of the soil deposit. De-amplification of shaking is thus also possible. Documented case histories of de-amplification of seismic motion by soft/loose soil layers have been presented by Seed and Idriss (1970) and Gazetas, et al. (1990).

2.2.2 Causes

Excessive levels of ground shaking are caused by the response of geologic materials of various geometries and material properties to excitation from an earthquake source. The energy released by the earthquake is largely manifested as seismic waves that propagate away from the source. These waves travel through various geological materials producing ground motion that varies, due to geologic structure and radiation and material damping, with distance from the source. The resulting excitation at the base of a soil deposit is a function of, among other things, source

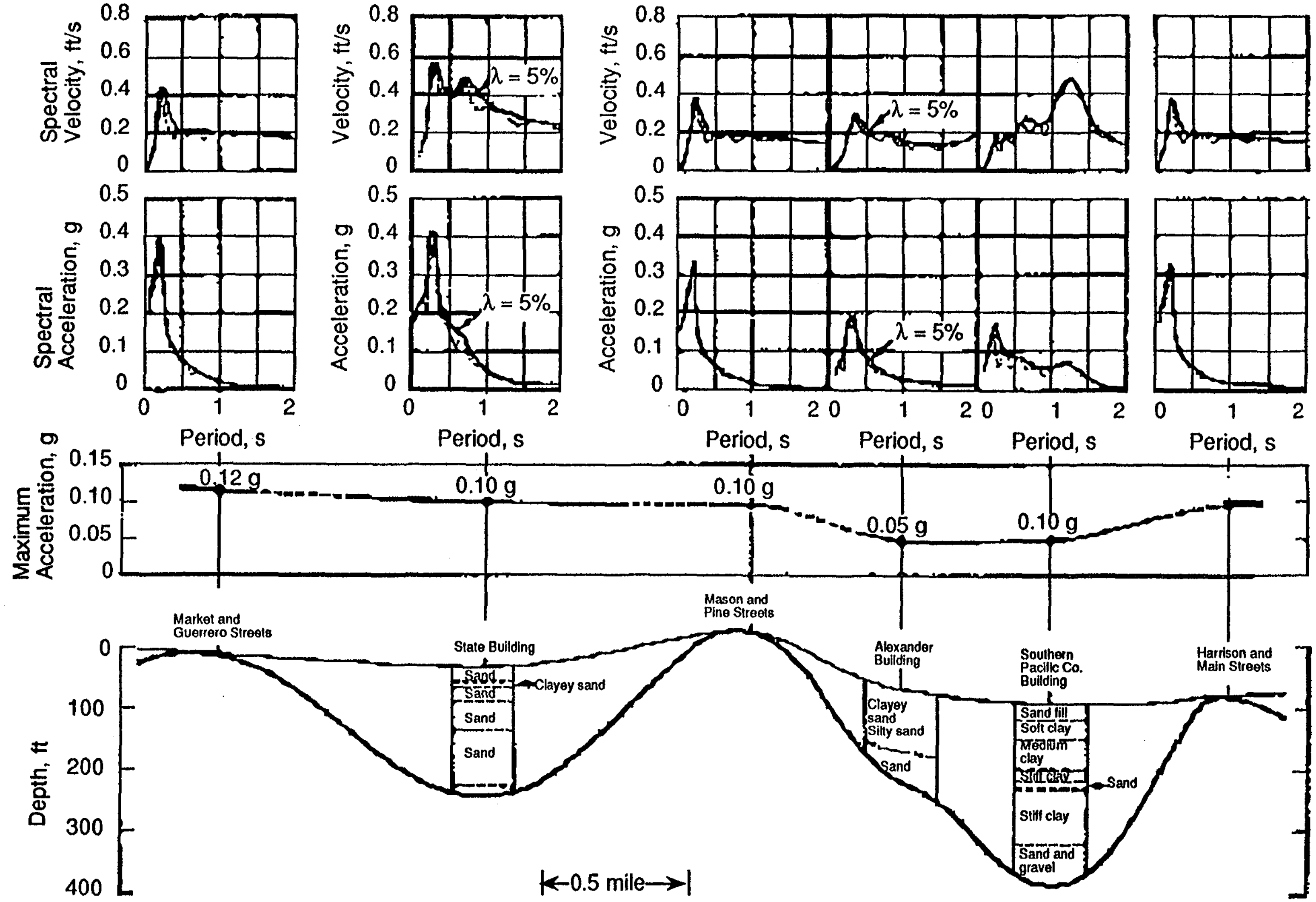


Figure 2.1. Variation of ground shaking characteristics at different soil profiles in 1957 San Francisco earthquake (after Idriss and Seed, 1968).

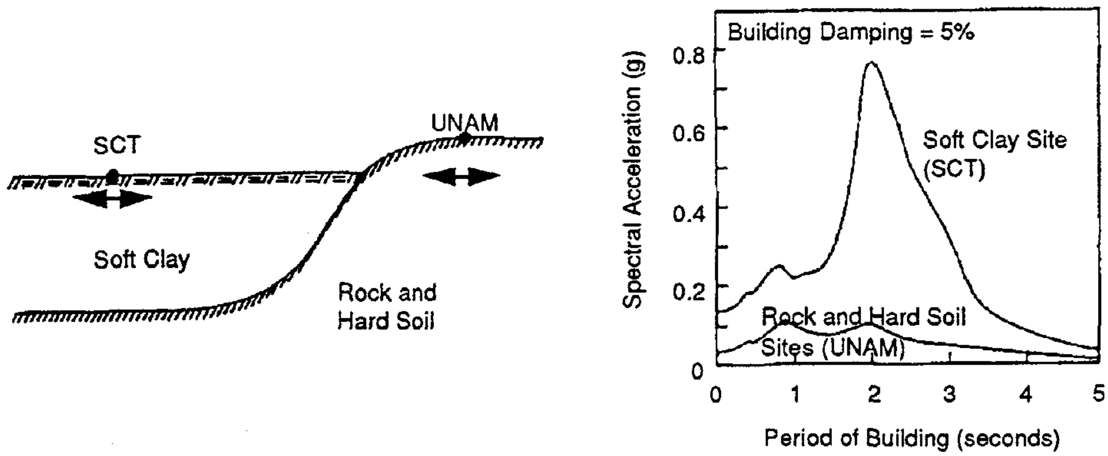


Figure 2.2. Comparison of response spectra for rock and soft clay site in Mexico City (after Dobry and Vucetic, 1987)

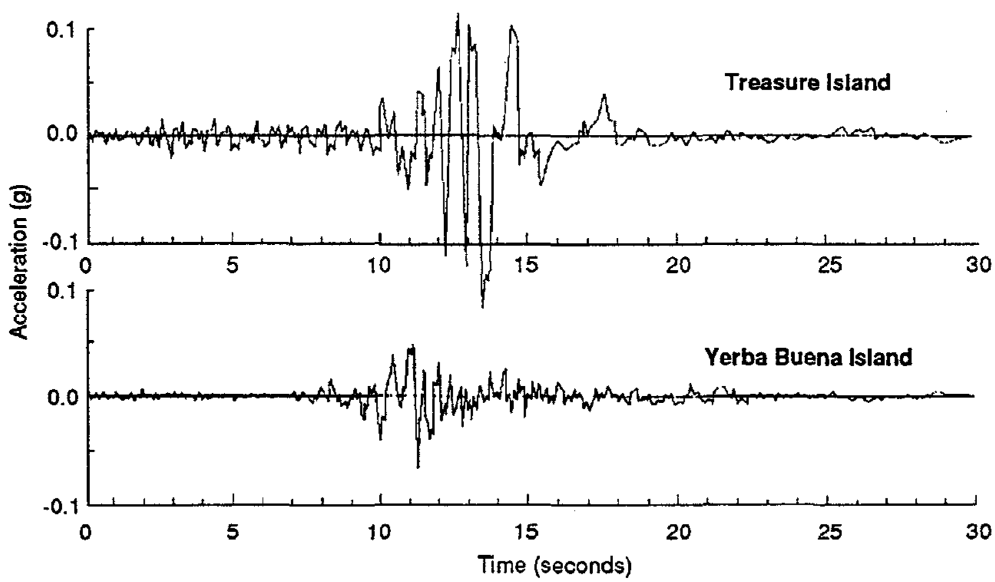


Figure 2.3. Accelerograms for Yerba Buena Island (rock outcrop) and adjacent Treasure Island (soft soils) in 1989 Loma Prieta earthquake (after Housner, et al., 1990)

mechanism, source geometry and orientation, earthquake magnitude, and travel path characteristics.

When these seismic waves reach the soil/bedrock interface near a site of interest, they impose a form of loading on the soil deposit at the site. The response of the soil deposit is influenced by its geometry and by the material properties of the soil. The material properties that control the dynamic response of the soil are density, stiffness, and damping characteristics. Of these, the response is far more sensitive to stiffness and damping than to density. Contrasts between properties at various layer boundaries also influence the nature of shaking at the ground surface.

2.2.3 Mitigation

Modification of soil properties, particularly of the soils nearest the ground surface, will change the ground motion characteristics during an earthquake. It is important to note, however, that the effects of soil modification on ground shaking hazards are not like the effects on the other hazards described in this report. When soil modification techniques are used for mitigation of the other hazards, e.g., liquefaction, foundation failure, slope and retaining structure failure, etc., they are intended to increase the soil resistance to the hazards. They tend to move the "state" of the soil from a condition that may be close to failure to a new state further from failure. Ground shaking hazards, on the other hand, do not generally involve failure. Rather than moving the state of the soil farther from or closer to a failure state, soil modification results in some alteration of the ground motion characteristics. The effects of such alteration may, depending on the characteristics of the site and any structures on it, not always be beneficial. Thus, mitigation of ground shaking hazards represents a complex and difficult task.

2.2.4 Discussion

Ground shaking hazards affect structures (including earth structures) and facilities founded on, within, and adjacent to the problem ground. Ground shaking, and consequently the resulting damage, is highly dependent on site geology, soil conditions, earthquake characteristics, and structural response characteristics. All methods for evaluation of hazards and all designs for hazard mitigation are critically dependent on the anticipated level of ground shaking; yet ground motions are probably the single largest unknown in earthquake analyses. Methods for characterizing ground motions with respect to their potential for inducing geotechnical hazards are urgently needed.

Additional research on dynamic properties of soils, particularly for gravels, silts, and very soft organic soils, is also needed. Advancements in methods of ground response analysis, including the proper consideration of topography and ground motion coherence, will also provide significant benefits in the identification and evaluation of geotechnical seismic hazards, and in the design of measures for mitigation of those hazards.

2.3 Liquefaction

Liquefaction is a process by which the shearing resistance of a loose, saturated, cohesionless soil is reduced by the buildup of excess porewater pressure. Liquefaction can occur under static loading conditions (Terzaghi, 1956) but is more commonly associated with earthquake activity (Seed and Idriss, 1967; Seed, 1968; Ambraseys and Sarma, 1969; National Research Council, 1985). The hazards associated with liquefaction can be grouped into four main categories for level or near level ground:

1. *Surface manifestation effects*

Subsurface liquefaction often manifests itself on the ground surface in the form of sand boils, ground cracking, or ground lurching. Such effects can result in loss of bearing capacity, structural damage due to differential displacement, foundation uplift, and ground settlement.

2. *Post-liquefaction settlement*

Even for cases where surface manifestation effects do not occur, post-earthquake dissipation of high excess pore pressures in the subsurface soils may cause excessive settlement. Post-liquefaction settlement generally increases with decreasing soil density and increasing thickness of liquefied zones.

3. *Lateral Spreads*

For gently sloping ground or where liquefiable strata "daylight" in river banks, the low residual undrained shear strength of a liquefiable shallow, superficial soil may result in the accumulation of lateral ground displacements during earthquake shaking. Such displacements will usually cease at the end of the earthquake, and are generally characterized by surface ground cracking and differential ground movement. Displacements may range from a few centimeters to several meters.

4. *Flow Slides*

Where residual undrained shear strengths of liquefied soils are less than the static shearing stresses required for equilibrium in sloping ground, very large lateral deformations may occur. In some cases, due to the effects of post-earthquake redistribution of excess pore pressure, such flow slides may be triggered after the earthquake event.

2.3.1 Examples

The effects of liquefaction were first brought to the attention of most geotechnical engineers in 1964 by the dramatic failures at Niigata, Japan (Japan National Committee on Earthquake Engineering, 1965; Yamada, 1966; Yokomura, 1966) and Anchorage, Alaska (Ross, et al., 1969; Seed and Wilson, 1967; Scott, 1973) during separate earthquakes. In the Niigata earthquake, widespread liquefaction occurred in low-lying areas of the city causing widespread damage as illustrated by the well-known photograph of Figure 2.4. Liquefaction caused bearing failure of foundations for buildings and bridges and failure of quay walls. Lateral spreading of liquefied soils damaged bridge approach embankments, buildings, buried structures and pipelines. The Good Friday earthquake in Alaska caused localized landslide damage in Anchorage and

Figure 2.4. Tilting of apartment building in Niigata, Japan (after Seed and Idriss, 1982)

a massive flow slide in the Turnagain Heights area of Anchorage shown in Figure 2.5. Additional liquefaction failures produced considerable damage to port and waterfront facilities of Seward and Valdez.

Liquefaction failures have been observed on many occasions and at many locations since 1964, most recently in the San Francisco Bay area during the 1989 Loma Prieta earthquake (Housner, et al., 1990). Widespread liquefaction in natural and man-made soil deposits was responsible for much of the damage sustained in the earthquake.

2.3.2 Causes

The causes of liquefaction of saturated cohesionless soils due to earthquake induced cyclic loading are fairly well understood and have been documented in a comprehensive manner in a National Research Council (1985) report. Basically, liquefaction is caused by the buildup of excess pore pressure associated with cyclic straining induced by earthquake shaking. This buildup of pore pressure results from the tendency of liquefiable soils to densify, or contract, upon shearing. Evaluation of liquefaction hazards has historically developed along two lines — evaluation of the potential for initiation of liquefaction and evaluation of the stability of liquefied soils. The former approach involves careful consideration of the process of pore pressure generation that occurs at relatively low strains, while the latter is concerned with the residual, or steady state, strength mobilized at large strains. Currently, the factors influencing, and consequently the procedures for evaluation of, the initiation of liquefaction are better understood than those influencing the residual strength of liquefied soil. Regardless, the application of soil improvement techniques to liquefiable soils will influence both the potential for initiation of liquefaction and the residual strength of the soil.

Figure 2.5. The Turnagain Heights landslide near Anchorage, Alaska (after Seed and Idriss, 1982)

2.3.3 Mitigation

Methods for mitigation of hazards associated with the occurrence of liquefaction can deal directly with the factors that cause liquefaction to be initiated, or they can address the potential effects of liquefaction. Most mitigation techniques, however, influence both.

Liquefaction is triggered by the buildup of positive excess pore pressures; consequently, methods for prevention of its occurrence must reduce the tendency for buildup of these excess pore pressures. Reduction of pore pressure generation can be accomplished in a number of different ways, including:

1. *Densification*

Since the tendency for pore pressure buildup is strongly related to the density of the soil, increasing its density will decrease the tendency for positive pore pressure buildup and consequently reduce liquefaction potential. Densification will also increase the residual strength of the soil, thereby reducing the effects of any liquefaction that should occur. Densification has historically been the most commonly used technique for improvement of liquefiable soils. However, its application to mitigation of liquefaction hazards in areas of existing structures and utilities is limited by the tolerance to the settlements inevitably associated with densification.

2. *Drainage*

Since the process of liquefaction involves the buildup of excess pore pressures, mitigation of liquefaction hazards can also be accomplished by the provision of drainage within the liquefiable soil. A drainage path extending through a liquefiable soil layer allows water to flow from the layer when excess pore pressures are generated. Such flow reduces the pore pressures in the liquefiable layer and increases the density of the soil in that layer both during and after the earthquake. Some amount of settlement, which may be intolerable in some instances, may be associated with this drainage. Though some soil improvement methods, e.g., stone columns, introduce drainage paths into liquefiable soils, it is often the densification associated with their installation rather than their drainage capabilities that is relied upon for mitigation. Alternatively, the generation of excess pore pressures can be greatly retarded by reducing the degree of saturation of the soil.

3. *Chemical Modification*

The tendency for contraction of a loose soil, and hence for pore pressure buildup, could also be reduced by increasing the strength of particle-to-particle contacts. Strengthening these contacts by chemical means will increase both the stiffness and the strength of the soil, thus reducing the amplitude of cyclic strains and the contractive tendency of the soil.

Combinations of two or more of the above methods, or perhaps the development of new and innovative methods, can also be used to mitigate liquefaction hazards. In some cases, it may be more economical to undertake mitigation measures that limit the damaging effects of liquefaction. This is most readily accomplished by increasing the residual strength that the soil would have if it were to liquefy, most commonly by densification. The use of stabilizing buttresses and berms or structural inclusions, however, may also be used to prevent large deformations of liquefied soil.

2.3.4 Discussion

Mitigation of liquefaction hazards is often expensive and evaluation of its necessity is critically dependent on understanding of and reliable assessment of both the causes and the potential effects of liquefaction. A great deal of research has addressed these latter issues, however, empirical methods based on case histories (aided and retained by theoretical and experimental data) currently form the backbone of design approaches for assessing both the potential for liquefaction hazards and for acceptance of design criteria for soil improvement or foundation remediation techniques.

In order to improve methods for identification and evaluation of liquefaction hazards, additional research is needed. Seismically induced pore pressure generation in clean sand is reasonably well understood; our understanding of the pore pressure response of gravels and silty and clayey sands is not as well established. Incorporation of earthquake-induced pore pressures in stability analyses is not done uniformly, nor does there exist a consistent definition of a factor of safety against liquefaction. In addition, due to complex geology and hydrogeology, the prediction of seismically-induced pore pressures in natural slopes is uncertain. Though lateral spreading of such slopes has caused considerable damage in past earthquakes, it has been poorly understood until relatively recently (Youd and Perkins, 1987; Dobry and Baziar, 1992). Improved methods for identification of liquefiable soils, particularly when they occur in thin lenses or seams, are needed. Further development of in situ test methods is likely to contribute to improved capabilities in this area. Advances in characterization of the residual strength of liquefied soils are also needed.

Additional research, in the form of field investigations and instrumentation of liquefaction-susceptible sites and laboratory investigations such as the NSF-supported VELACS project, will allow improved understanding of the liquefaction process. Such research is needed to improve the accuracy of liquefaction evaluation methods and the economy and reliability of liquefaction hazard mitigation techniques.

2.4 Foundation Failure

The performance of foundations during earthquakes is critical to the performance of the structures they support. Foundation failure hazards are most conveniently classified under the traditional foundation categories of deep foundations and shallow foundations. Deep foundations consist of relatively slender structural members that transfer load from the base of a superstructure to deeper soils with greater supporting capacity, or that develop supporting capacity along their length. Shallow foundations derive support from the soil immediately below the structure.

Satisfactory performance of deep foundations during earthquakes requires that they not deflect excessively during the earthquake, and that they retain their supporting capacity after the earthquake. They must therefore, provide sufficient resistance to both lateral and axial loads. Foundation failures may therefore be categorized as hazards associated with capacity, settlement, and dynamic response.

1. Capacity

Pile-supported structures usually have a high factor of safety against failure due to downward-acting vertical loads. Consequently, failure or excessive deformation of piles in compression is unusual. Research and experience have also indicated that pile buckling is virtually impossible, even when the piles extend through very weak materials. Earthquake-induced ground motions may also induce bending and torsional loading in individual piles, particularly near the interface between very soft and very stiff soils. However, their effects in pile groups are generally less significant than the effects of lateral and axial loading since pile groups are able to mobilize resistance to overturning moments through their axial capacities (Figure 2.6). When overturning moments on pile groups are large, some piles may be required to resist tensile, or uplift, loads. Uplift loads are generally more critical than downward-acting loads, both with respect to the pullout capacity of the soil/pile system and with respect to the structural capacity of the pile/pile cap system itself.

Since earthquakes primarily impart horizontal accelerations, the lateral resistance of soils surrounding deep foundations may be fully mobilized, particularly in loose or compressible zones near the ground surface. In loose sands below the groundwater table, partial or complete liquefaction may result in a dramatic loss of lateral resistance. Movements

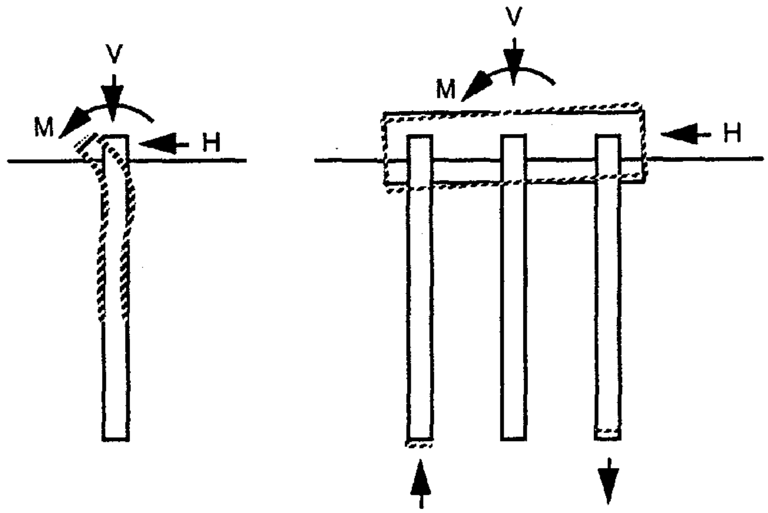


Figure 2.6. Mobilization of resistance to vertical, lateral, and overturning loads by a single pile and a pile group (resistance to overturning of pile group induces vertical and uplift loads in exterior piles)

of liquefied soil, or of non-liquefied soil "floating" on liquefied soil, can impose large lateral loads on foundations. In soft clays, particularly those which are sensitive, seismic motions may propagate as mud waves with considerable lateral flow and spreading, and this may cause excessive horizontal movement at the pile heads. Overstressing may also result from large bending moments induced in the foundation elements.

Shallow foundations are typically designed with large factors of safety against bearing capacity failure. Consequently, they are usually able to resist transient increased loads without distress, as long as the supporting capacity of the soil is maintained. Seismically induced reduction of shallow foundation bearing capacity can result from build-up of excess pore pressures in saturated granular soils and from a possible reduction in shear strength of cohesive soils (i.e., cyclic degradation). On the other hand, the current practice in the construction of storage tanks is to design the foundation with a factor of safety of about one, though subsequent water testing of the tank may cause consolidation that increases the factor of safety against bearing failure. This design practice, however, can leave storage tanks in a potentially vulnerable state with respect to earthquake loading.

2. *Settlement*

Structures properly supported on deep foundations are normally not prone to large settlements during or after an earthquake, but connected appurtenant facilities that are not similarly supported may settle significantly. The resulting differential settlements may be damaging to the connected facilities. Those include lifeline items such as utilities (water, gas, sewer pipes, electrical cables, communications cables, etc.) and other important facilities such as stairways, access ramps, loading docks, etc. For a new structure, provisions for differential settlement can be readily incorporated in design; however, they may be difficult to accommodate economically in an existing structure.

Loose, dry sandy soils tend to contract, or densify, when subjected to ground shaking that exceeds the threshold shear strain. Saturated sands will also settle as a result of earthquake ground shaking, when excess pore pressures dissipate. Settlements can be very large if liquefaction occurs. Significant foundation settlements have also resulted from liquefaction-related lateral spreading of soils supporting shallow foundations. Thus, shallow foundations supported near the ground surface may experience both total and differential settlement due to seismic shaking. Even a few centimeters of settlement may cause of distress in some deformation-sensitive foundation systems.

Pile and sheet-pile driving has also been known to cause densification of loose sandy layers (Lacy and Gould, 1985; Picornell and del Monte, 1985). Ground surface settlement associated with such densification may have detrimental effects on sensitive neighboring structures or facilities.

Foundation settlement problems may also result from combinations of foundation types. Installation of new foundations adjacent to old or deep foundations next to shallow foundations may be subject to significant differential settlement. Such problems are well known for static conditions but may be exacerbated by the dynamic conditions associated with earthquake shaking.

With complete liquefaction of the surrounding foundation soil, buried facilities such as tanks and pipelines may become buoyant and float. The resulting differential movements can cause significant damage to connected appurtenant facilities. In extreme cases, buried structures can float to the ground surface (Seed and Idriss, 1967).

3. *Dynamic Response*

Foundations must often support instruments, equipment, or structures which are particularly sensitive to vibration at specific frequencies. When failure is interpreted as non-conformity of actual performance to some design criterion, excessive dynamic response of foundations may be considered as a potential mode of failure.

Batter, or inclined, piles are often included with vertical piles in a pile group to provide increased resistance to lateral loads. The seismic design of batter piles requires interaction between structural and geotechnical engineers. Their design in areas of high seismicity requires careful consideration of geotechnical factors including:

- the nature of the ground motions which will introduce bending, axial and lateral loads in the piles.
- the influence of the connection between the pile and the pile cap on the deformation characteristics of the pile.
- the increased lateral stiffness of batter piles that will stiffen the overall structure and probably induce higher seismic forces.

In most ground response and soil-structure interaction analyses, the common practice is to assume horizontal soil layers of infinite lateral extent. More often than not, however, the base layer is actually sloping as in the common case of bridge crossings of narrow rivers illustrated in Figure 2.7. The wave propagation phenomena in such cases are complicated. Waves striking the foundation come at various angles, directly or after multiple reflection, and include Rayleigh waves (Figure 2.7a). Even at sloping base angles of 10-20 deg, the motion induced on two sides of a foundation of large lateral dimensions will be of different amplitude and clearly will be out of phase. Differential foundation motions that cause unfavorable response of the structure-foundation system may result. Similarly, the kinematic deformations imposed on piles may be unfavorable. Figure 2.7(b) shows a well-instrumented case history involving a bridge foundation in Japan, (Gazetas, et al., 1992) underlain by a base slope of 15 deg, which clearly demonstrated this possibility through records of motion. Figure 2.7(c) shows a comparison of analytically predicted horizontal displacement profiles for one- and two-dimensional analyses near the edge of a soft soil deposit underlain by a sloping stiffer layer (Faccioli, 1991).

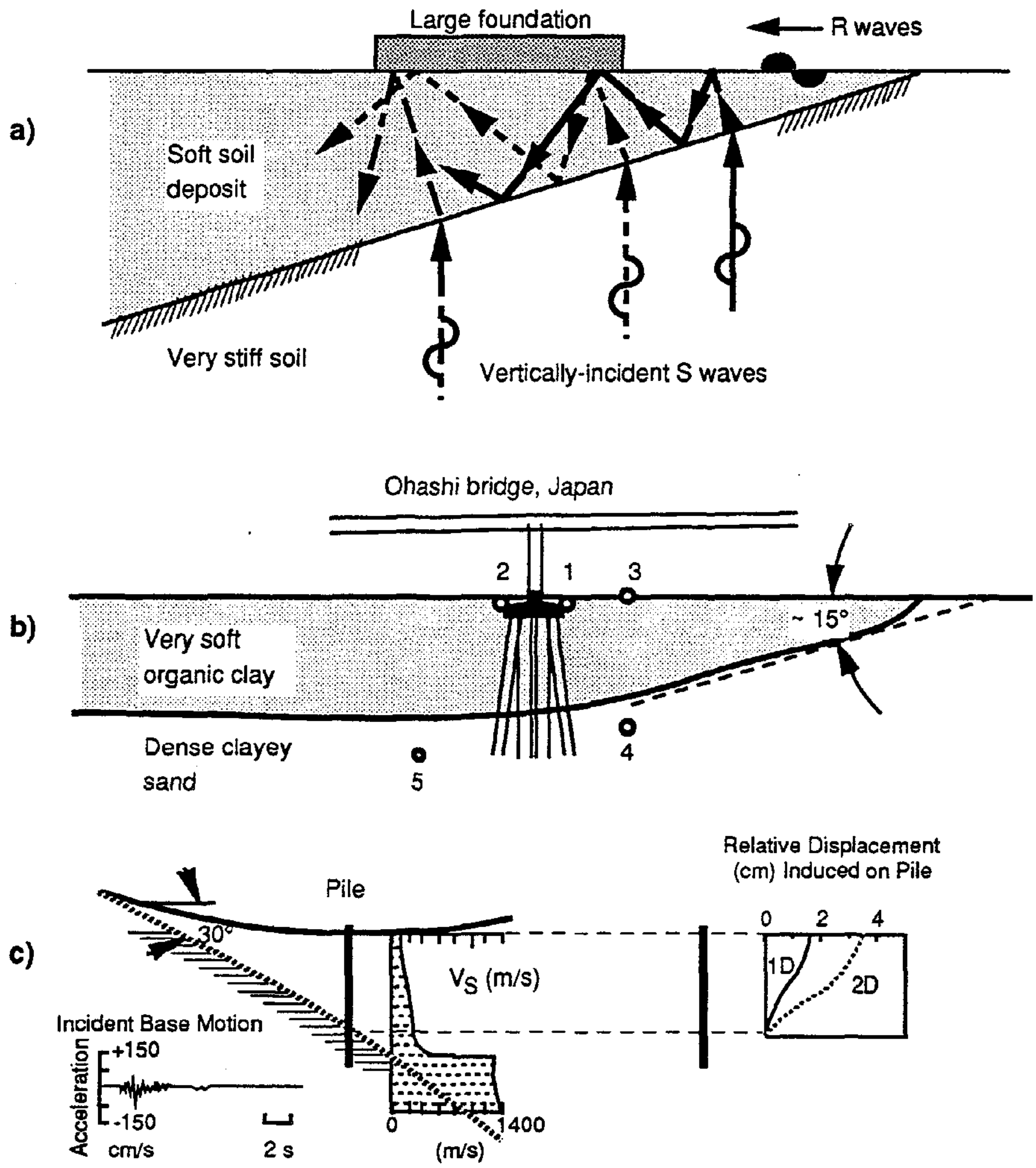


Figure 2.7. (a) Foundation on soil deposit underlain by sloping base layer; potential for differential excitation of the two sides

(b) Pile-group foundation in soft soil underlain by a sloping base; records at points 1, 2, 3, 4 and 5 reveal the strong influence of base slope ("2-D" effect) (from Gazetas, Fan, and Makris (1992) and Tazoh, et al. (1989))

(c) Calculated relative displacements induced on a pile embedded in a soil deposit underlain by steep rock (adapted from Faccioli, 1991)

2.4.1 Examples

Most examples of classical bearing capacity failures during earthquakes have been associated with liquefaction of near-surface soils. The overturned apartment buildings in Niigata, Japan, shown previously in Figure 2.4, provide the best known example of this type of failure.

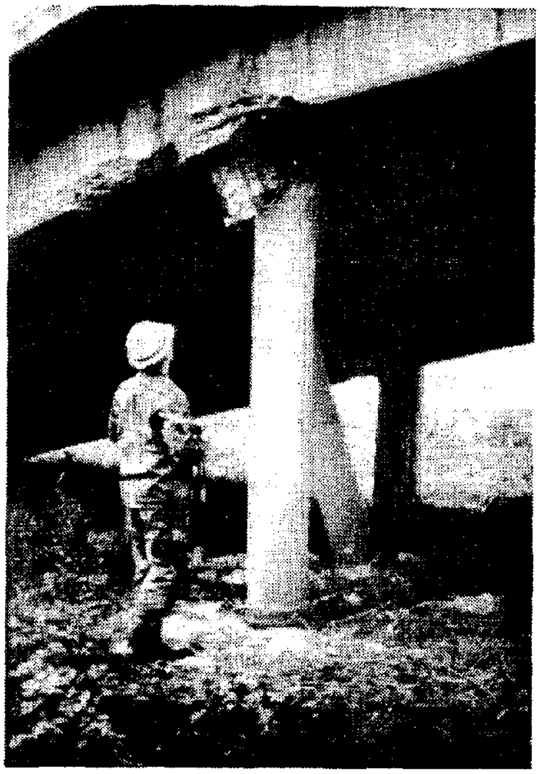
Treasure Island was formed in San Francisco Bay during the 1930s by placement of up to 90 feet of hydraulic fill over soft clay deposits. Over the years, light to moderately heavy structures have been built on the island using a variety of foundations including driven piles, stiffened shallow footings on fill densified by vibroflotation, displacement piles, or terraprobes, and conventional spread footings. There has been slow subsidence of the island due to consolidation of the underlying soft clay. During the 1989 Loma Prieta earthquake, sites where soil improvement had been performed did not experience differential settlement, lateral spreading, or sand boils, all of which were widespread over the rest of the island. Lateral spreading did occur adjacent to the shoreline slope. The site of the Medical/ Dental building, where vibroflotation had been performed, settled uniformly about 25 mm. The densified approach area near Pier 1 exhibited no signs of ground deformation while sand boils, sink holes, and spreading cracks developed in adjacent areas. Several buildings supported on conventional footings in areas where ground improvement had not been performed experienced significant differential settlement and foundation cracking. Pile supported buildings performed well but non-pile supported floors settled about 150 mm. Damage to buried utilities was extensive.

Failures of foundations due to lack of lateral or uplift resistance have also been observed. Sensitivity of the confining soil may also play a significant role in both lateral deformations and tensile capacity of the pile. For example, during the 1985 Mexico City earthquake, pile foundations were subjected to approximately 20 cycles of loading. Some of the soils in the vicinity of the piles were identified as having a sensitivity of about 15. After 2 or 3 cycles of loading, the cohesion of the soil significantly decreased, reducing the skin friction. This reduction resulted in a low pullout resistance. Resistance to lateral deformation was also most likely reduced.

Large lateral displacement of piles supporting the Struve Slough Bridges near Watsonville, California in the 1989 Loma Prieta earthquake (Housner, et al., 1990) caused excessive rotations at the bridge pier/deck connection. Each bridge consisted of a flat slab spans with approximately 22 bays of 11 m length, each supported on four Raymond step taper piles that were approximately 21 m long with 250 mm toes and 380 mm heads. The piles extended through a 11 m thick peat deposit and into a silty clay whose density increased with depth. A 3.6 to 4.6 m-long, 380 mm diameter circular concrete column extended up to the bridge deck. The extension and at least the top portion of the Raymond pile were reinforced with 4 to 6 No. 6 bars. After the earthquake, approximately 40% of the spans had separated from the piles or had broken the piles and fallen into the peat under the bridge (Figure 2.8).

Severe damage occurred at Berths 35-58 Public Container Terminal in Oakland due to the Loma Prieta Earthquake (Figure 2.9). Batter piles were badly damaged in the section below the deck in brittle shear partly as a result of insufficient confinement reinforcement. Settlement and lateral spreading of hydraulic placed fills behind a rock dike and loose saturated sands beneath the dike due to liquefaction contributed to the damage (Figure 2.10).

An example of foundation failure due to excessive settlement was the failure of prestressed tension piles under a drydock in Greece during a cluster of three earthquake shocks producing accelerations of 0.15 - 0.20 g each. The densification of a thick sandy layer under the drydock slab was one of the consequences of that failure (Tassios, 1987).



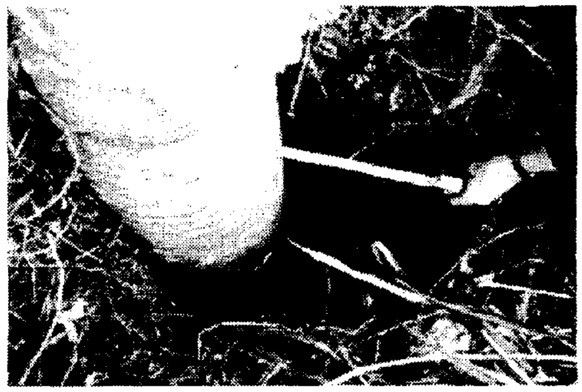


Figure 2.8. (a) Large lateral displacement of Struve Slough Bridge piles; (b) resulting damage to pier/deck connection (after Seed, et al., 1989)

2.4.2 Causes

There are a number of causes of foundation failure hazards. Some are related to the soil surrounding the foundation, some to the foundation, and some to the interaction between the soil and foundation.

Foundation failure due to lack of supporting capacity is typically a soil strength problem. A lack of sufficient strength to resist dynamic loading may be inherent in the soil, though the customary use of large factors of safety in foundation design suggests that this mechanism is not likely to be common. Reduction of the available strength, however, due to excess pore pressure generation or cyclic degradation effects, can produce failures of both deep and shallow foundations. Structural failure of one or more elements of a foundation system may also be caused by defects, splices, or joints, or may result from inadequate consideration of the compatibility of different foundation elements in design. The latter can be illustrated by the historically poor performance of foundations using batter piles, which introduce stiffness into the foundation system that must be accounted for in the structural design of the pile cap.

Foundation failure due to excessive earthquake-induced settlement is caused by the contractive nature of loose, cohesionless soil. When such soils are dry, seismic compaction-induced settlements can occur very quickly, predominantly during the period of strong shaking. When they are saturated, positive excess pore pressures are induced by cyclic straining. Even if these pore pressures do not reach levels sufficient for the initiation of liquefaction, their subsequent dissipation leads to densification and settlement.

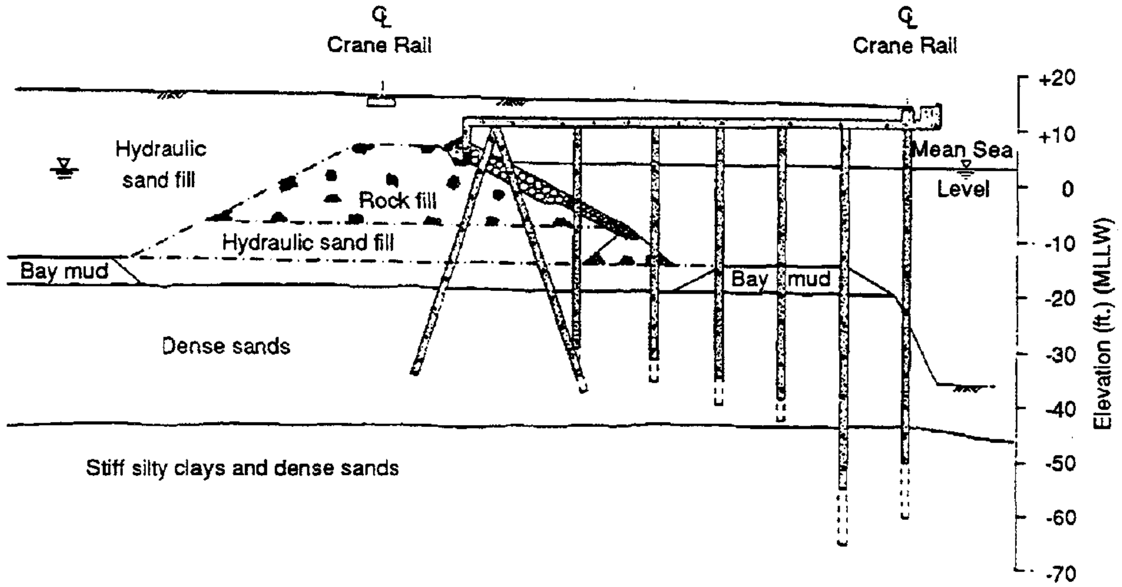


Figure 2.9. Cross-section through 7th Street Terminal at Port of Oakland (after Seed, et al., 1989)

Figure 2.10. Damage to tops of batter piles beneath Seventh Street Terminal, Port of Oakland (after Seed, et al., 1989)

Unsatisfactory foundation performance can result in the transfer of excessive levels of shaking to structures or equipment supported on the foundations. The unsatisfactory performance, which may be characterized by excessive ground motion amplitudes or frequency contents that produce resonance effects, is related to the characteristics of both the soil (stiffness, damping characteristics) and the foundation (stiffness, mass, depth), and the loading (ground motion amplitude, frequency content, and duration).

2.4.3 Mitigation

Mechanisms for mitigation of potential foundation failure hazards depend on the various anticipated modes of failure. Reduction of the potential for bearing failures requires strengthening of the soil and/or reduction of pore pressure generation potential. Both can be accomplished by densification or grouting. Drainage techniques can be used for reduction of pore pressures during and after earthquake shaking, but provide no increase in the inherent strength of the soil.

Excessive settlement of foundations due to earthquake shaking can be mitigated by methods that improve the ability of the soil to resist densification due to cyclic shearing. Such methods include densification prior to construction, physical or chemical modification, or the use of stiff inclusions that transfer at least some of the support of the structure to soil at greater depths.

Hazards associated with excessive dynamic response of foundations can be mitigated by improving the soil in the vicinity of the foundation or by modifying the foundation itself. The stiffness of the soil can be increased by a variety of standard soil improvement techniques. Techniques that increase soil stiffness generally decrease hysteretic damping; however, hysteretic damping is usually much smaller than radiation damping for most foundation systems. The natural frequency of a footing can be increased by increasing its mass or decreasing its dimensions. Decreasing the footing mass or increasing its dimensions will have the opposite effect. Increasing the depth of embedment of a footing will increase both its natural frequency (except for the horizontal translation mode of vibration) and damping ratio, provided that good contact between the sides of the foundation and soil is maintained.

2.4.4 Discussion

Foundations have, in the absence of liquefaction, generally performed well during earthquakes. Perhaps the most critical problems with respect to mitigation of foundation failure hazards are those associated with existing structures. Evaluation of the condition and physical characteristics of older foundations that have been in service for extended periods of time remains a difficult task. Remediation of such foundations, particularly in congested urban areas where sensitive structures or buried utilities are common, is also difficult.

2.5 Slopes and Retaining Structures

A great deal of the geotechnical damage observed during and after earthquakes has been associated with slopes and retaining structures. Slopes may be divided into three categories: (i) natural slopes; (ii) excavated slopes; and (iii) compacted earth and rockfill embankments. Any of these types of slopes and retaining structures may fail by gross instability or by excessive cumulative deformation, the latter of which can lead to either unsafe conditions or loss of serviceability.

1. *Slopes*

Natural slopes consist of geologically-deposited soil or rock strata that can fail as a result of inadequate static or seismic stability. The periodic instability of natural slopes is a natural process of landscape evolution, and failures of natural slopes occur frequently even in the absence of earthquakes. At any given time, unstable or marginally stable slopes are common in many areas. When these slopes are subjected to strong earthquake shaking, slope failures may occur.

Excavated slopes consist of geologically-deposited soil or rock strata through which an excavation has been made. As with natural slopes, excavated slopes may undergo gross instability or excessive cumulative deformation resulting from inadequate static or seismic stability.

The primary hazards associated with compacted earth and rockfill embankment structures are failures of the foundations on which these structures rest. Failure may result from liquefaction or pore pressure buildup in saturated sandy or silty foundation soils or inadequate undrained strength of clayey foundation soils. There should be little hazard associated with slope failure of modern embankment fills and dams due to the strict engineering controls that go into their design and construction. Older embankment structures, particularly those constructed by the hydraulic fill technique, however, may be susceptible to seismically-induced failure.

2. *Retaining Structures*

Earth retaining structures retain either geologically-deposited materials or fill soil or rock. These structures may also undergo failure as a result of inadequate static or seismic stability. Mechanisms of failure include sliding or overturning as a result of the build-up of excessive thrust from the retained soil as a result of ground motion induced inertial forces, loss of shear strength in the retained soil due to pore pressure buildup, or loss of shearing resistance in the foundation soil as a result of pore pressure buildup or cyclic degradation. Furthermore, hydrodynamic forces may contribute to failure of waterfront structures.

Experience shows that most earth retaining structures that have been designed for static loading with conventional factors of safety perform satisfactorily in an earthquake. Most retaining structure failures that have occurred have been the result of liquefaction of the retained or foundation soil resulting for example in excessive lateral thrust or loss of resistance of anchors or deadmen. Numerous examples of this kind of failure are available in Japanese Port and Harbor Authority publications.

An important category of retaining structure is reinforced backfill structures, i.e., structures constructed with steel strips and wire mesh, geogrids, geotextiles, etc. Adequate performance of these structures requires proper design and performance of the structural reinforcing elements as well as the soil in which they are embedded. Failure of these elements may lead to gross instability or excessive deformation of the face of the retaining structure. Similar to the structural elements used in reinforced soil structures, tiebacks and soil nails used to support excavated slopes may also fail due to excessive shear or tension, although examination of a number of tieback walls in various stages of construction during the 1987 Whittier earthquake revealed no instances of failure or significant distress (Ho, et al., 1990). Failure of structural reinforcing elements may lead to gross instability or excessive deformation of the face of the excavation.

2.5.1 Examples

The 1964 Turnagain Heights slide in Alaska, shown in Figure 2.5, is a well known example of an earthquake-induced landslide. The Turnagain Heights slide involved a length of about 2.6 km of coastline and extended inland an average distance of approximately 275 m, encompassing an area of more than 4000 m^2. Some residential structures in the slide zone moved laterally as much as 150 to 180 m. Earthquake-induced failures of natural slopes are shown in Figures 2.11 and 2.12. Failures of excavated slopes were observed in the banks of the All American Canal and the Solfatara Canal in California during the 1940 El Centro earthquake. Liquefaction of hydraulic fill forming the upstream slope of the Upper San Fernando dam during the 1971 San Fernando Valley earthquake illustrates the potential for earthquake-induced failure of such embankments.

Most failures of retaining structures during earthquakes have been associated with liquefaction of backfill and/or foundation soils. Many failures of quay walls in the

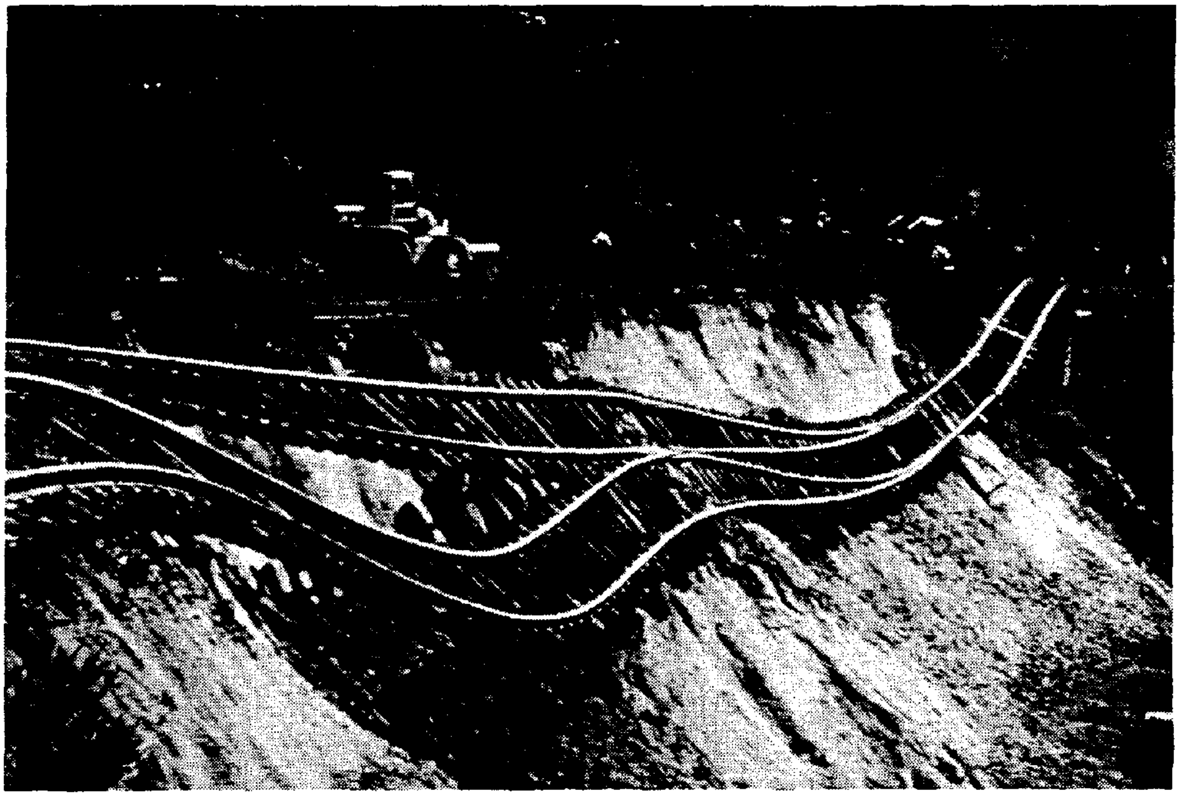


Figure 2.11. Slope failure along Union Pacific railroad right-of-way in 1949 Olympia, Washington earthquake (photo by G.W. Thorsen)

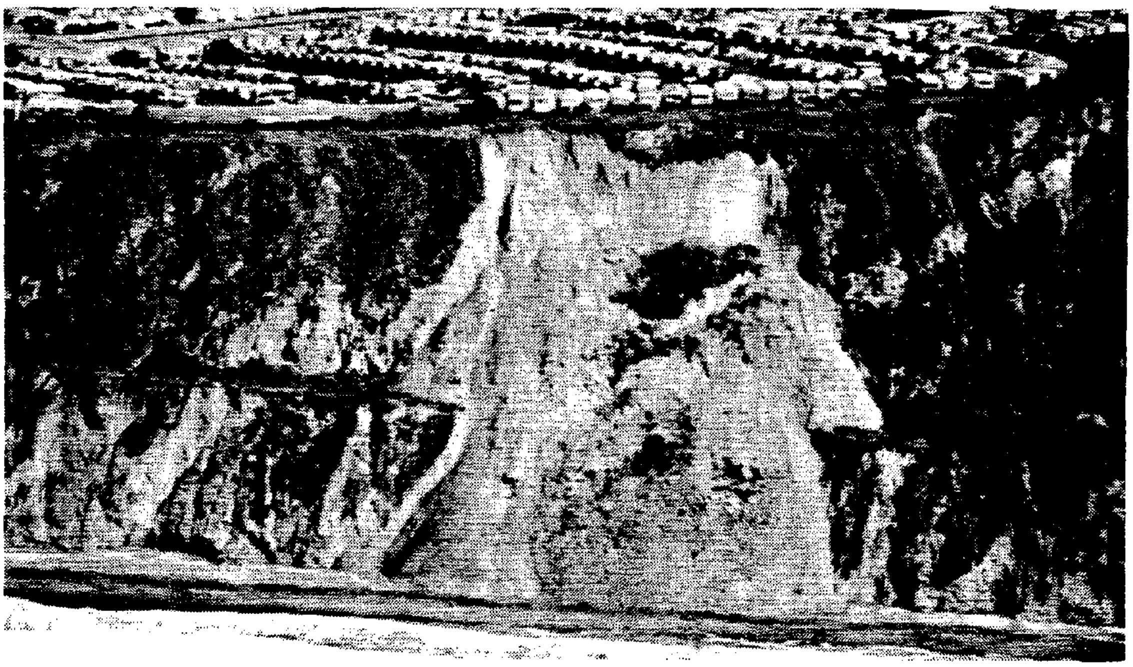


Figure 2.12. Failure of steep coastal bluff in Daly City, California in Loma Prieta earthquake (after Seed et al., 1989)

harbor area of Niigata were observed in 1964 (Figure 2.13). Failures of bridge abutment walls have also been observed as a result of earthquake shaking.

2.5.2 Causes

Slope and retaining structure hazards may be broadly divided into two categories — failures due to earthquake-induced inertial stresses that temporarily exceed the available strength of the soil and failures due to earthquake-induced weakening of the soil.

Strong ground shaking can induce large dynamic stresses in slopes and retaining structures. When these dynamic stresses exceed the strength of the soil, deformations will develop. The sliding block analog is useful for illustration of the resulting accumulation of permanent deformations and has formed the basis for methods of analysis of permanent deformations of slopes (Newmark, 1965) and retaining structures (Richards and Elms, 1979). Such analyses clearly indicate the dependence of permanent deformations on shear strength and identify insufficient shearstrength as the principal cause of those deformations.

Seismically-induced shear strength degradation is another factor that may contribute to a slope or retaining structure hazard. Excess pore pressures in a slope or in the backfill or foundation of a retaining structure can be generated by earthquake shaking. These pore pressures can have three adverse affects: (i) increased driving forces in the slope or retaining structure; (ii) decreased soil strength; and (iii) decreased soil stiffness. Strength degradation may result from the pore pressure buildup associated with an earthquake as well as from changes in soil structure due to prior shearing. The technical literature contains information on residual strength of sands and clays.

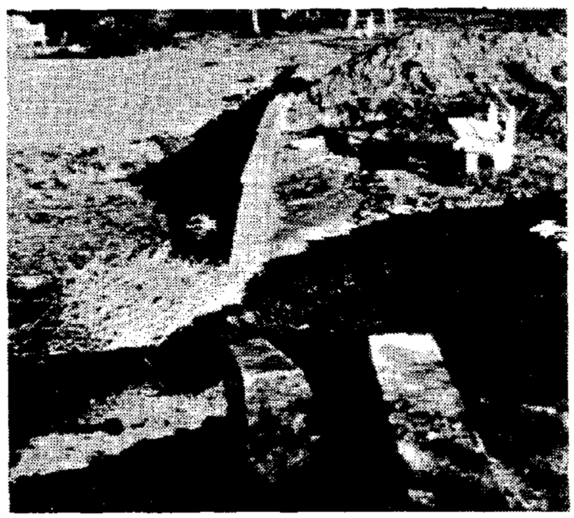


Figure 2.13. Failure of (a) quay wall due to liquefaction in Niigata, Japan, and (b) retaining wall due to inertial forces in 1960 Chile earthquake (after Seed, 1970)

Changes in slope geometry can also cause a hazard. Changes in geometry may result from human activity, as in the case of construction excavations near the base of a slope, or natural actions in the form of the familiar process of erosion.

2.5.3 Mitigation

For a soil improvement technique to be effective for mitigation of slope and retaining structure hazards, it must influence the causes of the hazards by either: (i) alteration of the forces affecting equilibrium (i.e., reducing the stress level acting on soil elements); (ii) alteration of soil or rock material behavior and properties; or, (iii) control of the geometry of the slope or retaining structure so that actions by man or nature do not adversely impact stability.

With respect to the forces affecting equilibrium, requirements for hazard mitigation may include decreasing the dynamic forces acting on the slope or retaining structure through control of geometry and material properties. Mechanisms for mitigation of slope and retaining structure hazards also depend on the nature of the anticipated mode of failure. Mitigation of failure due to exceedance of soil strength by dynamic stresses requires improvement of the strength of the soil. Failure due to generation of excessive pore pressure must be mitigated by measures that either reduce the tendency for pore pressure generation or that allow dissipation of any generated pore pressures during and after earthquake shaking. Hydrodynamic forces on waterfront structures can be reduced through the use of energy dissipation methods.

With respect to geometry, the requirements for hazard mitigation must result in control of the factors affecting geometry. For example, stream erosion of natural slopes should be prevented and slope cuts should not occur without proper consideration of stability and erosion protection.

2.5.4 Discussion

Despite advances in analytical methods and material characterization, the stability of slopes and retaining structures is most commonly evaluated using pseudostatic methods, which represent the complex effects of earthquake shaking by a single seismic coefficient. Even with these simplified methods, uncertainty remains in selection of the appropriate strengths, particularly for sands, silts, sensitive clays, and for natural slopes with fault gouge and joint infilling. The development and accumulation of permanent deformation during periods of strength exceedance may lead to unsatisfactory performance, and cases of excessive slope, retaining structure, and foundation deformations are common in the literature. Methods for estimation of permanent deformations are available and are used in practice, at times for conditions other than those for which they were originally developed. Additional research on the application of such methods to slopes other than embankment dams would be beneficial. Development of methods for prediction of permanent deformations in reinforced earth and soil nailed walls and embankments is needed. The stability of slopes in lined waste impoundments is a growing concern in modern geotechnical engineering practice and deserves increased attention from researchers.

2.6 Summary and Conclusions

Earthquake damage can be caused by a variety of geotechnical hazards. Broad division of these hazards into the categories of liquefaction, ground shaking, foundation failure and slope and retaining structure failure provides a framework for consideration of their basic causes. Consideration of these causes, however, indicates several recurring themes that are common to many of the hazards.

Many geotechnical hazards are caused by the temporary exceedance of the available strength of the soil by earthquake-induced shear stresses. It is necessary to understand the magnitude and distribution of these stresses if seismic stability and seismically-induced deformations are to be evaluated. Excessive shear stresses can be caused by unfavorable combinations of soil properties and geometry, and input motion amplitude and frequency content. Presently, however, significant uncertainty exists with respect to the estimation of these dynamic stresses, indicating that further research in ground motion characterization, ground response and soil-structure interaction analysis is needed.

Many geotechnical hazards are caused by an earthquake-induced reduction of shearing resistance, as in the case of liquefaction. Failures of this type are caused by excessive pore pressure buildup during and after earthquake shaking, and can have catastrophic consequences. Mitigation of liquefaction hazards is known to require reduction of pore-pressure generation or improvement of the residual strength of the soil; however, a number of issues related to evaluation of liquefaction hazards require additional research.

The requirements for mitigation of geotechnical hazards depend on many factors including the nature of the hazards, the geotechnical conditions, the cost of mitigation, and the nature of any nearby development. Because soil improvement and foundation remediation may be required in close proximity to sensitive structures and facilities, it is necessary to ensure that the mitigation process does not cause any damage to such facilities. Methods for mitigation of seismic hazards by soil improvement or foundation remediation techniques must also take into account the specific causes and mechanisms associated with the various hazards. The methods must directly influence those causes and mechanisms and, in order to be used with confidence, their effects must be verifiable.§

3. Soil Improvement and Foundation Remediation Techniques

3.1 Introduction

As the number of soil improvement and foundation remediation techniques and their applications is quite broad, we have divided them into (1) densification, (2) drainage, (3) physical and chemical modification, (4) inclusions, and (5) foundation remediation techniques.

After each technique is briefly described, its historical use, a few pertinent case histories, and a discussion of the observed effectiveness of each is given. Finally, current issues in the application of each technique to seismic hazards and foundation remediation are mentioned.

3.2 Densification Techniques

Since most desirable soil properties improve with increasing soil density, densification is one of the most commonly used techniques for soil improvement. A number of different densification methods have been developed and used successfully, and their use and effectiveness are discussed in this section. The densification methods considered are dynamic compaction, vibro compaction and vibro replacement, compaction grouting, and other techniques such as compaction by explosives and compaction piles.

3.2.1 Description of Densification Techniques

Dynamic Compaction

Dynamic compaction is a simple and economical means of densifying loose granular deposits. Typically, steel or concrete weights of 5 to 20 tons are repeatedly dropped on a site using the single cable of a standard crawler crane from heights of between 10 to 30 m. In one special U.S. case, weights of 35 tons were used with two lines on two separate drums with synchronized clutches and brakes. In another unusual case, a special crane was able to lift and drop 35 tons on a single line. Figure 3.1 shows dynamic compaction in progress.

Dynamic compaction has essentially evolved on a trial-and-error basis as a method for solving site development problems. Since no special equipment is required, the method can be quite economical, especially for treatment depths over 3 m and for areas over 2,500 m^2. It has been estimated that about 2,000 sites worldwide have been treated by dynamic compaction. In a majority of these projects, the process was used for the improvement of loose natural sands, granular fills, cohesive fills, rubble, and miscellaneous materials for a variety of civil engineering projects, generally in non-seismic areas. A number of cases are reported in the literature where dynamic compaction was used to reduce liquefaction potential. In these cases, repeated drops were

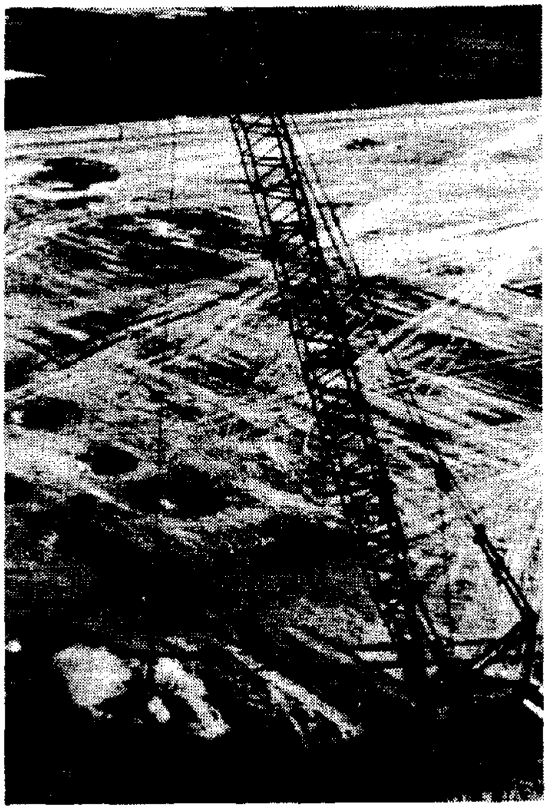


Figure 3.1. Dynamic compaction at a site in Bangladesh using a 100 ton crane dropping a 16 ton weight 30 m. (Holtz and Kovacs, 1981).

used to densify loose sands to a sufficient degree that it appeared that liquefaction would no longer be a concern. Dynamic compaction has also been successfully utilized to improve collapsible soils in Utah, Montana, Arizona, Bulgaria and the USSR.

Since the weight is dropped onto the ground surface, the method is limited in its ability to treat soils at great depth because stress wave amplitudes attenuate with depth due to radiation and material damping. According to Welsh, et al. (1987), the maximum practical treatment depth is about 12 m depending upon soil conditions and the size of the project.

Vibro Techniques

Loose deposits of clean granular materials may also be densified by inserting some type of vibrating tube, probe, or blade at different locations and depths in the deposit. Sometimes water jets and/or air pressure are used to aid in insertion, and usually the probe is repeatedly inserted and withdrawn at the same location. In vibroflotation and sand compaction pile systems, water and additional clean sand are added during withdrawal of the probe so that a column of denser material remains after the process is completed. Figure 3.2 shows a schematic of the vibro compaction equipment and process. In addition to the vibroflotation and sand compaction pile systems, other vibro compaction systems include the Foster Terra-Probe, Vibro Rod, Vibro Wing, and the Franki Y-Probe. Welsh, et al. (1987) and Massarsch (1991) provide good summaries of vibro densification techniques.

Densification by vibro techniques and its limitations are fairly well understood. Important parameters include soil type and gradation, distance from vibrating source, vibration levels and whether the soil liquefies during the installation procedure. Two mechanisms have been recognized as responsible for densification in granular soils: (1) pore pressure generation leading to controlled liquefaction, and (2) displacement of soil due to intrusion of gravel or sand.

For cohesive soils, vibration alone will not improve the soil, so some other material such as sand (sand compaction piles), sand and gravel (sand-gravel piles), or gravel alone (stone columns) is introduced into the soil and densified, usually by displacing gravel or sand around the probe. Sand and stone columns are made in a manner very similar to the vibro compaction methods described above (Figure 3.3). Depending on the spacing, usually between 15 and 35% of the volume of the soft soil is replaced by stone. Columns are installed in a triangular or rectangular grid pattern at typical center-to-center spacings of 1.5 - 3.5 m. Vibro replacement methods are appropriate for a rather wide range of soils including silty sands to clays. Stratified sands or sands with some clay that cannot be effectively treated by vibro compaction methods are good candidates for stone columns. They are not recommended for highly sensitive clays nor for peats or other organic materials. Vibro concrete columns can be used in these situations.

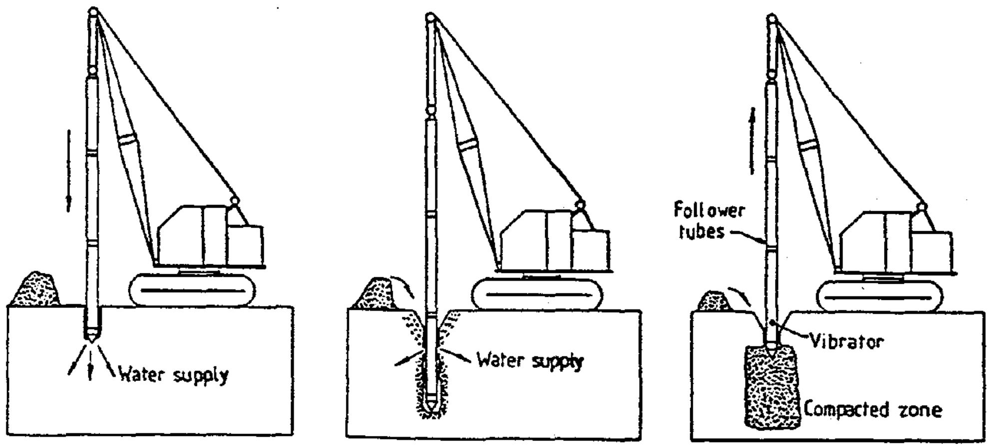


Figure 3.2. Vibrocompaction equipment and process (Welsh, et al., 1987)

DiMaggio (1978) and Barksdale and Bachus (1983) provide good descriptions of the design and construction of stone columns.

Compaction Grouting

Compaction grouting involves the injection of low slump mortar grout under relatively high pressure to displace and compact in-situ soils. Silty sand is used with or without Portland cement and additives such as fly ash, fluidizers, and accelerators. Only enough water for a 0 - 25 mm slump is used. Figure 3.4 illustrates how compaction grouting densifies loose soils by displacement.

Compaction grouting has been used most often to arrest or eliminate foundation settlements, to lift and level slabs, and for foundation slabs on grade. It has also been used very successfully to control surface settlements occurring during soft ground tunneling, to rectify sinkhole problems, and to den sify liquefiable soils under both new and existing structures.

Other Densification Techniques

Other densification techniques such as compaction by blasting and by driving displacement piles have been occasionally and successfully used to densify loose deposits. Although quite respectable relative densities can be economically achieved by blasting, the results may be somewhat erratic in deposits which are not very homogeneous. Dense layers and lenses are likely to be loosened somewhat, but the overall improvement will probably be satisfactory. An almost immediate surface settlement of between 2 to 10% of the layer thickness will occur after blasting.

Driving displacement piles into a loose deposit also densifies the soil by displacement and vibration. Sometimes such piles are called compaction piles. Low cost timber piles (e.g., telephone and power pole rejects) are commonly used for this purpose. They are not necessarily attached to any cap or super structure but merely used for in situ densification. Most of the time the piles are

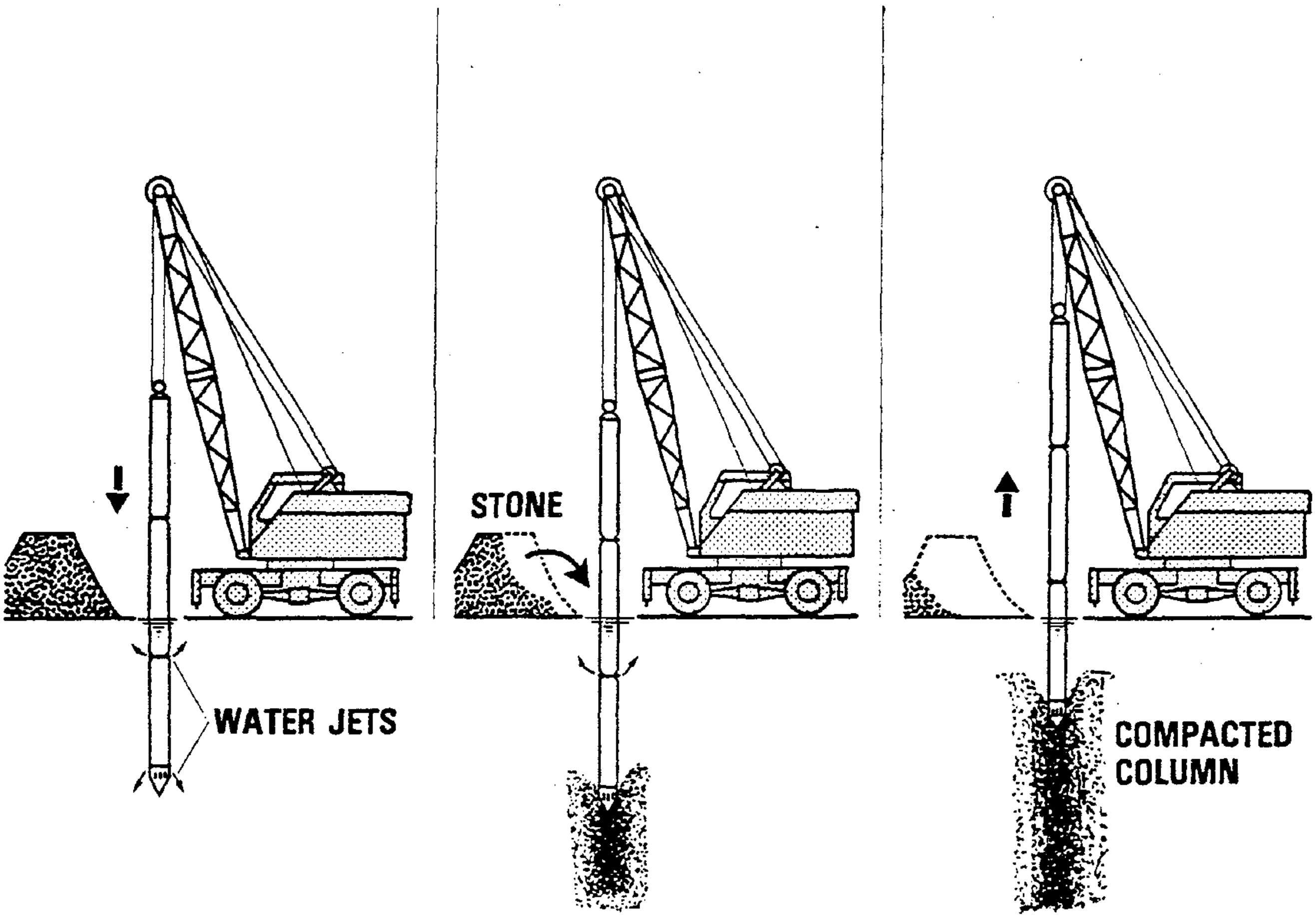


Figure 3.3. Stone columns constructed by vibroreplacement (DiMaggio, 1978)

left in place, but if they are withdrawn, then the hole is backfilled during withdrawal of the pile. Backfilling automatically takes place with the type of compaction piling described by Solymar and Reed (1986). They used a 0.5 m diameter closed-end pipe pile driven to refusal then filled with sand. Then the pile was withdrawn about 2m so that the hinged driving shoe opened and allowed sand to flow into the hole. The pile was repeatedly driven and withdrawn to densify the sand.

3.2.2 The Practice of Soil Improvement by Densification

Densification techniques are among the most commonly used methods for soil improvement. A great deal of practical experience has been obtained with many densification techniques; some newer methods are less well tested.

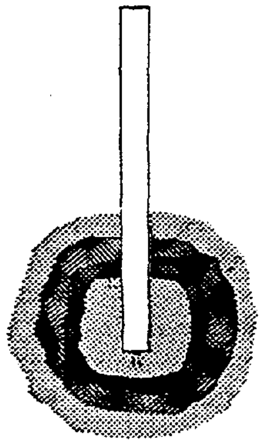


Figure 3.4. Schematic of compaction grouting (Welsh, et al., 1987)

3.2.2.1 Historical Use of Densification Techniques

Dynamic Compaction

Dynamic compaction is one of the oldest known densification techniques. There is good evidence that compaction of loose deposits by repeatedly lifting and dropping stone weights took place in China around 1000 A.D. In modern times, dynamic compaction was used in the U.S.S.R. and Germany in the 1920s and '30s, primarily to densify loose sands and loess deposits. In the late 1930s, the U.S. Army Corps of Engineers used dynamic compaction to densify certain parts of Franklin Falls Dam, New Hampshire, which was constructed by hydraulic filling.

After those early uses, the technique was under-utilized until the early 1970s when L. Ménard in France and R.G. Lukas in the U.S.A. started using large weights dropped from crawler cranes to densify all types of loose deposits and waste fills.

Vibro Techniques

Vibro compaction (vibroflotation) techniques are among the oldest densification methods. Vibroflotation was developed and patented in Germany in the 1930s, and introduced into the U.S. in 1941. The Vibroflotation Company of Pittsburgh was one of the first U.S. contractors specializing in foundation soil improvement techniques. Other vibro compaction techniques such as the Terra-Probe and Vibro Wing were developed much later, in the 1970s. Mitchell (1970, 1981) describes some of the early developments in vibro compaction systems. Recent developments are described by Welsh, et al. (1987).

Stone columns are somewhat older. For example, according to Handa (1984), hand dug stone columns were used to support the Taj Mahal in India. Modern use of stone columns was a logical outgrowth of sand replacement and densification methods (vibroflotation), and they have been used in increasing numbers in the last 10 to 15 years, according to Munfakh, et al. (1987) and Barksdale and Bachus (1983).

Compaction Grouting

In contrast to many other soil improvement techniques, compaction grouting is a uniquely American development. Warner (1982) provides an excellent historical description of the development of compaction grouting, while Graf (1992a) and Warner, et al. (1992) provide overviews of current practice.

Other Densification Techniques

Blasting as a means of densifying loose granular deposits is a rather old densification technique. According to Lyman (1942), blasting was used to densify Franklin Falls Dam in New Hampshire in the late 1930s. It has also been used for many years in the Soviet Union to densify loess soils (Mitchell, 1970).

Compaction piles are not well documented in literature. According to Mitchell (1970), references about using piles to densify granular soils only appeared in the 1950s, although the first edition (1948) of Terzaghi and Peck (1967) mentions the practice. Apparently, also, loess in the Soviet Union was compacted by compaction piles in the 1930s and '40s.

3.2.2.2 Case Histories

Recently, Mitchell and Wentz (1991) evaluated the performance of improved ground during the 1989 Loma Prieta earthquake, where treatment methods such as vibro replacement, vibro compaction, sand compaction piles, non-structural timber displacement piles, deep dynamic compaction, compaction grouting, and chemical permeation grouting were used. Twelve sites from San Francisco Bay to Santa Cruz were studied where maximum peak ground accelerations ranged from as low as 0.11g at Marina Bay in Richmond to as high as 0.45g at two sites in Santa Cruz. Mitchell and Wentz reported that without exception, there was no distress or damage to the improved ground or the structures supported on this ground. In many cases, untreated adjacent ground settled, cracked or showed signs of liquefaction sand boils.

Dynamic Compaction

Dynamic compaction has seen considerable use for remediation of embankments and dams supported on potentially liquefiable foundation soils. A good example is Mormon Island Auxiliary Dam, a part of the Folsom Dam and Reservoir Project, located near Folsom, CA. Preliminary investigations downstream of the embankment indicated that the dredged alluvial foundation materials consisted primarily of gravels with cobbles and sand, and cobbles with gravel and sand. As a result, the Becker Penetration Test (BPT) method was selected by the Corps of Engineers as the primary tool for evaluating the liquefaction potential of these materials. It was concluded that extensive liquefaction could be expected and that catastrophic loss of the reservoir might result.

Drought conditions and resulting low reservoir levels in 1990 provided an opportunity to perform at least partial remedial treatment along the upstream portion of the embankment. Liquefaction remediation was required to depths as great as 18 m and densification by dynamic compaction was selected for remediation based on the amount of time available for construction, technical feasibility, and overall cost. Dynamic compaction was performed on a grid pattern consisting of primary, secondary and tertiary impact points. Primary impact points were on 15 m centers with 30 drops specified at each point. The grid was completed with 30 secondary and 15 tertiary drops at intermediate drop points.

After treatment, the Becker data indicated that a high level of compaction effectiveness was achieved in the upper 9 to 12 m of the treated zone. Below 12 m, analyses indicated a marked reduction in improvement, although increases in baseline blowcount values were obtained. There was some question as to whether the marginal increases observed at some locations and at greater depths was the effects of friction on the Becker hammer casing as it penetrated the highly treated and dense upper 9 m of the treated zone. An increase in the number of BPT$(N_1)_{60}$ values less than the established criteria for a factor of safety against liquefaction (FSL) of 1.0 was observed in the lower 6 m of the treatment zone.

Generally, the middle third of the 46 m wide treatment zone was provided adequate treatment to preclude the occurrence of liquefaction, under the assumption that friction has a minimal effect on the BPT $(N_1)_{60}$ values at depth. Areas in which the desired results (FSL=1.0) were not achieved were along the undredged/dredged alluvial contact and at depth along the edges of the treatment zone. Field observations indicated that excessive pore pressures were developed within materials along the undredged/dredged contact during later phases of the compaction process. These may have resulted from some combination of confinement of water against the relatively impermeable undredged material, lack of drainage features (i.e., perimeter trench, wick drains, etc.) to reduce pore pressure development and excessive energy input per drop in this area.

Lukas (1986) presents three case histories where detailed research was done on densification using dynamic compaction. Other case histories are reported by Leonards, et al. (1980), Ménard and Broise (1975), Welsh, et al. (1987), Hussin and Ali (1987), and Keller, et al. (1987). The latter two papers described tests to improve the seismic stability of loose foundation soils.

Vibro Methods

At the Fairview Terminal in Prince Rupert, B.C., in order to provide a quay wall in 13 to 21 m of tidal water, concrete box caissons were placed on a gravel fill pad about 7 m thick on bedrock. The initial design called for the foundation pad to be rockfill compacted in place, in two lifts, using dynamic compaction underwater. The final scheme adopted used a gravel fill that was compacted in situ in one lift using the vibroflotation technique. The design earthquake PGA was 0.14 g, and PGV = 0.3 m/s. Figure 3.5 illustrates the application.

Dobson (1987) describes two case histories in which vibrotechniques were used in an attempt to reduce the risk of liquefaction. In one case, foundations for a 40 m diameter LNG tank supported on timber piles were strengthened. The foundation conditions were loose sandy silts, silty sands and sands and the stabilizing system was by a ring of stone columns surrounding the tank out to a distance of approximately 25 m. In the second case, stone columns were used quite successfully to stabilize the foundations for a dam in South Carolina.

Other case histories on vibrotechniques used to improve seismic resistance have been reported by Solymar, et al. (1984), Keller, et al. (1987), Hussin and Ali (1987), Hayden and Welch (1991), Neely and Leroy (1991), Ergun (1992), and Egan, et al. (1992). Mitchell and Wentz (1991) reported satisfactory performance at seven sites where vibro techniques were used to mitigate the risk of liquefaction. On the other hand, an unsuccessful attempt at using vibroflotation to densify

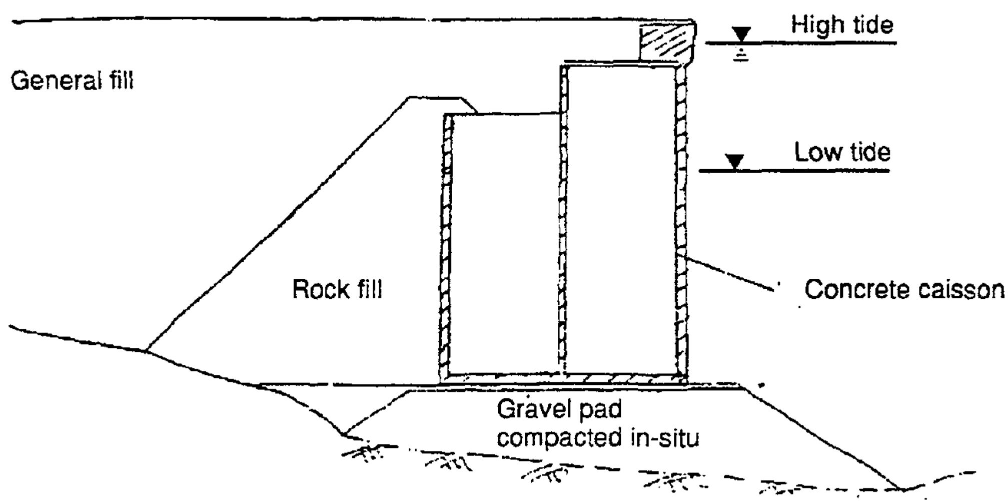


Figure 3.5. Caisson quay wall supported on a gravel pad densified by vibroflotation (Mr. A. Wightman, Klohn Leonoff Ltd., personal communication, August 1991)

loose deposits of silty sands to increase their seismic resistance has been reported by Harder, et al. (1984).

Compaction Grouting

An excellent case history on the use of compaction grouting for tunnel construction has been reported by Baker, et al. (1983) and summarized by Welsh, et al. (1987). Another case history, summarized by Welsh, et al. (1987), was the use of compaction grouting to densify the foundations for a power plant in Jacksonville, Florida (Schmertmann, et al., 1986). Warner (1982) also describes two case histories of compaction grouting.

The use of compaction grouting specifically to mitigate the potential for earthquake damage is not common. A successful testing program conducted to determine the feasibility of compaction grouting a loose sand layer beneath at Pinopolis West dam in South Carolina was described by Salley, et al. (1987). It is not clear whether the technique was utilized under the entire dam. Mitchell and Wentz (1991) reported that no damage was observed after the Loma Prieta earthquake at Kaiser Hospital and surrounding paved areas on loose sandy soils previously improved by compaction grouting. Graf (1992b) described a case history in which liquefiable sands under the proposed addition at a California hospital site were improved by compaction grouting. The existing hospital building was pile supported, and the need to keep the facility open during construction precluded the use of driven piles, vibroflotation, and dynamic compaction. Cost analyses showed compaction grouting was significantly cheaper than the other feasible alternates considered (excavation and replacement with a diaphragm wall and dewatering; chemical grouting; drilled shafts). After a successful test program, the final grouting pattern was holes on 3 m centers up to 11 m deep. Intermediate holes at 1.5 m spacing were grouted between 2 and 5 m deep. In all cases, grouting was staged at 0.9 m intervals. SPT(N) values increased from 10 to 20 before grouting to 30 to 35 afterwards. Interestingly, the structure experienced the 1989 Loma Prieta earthquake with no damage (Graf 1992b).

Other Densification Methods

Solymar, et al. (1984) presented an interesting case history of the use of blasting to densify a deep liquefiable deposit of sand under a dam in Nigeria (see Sutton and McAlexander, 1987, for a brief summary). La Fosse and von Rosenringe (1992) reported the successful use of blasting to densify a potentially liquefiable loose sand layer 6 to 15 m deep below a site for building foundations in Massachusetts. Mitchell (1970) presented summaries of five case histories on compaction piles which were documented in the literature up until that time. Since then, the only published case history of their use that could be located was reported by Egan, et al. (1992).

The Sealand pier in the Port of Tacoma, Washington, is supported on precast concrete piling driven through loose to medium dense silty sand and bearing in dense sand at some depth. The upper 15 m of soil along the pierhead line was particularly loose (SPT(N) values typically were less than 8) prior to construction. Using Seed's method of analysis, the liquefaction potential was found to be high for even a small to moderate earthquake. Timber "pinch" piles were driven at 2 m spacings along the pierhead line to densify the soils in this area. After the piles were driven to the required depth they were broken ("pinched") off at the mudline to prevent interference with shipping. No postconstruction verification of improvement was conducted.

3.2.2.3 Observed Effectiveness of Densification Techniques

The observed effectiveness of the various densification techniques described in this section varies considerably. Solymar and Reed (1986) made a detailed study of three project sites with underlying loose granular soils, at which dynamic compaction, vibro compaction, compaction (sand) piling, and deep blasting were used. Their observations and conclusions provide a good indication of the effectiveness of these densification techniques.

Dynamic compaction is suitable for sands, even if the deposit "contains layers with some cohesive properties." (On the other hand, Leonards, et al., 1980, found that the energy of impact appeared to be damped out by a thin clay layer.) The technique requires commonly available equipment that is not difficult to operate. Dynamic compaction was the most practical for depths between 15 and 20 m. D_r values of 65 - 75% are attainable at depths greater than 10 - 12 m and at shallow depths, D_r can be up to 75 - 85%.

Vibro compaction appears to be best suited to loose, clean, saturated sands. Specialized equipment and expertise are required, particularly at greater depths. D_r values of 70 - 80% are possible below 25 m, with even greater densities at shallower depths.

Compaction (sand) piling is suitable for layered or stratified materials, through some expertise as well as a source of suitable sand backfill is required. Depths greater than 20 m are possible with D_r values of 75-80%.

Deep blasting is appropriate for partly or fully saturated clean loose sands and saturated silt deposits. Blasting expertise is required, as is suitable drilling equipment capable of casing holes to the desired depth. Maximum D_r values seem to be about 65-70%.

During its 50 year development, compaction grouting has been successfully used in thousands of projects. In addition, there is the satisfactory performance of numerous compaction grouted structures in the 1989 Loma Prieta earthquake.

3.2.3 Current Issues in Application of Densification Techniques

Many densification techniques have not been standardized or codified. Very little research has been undertaken to establish the fundamental mechanisms by which they work, or to evaluate the effects of various soil, material, and construction method parameters on their effectiveness. However, despite the fact that many of these parameters vary widely in practice, the methods appear to work quite well.

3.2.4 Summary

Because most soil properties improve with increasing density, densification is one of the most commonly used soil improvement methods. Densification techniques described in this section include dynamic compaction, vibro compaction, vibro replacement, compaction grouting, deep blasting, and compaction piles. The suitability of each technique depends on soil and site conditions, economics, whether it is new construction or remedial work, etc. A very important parameter in determining effectiveness is the relative homogeneity of the soils at the site. Although most soil improvement projects using densification have been for static conditions, a few case histories were found in which the procedures were successfully used to mitigate potential seismic hazards.

3.3 Drainage Techniques

It is well known that in many situations lowering the groundwater table can very effectively reduce the potential for failure of foundations, slopes, and retaining structures. Several techniques have been developed to facilitate the drainage of these features, and the design and installation of most drainage techniques is now fairly well established in geotechnical practice. This section summarizes the drainage techniques that may be appropriate for the mitigation of the hazards of liquefaction and ground shaking as well as failures of foundations, slopes, and retaining structures when subject to earthquake forces. Although drainage design and construction is relatively straightforward, a number of questions remain regarding the performance of drainage systems during seismic events and the suitability of some drainage techniques for the mitigation of seismically induced hazards.

3.3.1 Description of Drainage Techniques

A wide variety of techniques have been used for drainage of soil deposits, foundations, slopes and structures, and these are listed in Table 3.1. It is convenient to consider these techniques in terms of four functional

Table 3.1. Drainage Techniques

Drainage Technique	Function: Interception	Pore Pressure Control	Dewatering	Accelerate Consolidation
Gravel Drains		X		X
Sand Drains		X		X
Prefabricated Geocomposite ("wick") Drains		X	X	X
Wells	X		X	
Surface Drains	X			
Toe Drains	X			
Horizontal Drains				
- Borehole Drain	X	X		
- Blanket Drain		X		X
Gallery Drain Systems	X		X	
Electrokinetic/Electro-osmosis		X	X	X
Vacuum Extraction			X	X

drainage categories indicated at the top of the table: interception, pore pressure control, dewatering, and techniques used to accelerate consolidation.

Interception

Drains which redirect surface flow or alter the seepage patterns in slopes, embankments, or behind retaining structures are very common and have been used for many years. Surface drains include diversion and interceptor ditches, and near surface interceptor drains constructed in shallow trenches. These latter drains are sometimes called French drains. Because of its high stabilization efficiency in relation to design and construction costs, drainage of surface and groundwater is the most widely used and generally the most successful method for stabilizing slopes. Figure 3.6 illustrates these types of surface drains.

Subsurface drainage to lower the groundwater table is a very common treatment method for potentially unstable slopes. Traditional procedures include a) drainage blankets and trenches, b) drainage wells, c) drainage galleries, adits or tunnels, d) subhorizontal drains which may be drilled either from the slope surface or drainage wells or galleries, and e) subvertical drains drilled upward from drainage galleries. Some of these systems are illustrated in Figures 3.7 and 3.8. Most often these systems drain by means of gravity flow; however, pumps are occasionally used from low level collection galleries or wells. Descriptions of drainage systems applied especially to landslides are given by Gedney and Weber (1978) and by Holtz and Schuster (1992).

Drainage of the backfill behind retaining structures is essential for virtually all walls, and Figure 3.9 illustrates some of these systems. Geocomposite drains may be substituted for granular filters and drain rock.

Pore Pressure Control

Other drainage techniques (e.g., gravel drains, blanket drains, etc. — Table 3.1)

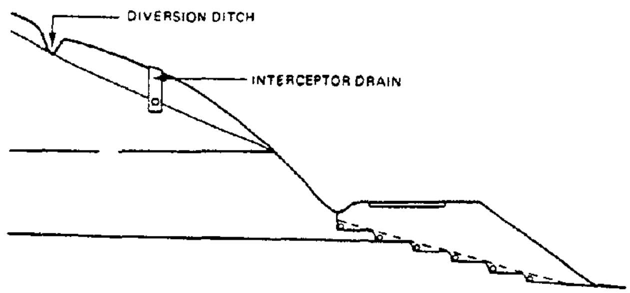


Figure 3.6. Surface drainage of a slope by a diversion ditch and interceptor drain (Gedney and Weber, 1978)

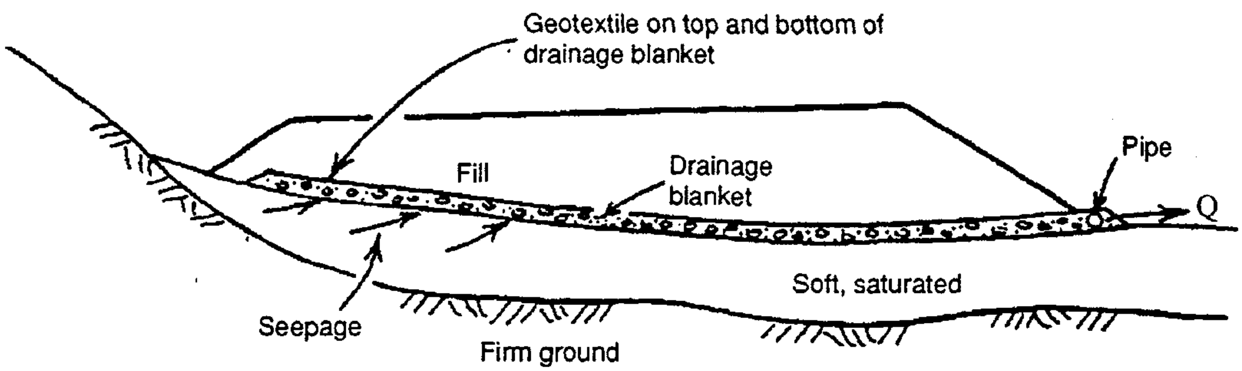


Figure 3.7. Drainage blanket used for stabilizing shallow foundations (after Cedergren, 1989)

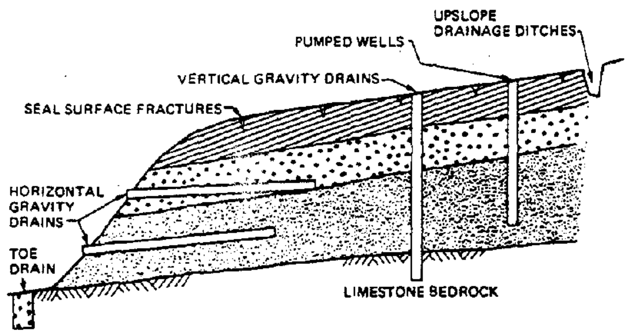


Figure 3.8. Subhorizontal and vertical drains used to lower ground water in natural slopes (Gedney and Weber, 1978)

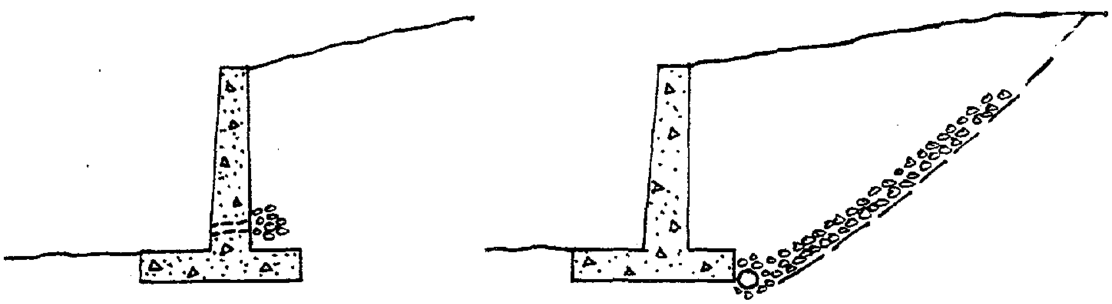


Figure 3.9. Common methods for draining retaining wall backfills

may also be used to reduce excess pore pressure resulting from ground shaking in soils that are already saturated. These methods are based on the concept that the pore pressures on one or more surfaces within the soil deposit are maintained at hydrostatic, so that any excess pore pressures generated by earthquake shaking will be rapidly dissipated by flow toward the drainage surface. This reduces the pore pressure within the soil deposit, thereby maintaining the effective stresses at higher values than they would be without drainage.

Gravel drains installed using an auger casing do not produce significant vibrations and densification; consequently their performance is based on the capability of the gravel column to control excess pore pressures, i.e., provide drainage. Simplified analyses of gravel drain response to cyclic loading for design purposes are available (Seed and Booker, 1976). Required parameters include those for the earthquake, stress state, soil properties, and drainage and filtration parameters. Limitations of the analyses include the fact that they are one dimensional, and the assumptions of (1) a constant coefficient of volume compressibility, and (2) that the gravel drains have a permeability large enough to prevent pore pressure generation and impedance to flow at the interface between the drain and the surrounding soils.

Basements, tanks, utility corridors, and other similar structures founded near the surface in potentially liquefiable deposits can be effectively stabilized through encapsulation by drainage materials (Figure 3.10) and by drainage blankets under the facility (Figure 3.7). Drainage blankets are especially effective for facilities in which the width of the facility is very large.

Pore pressure control can also be achieved in finer grain deposits by the use of vertical sand drains and prefabricated geocomposite ("wick") drains although these techniques are more commonly used for accelerating the consolidation of soft cohesive soils.

Dewatering

Conventional dewatering techniques lower the groundwater table or remove groundwater by active pumping by means of well-points (Figure 3.11), sump pumps (Figure 3.12), or submersible pumps in deep wells. Other types of surface and shallow drains have also been successfully used for this purpose. Although most dewatering systems are temporary, passive dewatering systems are more appropriate for permanent construction.

Details of dewatering for construction are given by Mansur and Kaufman (1962) and Cedergren (1989).

Lowering a high groundwater table in a potentially liquefiable deposit is a viable design alternative. Appropriate dewatering systems for this case include traditional well points or sump pumps, french and/or trench drains, blanket drains, vertical geocomposite ("wick") drains and deep wells.

Dewatering can very effectively improve foundation soils by increasing their shear strength and bearing capacity, reducing their potential for volume change, and increasing their resistance to seismic forces. Conventional drainage is also very important for retaining structures and abutments.

Among the dewatering techniques applicable to slopes are electrokinetic stabilization and electro-osmosis. Drainage is promoted by these techniques, which increases the shearing strength and thus the stability of the slope. Design and operational procedures, particularly for electro-osmosis, are well established.

Acceleration of consolidation of soft soil

Vertical drainage is often utilized in conjunction with preloading or surcharge fills to accelerate the consolidation of soft compressible cohesive soil layers in the foundation (Figure 3.13). Total settlements are reduced, soil shear strength and therefore foundation bearing capacity is increased, and resistance to seismically-induced deformations is thereby improved. Although conventional sand drains

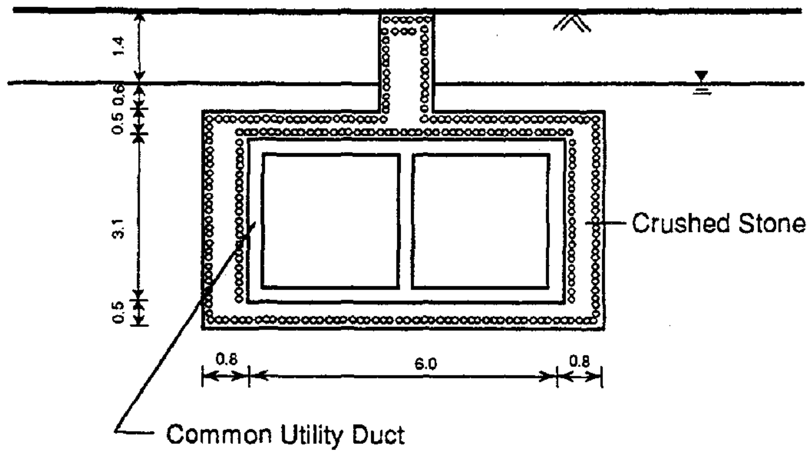


Figure 3.10. Cross-section of gravel drains applied to a common reinforced concrete utility duct in a loose sand in Japan; units in meters (Dr. Y. Koga, Public Works Research Institute, personal communication, August, 1991)

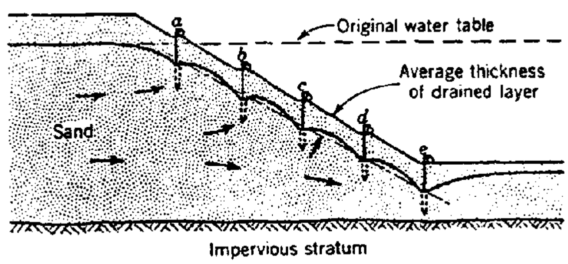


Figure 3.11. Drainage of an excavation by multi-stage well-points (Mansur and Kaufman, 1962)

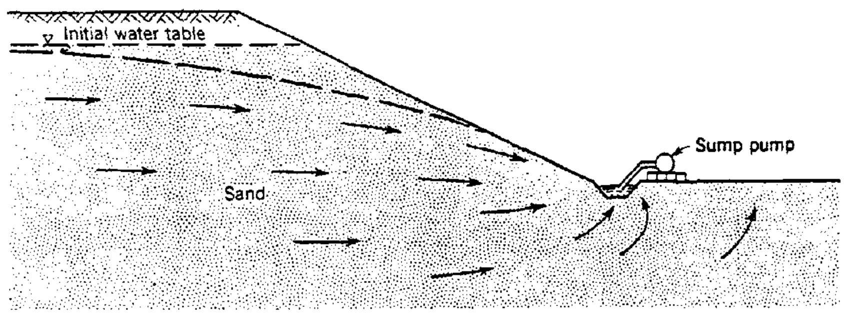


Figure 3.12. Collection of seepage in a slope by open ditches and sumps (Mansur and Kaufman, 1962)

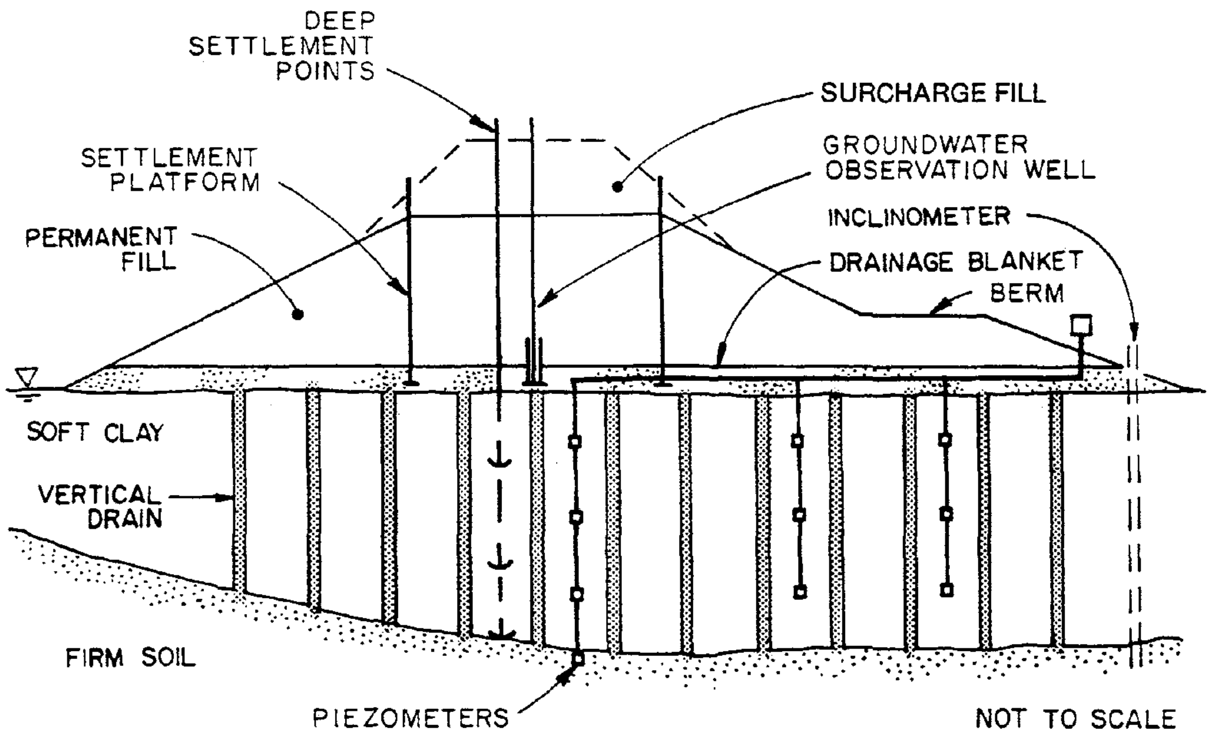


Figure 3.13. A typical well-instrumented vertical drain installation for a highway embankment (Rixner, et al., 1986)

have been used for nearly sixty years, during the last twenty years, they have essentially been replaced by prefabricated vertical geocomposite ("wick") drains, principally because they are much less expensive to install. Design principles and installation methods for wick drains are quite well established (Holtz, et al., 1991).

3.3.2 The Practice of Soil Improvement by Drainage

3.3.2.1 Historical Use of Drainage Techniques

Interception

According to Cedergren (1989), the California Division of Highways used subhorizontal drains to stabilize highway slopes as early as 1939. Other interception techniques such as surface drainage and interceptor drains are probably even older. Underground drainage galleries have been used for generations to stabilize slopes, and well systems, particularly relief wells, have been used to stabilize levees and dams and other hydraulic structures. Therefore, none of the interception techniques currently in use are particularly new.

Pore Pressure Control

Systems for pore pressure control are somewhat more recent than those for interception. Sand drains were invented in the late 1920s, while gravel drains (stone columns) are somewhat newer. The use of gravel drains as a possible method of stabilizing a potentially liquefiable soil deposits was first suggested by Seed and Booker (1976; 1977). Prefabricated geocomposite drains were developed in the 1970s (Holtz, et al., 1991), and as far as is known, they have not so far been used to reduce seismically generated pore pressures.

Dewatering

Mansur and Kaufman (1962) describe the early history of dewatering. The first recorded use of well points and large deep wells to lower the water table was in connection with the construction of the Berlin subways around the turn of the century. They also describe other early dewatering examples from Egypt, Europe, and the U.S.A. Dewatering has mostly been applied to stabilize temporary slopes and excavations.

Acceleration of the Consolidation of Soft Soils

Sand drains were invented by D.J. Moran, who received a U.S. patent on the concept in 1926. The first practical installations were in California a few years later (Porter, 1936). In Sweden, Walter Kjellman began experiments in the mid 1930s with wooden pipes; he was issued patents on the first prototype prefabricated drain made entirely of cardboard in 1938. The first modern geocomposite prefabricated drain was developed by O. Wager of the Swedish Geotechnical Institute in the early 1970s. The first drains used kraft paper filters; later models were provided with nonwoven geotextile filters. Competition has decreased the cost of geocomposite drains appreciably, and contractors have been very innovative in developing installation procedures. Consequently, the installed cost of prefabricated geocomposite drains is now relatively low and sand drains are obsolete (Holtz, et al., 1991).

3.3.2.2 Case Histories

Interception

As mentioned above, interception as a dewatering technique has primarily been utilized to improve the stability of slopes. Although most of the published case histories about the successful use of drainage for this purpose did not involve seismic hazards, there is no fundamental reason why such techniques would not also be suitable for the stabilization of slopes under seismic conditions. A number of case histories illustrating successful interception of groundwater in slopes are presented by Schuster (1992) and Holtz and Schuster (1992). Although not specifically designed to mitigate seismic problems, many of these cases are from seismically active areas (e.g., California, Italy, New Zealand).

Pore Pressure Control

Very few well documented case histories are available that describe the use of drainage techniques to mitigate liquefaction potential of loose granular deposits. Gravel drains (stone columns) have been utilized at a number of potentially liquefiable sites in Japan, but to date the system has not been tested, as no significant shaking has yet occurred at these sites. Still, the technique is relatively popular in Japan.

Dewatering

Dewatering techniques were used in the restoration work of Hachiro-gata reclamation dykes that were heavily damaged by liquefaction of the foundation in the 1983 Nihonkai Chubu Earthquake. About 20% of the total length of 51.4 km of the dykes settled 1 m or more. Since the damage was assumed to have been caused by liquefaction, the liquefaction resistance of the foundation was investigated. The following methods were employed to mitigate the liquefaction hazard: 1) counterweight fill was used to add a bearing load to the front and the back of the dyke; 2) cutoff sheet piles were placed at the toe of shore side slope and drains were provided in the dyke on land side for dewatering, and 3) impermeable asphalt facing was laid over the top and on the front slope of the dykes to prevent seepage of lake water and rain water through the dyke surface. Figure 3.14 illustrates these countermeasures.

Acceleration of the Consolidation of Soft Soils

The use of drainage techniques to accelerate soft soil consolidation has become commonly accepted in geotechnical engineering practice. Case histories on this technique are given by Johnson (1970), Rixner, et al. (1986), Cedergren (1989), and Holtz, et al. (1991).

3.3.2.3 Observed Effectiveness of Drainage Techniques

Interception

As noted by Gedney and Weber (1978), Schuster (1992), and Holtz and Schuster (1992), interception of surface and groundwater in unstable slopes is one of the most effective methods of increasing their stability. Numerous case histories can be found in the literature describing the successful performance of interception drainage techniques.

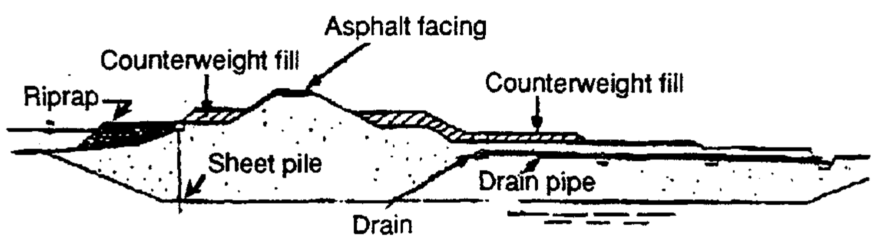


Figure 3.14. Example of countermeasures used to mitigate the liquefaction hazard in Hichiro, Japan (Dr. Y. Koga, Public Works Research Institute, personal communication, August, 1991)

Pore Pressure Control

As noted above, no case histories are available to demonstrate the successful utilization in the field of vertical drainage to mitigate liquefaction potential in loose granular deposits. In the laboratory, some investigators (e.g., Yoshimi, 1980; Sasaki and Tanaguchi, 1982; Iai, 1988) have used large shaking table tests to evaluate the performance of model gravel columns. These studies indicated that in loose (D_r = 33%) soils subjected to a peak acceleration of 0.1g, the area of influence of the gravel drain was limited to one diameter from its center. At greater accelerations, the drains were not as effective, leading to concern about the flow capacity of gravel drains. Theoretically, they should work by limiting the development of pore pressure; however, the accuracy of commonly used pore pressure generation models (e.g., Seed and Booker, 1976; 1977), has not been extensively verified by field performance.

Dewatering

As noted in the case history described above, dewatering has been apparently successful in at least one site in Japan. As with the use with gravel drains to control pore pressures, dewatering as a means for mitigating seismic hazards is theoretically viable.

Acceleration of Consolidation of Soft Soils

If properly designed and installed, vertical drainage of all types can be successfully utilized to accelerate the consolidation of soft cohesive soil deposits (Holtz, et al., 1991). One of the more spectacular failures illustrating improper drain selection was reported by Hannon and Walsh (1982) and Hoover (1987). These papers emphasize the need for proper testing, specification, and selection of the filter for the drains.

3.3.3 Current Issues in Application of Drainage Techniques

Although a number of drainage methods have been widely employed to mitigate liquefaction potential, their effectiveness has not been demonstrated under strong earthquake shaking conditions. Because of this some investigators (e.g., Yoshimi and Tokimatsu, 1991) have suggested that excess pore pressure ratios be limited to 0.4 when designing gravel drains for mitigation of liquefaction hazards. In some cases, this will require spacings so small as to render the technique uneconomical.

Another issue is the use of drainage techniques for rehabilitation, under existing structures because their installation would be difficult. For example, the installation of stone columns directly under existing structures would be impossible, although they have been installed as close as 3m from new and existing structures by Japanese and U.S. contractors. Their installation in city streets would be almost impossible due to buried utilities. However, drainage could be potentially provided by prefabricated geocomposite drains which have much smaller profiles and can be installed in much more restrictive conditions and at almost any angle. Although less permeable than gravel drains, prefabricated geocomposite drains may still be viable as a drainage technique because they can be installed economically at closer spacings.

3.3.4 Summary

As noted in this section, drainage is one of the oldest and surest means for mitigating potential instability in foundations, slopes, and behind retaining structures. Drainage methods which are suitable for static stability conditions seem to also be entirely appropriate for many of the same situations when they are subjected to seismic shaking. Although theoretical analyses indicate that drainage techniques should work, well documented case histories of their successful utilization under seismic conditions are not available.

3.4 Physical and Chemical Modification Techniques

Physical and chemical modification (PCM) techniques play a significant role among available methods for improving loose and soft soils, foundation remediation, and mitigation of potential damage due to seismic events. PCM methods alter the engineering characteristics of the soil and thereby cause it to be inherently more stable. Primary physical modifications include densification and that component of improvement that results from injecting or mixing another material in with soil. For example, the injection of a grout into the pores of a soil may decrease its liquefaction potential by virtue of decreasing its potential for volumetric contraction, in addition to any hardening or chemical bonding that may occur.

Chemical modification includes strengthening of soft clay by mixing in place with cementitious materials, and the creation of high strength grouted soil masses, columns, walls or grids using permeation or jet grouting techniques. Because the distinction is somewhat arbitrary and there is significant overlap in the definitions of the techniques, compaction grouting is considered in Section 3.2, Densification Techniques.

All of the PCM techniques have had extensive use in practice, and the advantages and limitations for each technique are relatively well established. In most cases, the strength improvement of the treated soil can be predicted with some accuracy. However, their use in some seismic hazard applications is not yet very common.

3.4.1 Description of Physical and Chemical Modification Techniques

The physical and chemical modification techniques discussed in this report will, for descriptive purposes, be divided into grouting techniques and soil mixing techniques.

Grouting

Numerous methods and materials can be used for grouting. In any discussion of grouting it is important to distinguish between displacement or densification grouting, such as compaction grouting (described in Section 3.2.2), and non-densification grouting. The processes by which non-densification grouting is conducted are intrusion grouting, permeation grouting, and jet grouting (Figure 3.15).

1. Intrusion grouting is a technique in which fluid grout is injected under pressure with the intention of introducing controlled fracturing of the ground. Sometimes this is called fracture grouting. Theoretically, the first fractures are perpendicular to the minor principal stress direction, but observations show that they usually follow the weaker bedding planes. Repeated injections will tend to fracture the densified ground along different planes. The permeability of the soil decreases, and some densification probably occurs, although it is secondary to the strength increase resulting from hardened grout lenses.

2. Permeation grouting is a technique by which the voids of a soil are filled, with little change in the physical structure of the soil. Materials injected are (1) particulate grouts, including Portland and micro-fine cement, fly ash, clay, and mixtures of these components, and (2) chemical grouts, such as lime, sodium silicates, acrylates, etc., in solution. Chemical grouts can permeate smaller pore sizes, as they usually are liquids with a low viscosity and no solid particles to clog the pores. Along with cement grouts, they offer the added benefit of cementing particles together. However, they are more costly than particulate grouts. Although many formulations of chemical grout are available, sodium silicate based grouts are the most widely used.

3. Jet grouting (Figure 3.16) cuts the soil with high pressure, high velocity air or water jets, and mixes it with an injected grout material such as Portland cement. Single or multiple jets are rotated around a central drill stem to cut the soil and mix it with the grout. Jet grouting is able to construct relatively uniform columns of improved soil in a wide variety of soil conditions. Continuous walls or panels of

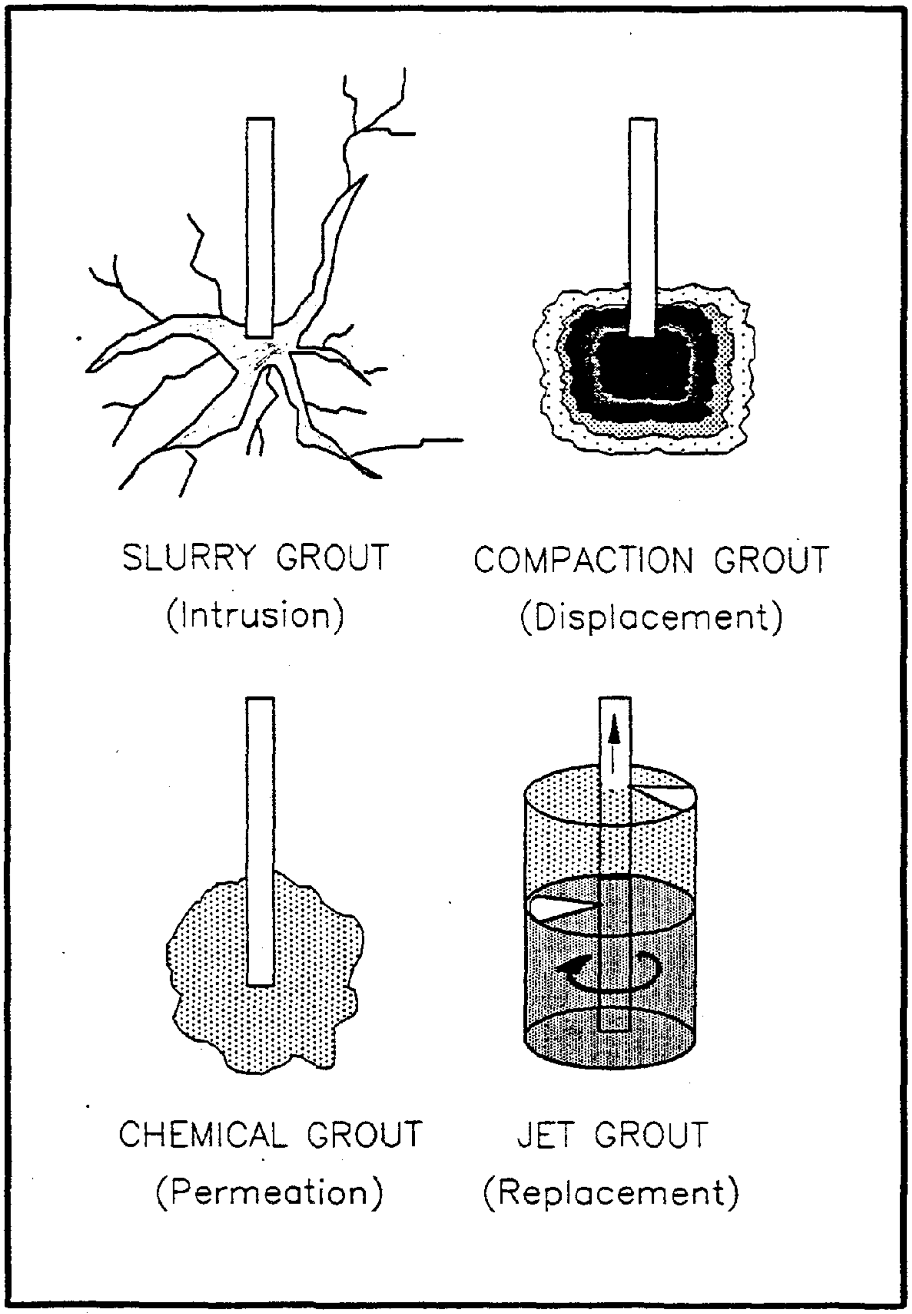


Figure 3.15. Types of grouting (courtesy of Hayward Baker Co.)

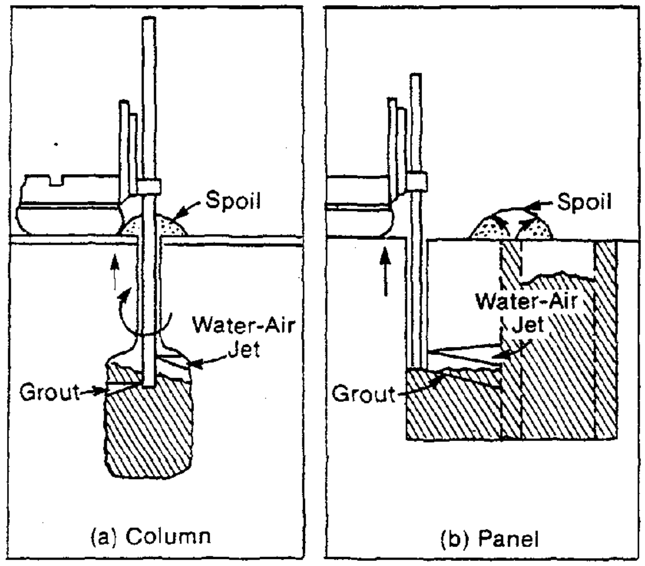


Figure 3.16. Jet grouting (a) columns and (b) panels (after Munfakh, et al., 1987)

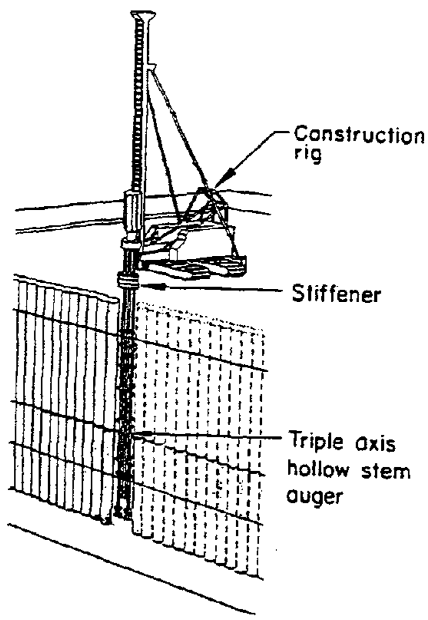


Figure 3.17. Schematic of the deep soil mixing rig (O'Rourke and Jones, 1990)

solidified soil can be connected to form cells. Jet grouting is applicable to sand, silt and clay deposits.

A good general description of cement and chemical grouting can be found in Chapter 14 of Hausmann (1990). Cement grouting for dam foundations is discussed in detail by Houlsby (1982) and Weaver (1991). Karol (1982) gives a complete description of chemical grouts, while Baker (1982) presents details for carrying out structural chemical grouting.

Detailed information on jet grouting is given by Gallavresi (1992) and Kauschinger, et al. (1992).

Soil Mixing

Soil mixing is a technique whereby soil is physically mixed with cementitious materials using a hollow stem auger and paddle arrangement. Available configurations include single shaft augers (0.5 to 4 m in diameter) or in gangs (2 to 5 shafts) of augers about 1 m in diameter. Figure 3.17 is a schematic of the Japanese triple axis auger system while Figure 3.18 shows the equipment used to make the Swedish lime columns. The single-row multiple shaft auger is generally used for in situ soil mixed walls while double-row multiple shaft augers (8 shafts) are used for areal treatment of soft or contaminated ground. As the mixing augers are advanced into the soil, grout is pumped through the hollow stem of the auger shaft and injected into the soil at the tip. The auger flights and mixing paddles blend the soil with grout in pugmill fashion. When the design depth is reached, the augers are withdrawn and the mixing process is repeated on the way up to the surface. Left behind are stabilized lime, soil-cement, or soil-cement-bentonite columns or panels. Depths of soil improvement are limited only by the available equipment. The Swedish lime columns are 10-15m deep, while depths greater than 30 m have been achieved in the United States and more than 60 m in Japan with soil-cement mixing.

Soil mixing produces an improved volume of soil that is very well defined. The mechanical mixing ensures constant element size with depth and enables columns, walls, and cells to be constructed in virtually all types of soils. The strength of the soil cement is dependent on the type of soil treated, mix design of the grout, and degree of mixing. Broms and Boman (1979) and Broms (1985) provide a summary of the lime column method (see also Holtz, 1989). Taki and Yang (1991) present an overview of the deep soil mixing technique, while Broomhead and Jasperse (1992) describe shallow mixing.

3.4.2 The Practice of Soil Improvement by Physical and Chemical Modification

3.4.2.1 Historical Use of Physical and Chemical Modification Techniques

According to Hausmann (1990), grouting with clay, lime, and cement has been around a few hundred years. It was primarily used to repair masonry walls, fill cracks in load-bearing structures, and stop unwanted seepage in rock fissures. Chemical grouting started in the mid 1920s with silicate based grouts. Acrylamide-based grouts (example: AM-9) were first developed in 1951(Karol, 1982). They were almost an ideal grout in terms of their penetration, viscosity, gel time, and strength. However, they are toxic, and thus are no longer manufactured. Since then, most of the chemical grouts utilized are sodium silicate based.

According to Weaver (1991), grouting for seepage cutoff in dam foundations began in the U.S. before 1890, and became quite common and highly developed by the 1930s. Applications to tunnels and foundations developed concurrently.

Jet grouting, on the other had, is relatively new; it started in Japan about 1965 (Kauschinger, et al., 1992). Developments occurred rapidly and the technology quickly spread to Italy, Germany, and Brazil. Although jet grouting was introduced in the U.S. as early as 1979, it has had a rather slow development, with relatively few projects completed so far. It does appear to be gaining wider acceptance in recent years.

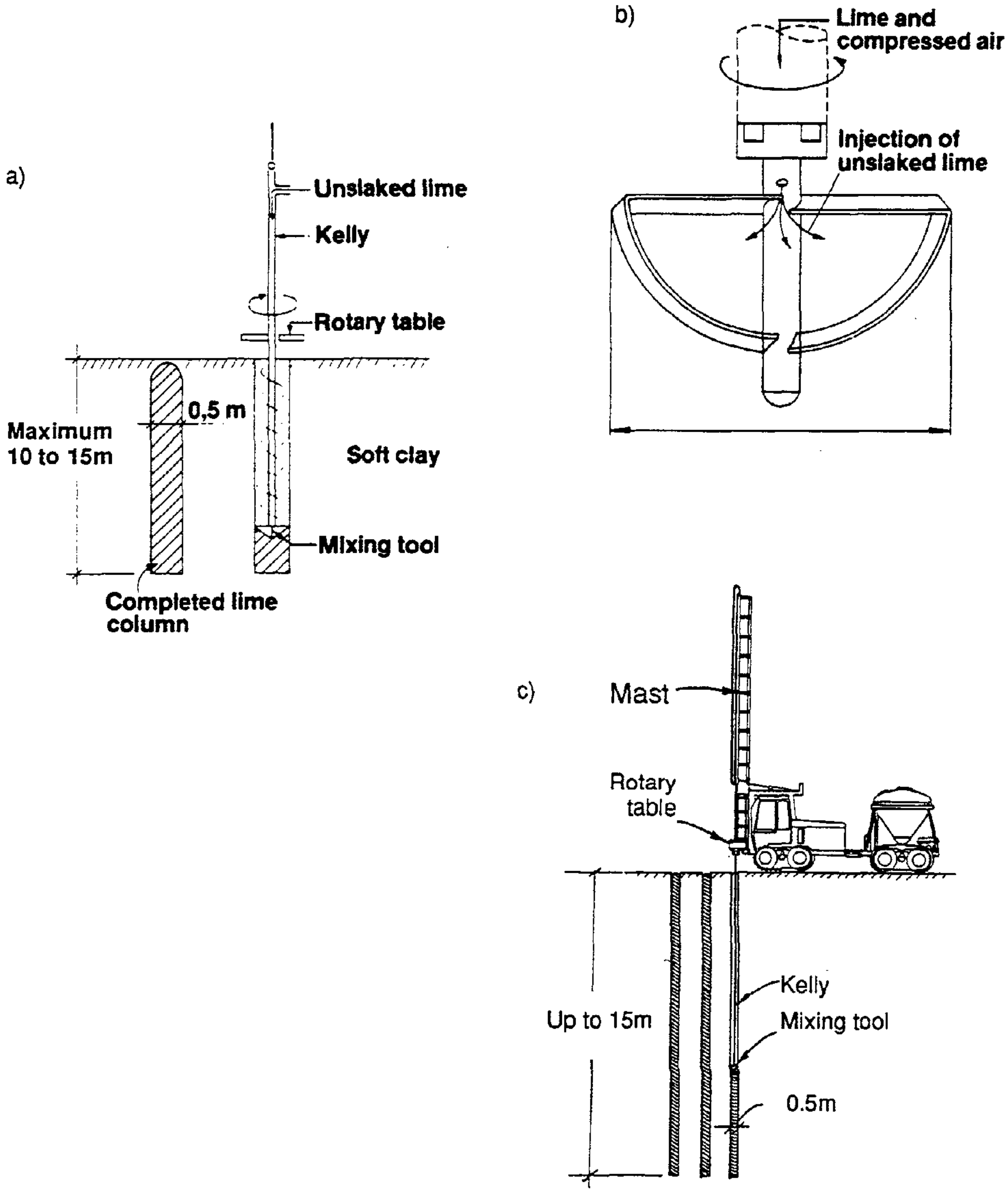


Figure 3.18. The Swedish lime column method: (a) schematic of completed column and auger system; (b) close up of mixing tool; (c) installation machine (after Broms and Boman, 1978; Broms, 1985)

Although deep soil mixing began in the U.S. in the 1950s (Ryan and Jasperse, 1989), it was really developed in Sweden and Japan in the 1970s and '80s. The Swedish lime column system (Figure 3.18) was initially used to reduce the settlements of shallow foundations, especially for highway embankments and small structures, on soft clays. Later, applications to improve the stability of slopes and excavation have proven to be feasible (Broms and Boman, 1979; Broms, 1985). The multiple shaft auger systems for deep soil mixing of soil-cement developed by Japanese contractors has been a significant advancement. These rigs greatly increased both the productivity and maximum depth of mixing. So far, most deep soil mixing projects have involved seepage control under dams and levees, containment of hazardous waste sites, and large area stabilization of contaminated sites.

Shallow soil mixing is a very recent development (Broomhead and Jasperse, 1992).

3.4.2.2 Case Histories

Very few case histories could be found in which grouting was utilized to increase the seismic resistance of a structure or foundation. Among theses are the case of Roosevelt High School, built in San Francisco in the 1920s using spread footings founded on clean sands. California regulations required all school buildings to be analyzed for earthquake resistance and, among other problems, it was discovered that the shallow footings were bearing on loose sands above the water table that were subject to earthquake "shock" densification and excessive settlements. The loose sands below the footings were stabilized with chemical grout (Zacher and Graf, 1979). No settlements of this building were observed following the 1989 Loma Prieta earthquake. Graf (1992b) summarizes three additional cases from the San Francisco area in which chemical grouting was successfully utilized to stabilize foundations against potential seismic damage. All three projects were completed prior to the 1989 Loma Prieta earthquake and all structures successfully withstood at least that test. Bruce (1992a), in a comprehensive paper about grouting for the rehabilitation of dams, mentions using grouting to improve seismic stability.

None of the six papers with case histories on jet grouting presented at the ASCE Specialty Conference on Grouting, Soil Improvement, and Geosynthetics (Borden, Holtz, and Juran, 1992) mentions seismic hazards as a reason for using jet grouting.

According to Mitchell and Wentz (1991), chemical grouting at the Riverside Avenue Bridge in Santa Cruz, California, which was subjected to a peak ground acceleration of 0.45g in the 1989 Loma Prieta earthquake, was very effective. No settlement or damage to the bridge was reported.

In Kawasaki, Japan, a combination of slurry walls and deep soil-mixed walls were constructed to create a containment within which permanent drawdown of groundwater was performed. Liquefaction potential was reduced by causing a portion of the liquefiable soils to be above the groundwater table and by increasing the effective stress in the soils which remained below the groundwater table.

At another project in Vancouver, British Columbia, a large tank was founded on a ring of deep soil-mixed columns placed tangent to one another to create a containment barrier similar to that in Kawasaki. In this instance, however, the containment was designed to hold in soil that would liquefy during an earthquake. The strength of the improved soil and the volume of treatment were designed to resist the shear stress induced during and after ground shaking, assuming the zone of concern to be either completely or partially liquefied.

In none of the case histories on the use of lime columns described by Broms and Boman (1979) and in the references in Holtz (1989) did seismic hazards appear to be a consideration. That is not the case, however, for multiple auger deep soil mixing with soil cement. The Jackson Lake Dam modification project described by Ryan and Jasperse (1989) and Taki and Yang (1991) was undertaken specifically to reduce the potential for liquefaction in the granular alluvial soils in the foundation. This was also the objective of the project reported by Babasaki, et al. (1991) in which large cells of deep soil mixing were constructed under a building founded on a deposit of very loose sand in Kagoshima City, Japan. Taki and Yang (1989) report on two successful uses of deep soil mixing for support and to control ground water in tunnel construction. In the shallow soil mixing case reported by Broomhead and Jasperse (1992), potential seismic loading was a design consideration.

3.4.2.3 Observed Effectiveness of Physical and Chemical Modification Techniques

The effectiveness of grouting and soil mixing technologies has been confirmed by successful field performance and by excavation of stabilized soils in conjunction with construction.

Permeation and fracture grouting have been used for more than 70 years for foundation soil improvement and remediation, and the characteristics and limitations of materials and methods of application are quite well understood. Permeation grouting is a proven method of strengthening soils and cutting off groundwater movement. Application of this process is limited to granular materials and/or fractured rock. Strength and stiffness of the grouted soil can be predicted in advance. Permeation grouting has been used to mitigate soil liquefaction, and to prevent failures of foundations, slopes and retaining walls. It has also been used to modify the response of soils to vibratory loads. In particular chemical grouts have been used successfully to stabilize loose sands subject to shock densification. Individual columns of grouted soil or continuous walls or panels can be connected to form cells. Intrusion or fracture grouting has been shown to be effective in control of seepage and, to a lesser extent, surface settlements. Success to date is largely based on empirical observations. Grouting can be used to achieve design objectives with a high degree of confidence, provided adequate geotechnical investigations are done in advance.

Although, as noted above, there are no case histories illustrating the effectiveness of jet grouting to mitigate seismic hazards, its efficacy as a foundation soil improvement technique is well documented in the literature. Judging from the properties and performance of jet grouted foundations and cutoff walls, it should be a viable technique in seismically active regions.

The proceedings of the ASCE Specialty Conference on Grouting, Soil Improvement and Geosynthetics (Borden, Holtz and Juran, 1992) presents a number of recent case histories on grouting, but except for those reported by Graf (1992b), none specifically concerned seismic hazard mitigation.

The effectiveness of soil mixing has also been fairly well documented in the literature, with applications to resist seismic loading conditions described by Taki and Yang (1989; 1991) and Broomhead and Jasperse (1992). These projects were designed to minimize pore pressure generation and contain liquefied deposits in order to minimize surface displacements. However, although the design concept suggests that these methods should be effective, none of the installations is known to have experienced an actual seismic event.

3.4.2.4 Potential Applications to Seismic Hazards

Liquefaction of low density saturated cohesionless soils can be mitigated by increasing their shear strength through cementation (permeation grouting, jet grouting or soil mixing) or through the addition of cemented lenses in conjunction with increased density (intrusion or fracture grouting). Recent applications of soil mixing walls suggest similar applications are possible for jet grouting and possibly permeation grouting. As at the Jackson Lake Dam in Wyoming, the improved soil can be installed in a grid or cellular pattern to isolate the liquefiable soils into individual zones, such that the buildup of pore water pressure during and after seismic ground shaking is reduced to a level so that liquefaction does not occur. Conceptually, jet grouting and perhaps permeation grouting could be used to create the same improved soil zones, depending on soil profile characteristics.

In addition to liquefaction, earthquake motions can result in densification of soils and damaging surface settlements and displacements. All of the PCM techniques have the potential to increase soil stiffness which may reduce the amplification of ground motions. Of course, permeation grouting will not be effective in cohesive soil profiles, and if continuous "shear walls" are required, either jet grouting or soil mixing will be required.

PCM techniques are widely used for both enhancing the stability of existing foundations and for the repair or renovation of damaged foundations. Most particularly grouting tools and techniques are well adapted to the low headroom and close quarters common to foundation work on existing structures. The use of permeation or fracture grouting to improve strength or to transfer loads to more competent layers at depth is common. These techniques can also be used to lift settled foundations.

PCM techniques are also applicable to improving seismic performance of slopes and retaining structures by reducing the potential for liquefaction of granular soils as well as by improving strength characteristics of both granular and fine-grained materials. Due to cost, PCM is generally considered only for limited areas or to construct stabilized zones or cells within a larger soil mass. PCM techniques have been considered for the seismic stabilization of earth embankments which are supported by relatively soft fine-grained soils when the associated improvement of these underlying layers is desired.

3.4.3 Current Issues in Application of Physical and Chemical Modification Techniques

Grouting Techniques

The verification of the effectiveness of grouting appears to be one of the most important issues. Appropriate techniques for evaluating the characteristics of grouted soil are also needed. The effectiveness of grouting to reduce pore pressure generation during seismic events is not well established, nor is the performance of stabilized zones and protecting structures from detrimental movements during shaking.

Soil Mixing Techniques

Although deep soil mixing appears to be a viable technique for groundwater cutoff and support of temporary excavations, the behavior and performance of deep soil mixed walls under seismic conditions is not well understood. Because soil-cement mixtures appear to be rather brittle, the movements generated during a seismic event may induce cracking and fracture in the structures, which of course would compromise their integrity and effectiveness.

3.4.4 Summary

As noted in this section, physical and chemical modification techniques are potentially very effective means for improving loose and soft soils for mitigating the damage to foundations and slopes due to earthquakes. Both conventional grouting techniques (permeation, intrusion, and jet) and both deep and shallow soil mixing appear to be viable techniques which should be considered in any seismically sensitive region or area.

3.5 Inclusions Techniques

The concept that in some situations soils require reinforcing is not particularly new. Tree roots, for example, can be quite effective as slope reinforcement. Other examples include adobe bricks, brushwood and bamboo facines, corduroy roads, and relief piles used to stabilize embankments on soft foundations. These examples indicate that the strength and stiffness of a soil mass in a slope or foundation can be increased by the inclusion of some other material with a much higher tensile strength. Modern examples include soil anchors and nails, reinforced soil retaining structures, and stone columns. All these techniques are called inclusions. For purposes of this report, four types of inclusions are considered: (1) soil nailing, (2) metal and geosynthetic reinforcement, (3) concrete and steel piles, and (4) stone columns.

3.5.1 Description of Inclusions Techniques

Soil Nails

Soil nails are steel bars or cables which are either driven or grouted into a drill hole in a vertical or sloping soil face (Figure 3.19). In the case of excavations, soil nailing is a "top-down" construction technique in which rows of nails are sequentially installed as the excavation proceeds downward. The face of the wall is then shotcreted. The nails are not pretensioned, but rather gradually take up load as the excavation deepens and the soils behind the face deform. Significant depths of exposed soil face must not be left without prompt nailing, and the soil must have sufficient strength to stand unsupported for several hours. When installed in existing slopes (Figure 3.19b), the nails will gradually pick up tension as soil deformation occurs. Soil nailing has been used in temporary excavations to depths up to 23 m in U. S. A. and up to 27 m in France. Permanent installations so far are in the 10 to 15 m range.

The design of soil-nailed structures is usually based on limiting equilibrium or kinematic methods which incorporate tension elements to simulate the nails. The nail itself must have sufficient cross-section to avoid failure in tension and must also resist pullout. In typical installations, the length of the nail is between 0.7 to 1.0 times the height of slope or depth of excavation. The spacing of the nails is usually about 1.5 or 1.8 m center to center both horizontally and vertically.

In practice, seismic design involves checking the adequacy of the static design under seismic conditions by incorporating an additional horizontal static force given by the Mononobe-Okabe procedure. Static factors of safety are typically about 1.5 and seismic safety factors are in the range of 1.1 to 1.2. Therefore, in most cases the excess capacity under static conditions can absorb the additional seismic force with a safety factor greater than 1.2. However, seismic design may control under very strong shaking, especially for high or deep structures.

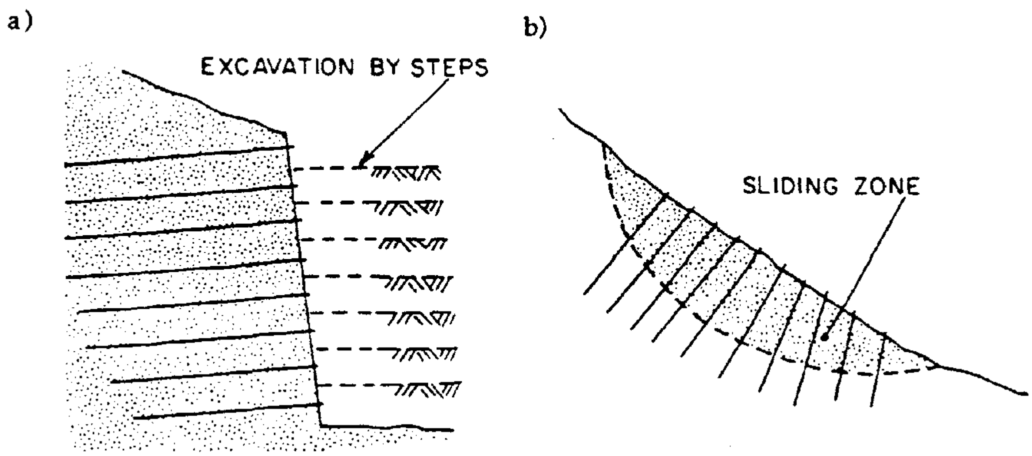


Figure 3.19. Schematic of soil nailing for (a) excavations and (b) natural slopes (Munfakh, et al., 1987)

References on soil nailing include Munfakh, et al, (1987), Mitchell and Villet (1987), Christopher, et al. (1990), Elias and Juran (1991), Schlosser, et al. (1992), and Byrne (1992).

Backfill Soil Reinforcement

Soil reinforcement by metal (Figure 3.20) or geosynthetic (Figure 3.21) inclusions is now a mature technology with a general consensus on design procedures and construction methods. There is also an impressive record of satisfactory performance in a wide variety of applications over long periods of time, including seismic conditions. For details the reader is referred to, for example, Ingold (1982), Jones (1985), Bonaparte, et al. (1985), Mitchell and Villet (1987), Christopher, et al. (1990), Koerner (1990), Allen and Holtz (1991), and Christopher and Leshchinsky (1991).

Reinforcement Piles

Concrete and steel piles have occasionally been used to limit the movements of slopes. Included are large diameter heavily reinforced drilled shafts installed to form tangent pile walls at the toe of an unstable slope, secant pile walls (often with tie back anchors), and more widely spaced driven piles and drilled shafts. See Holtz and Schuster (1992) for a description of these systems for landslide stabilization together with some case histories of their use.

Another approach to in situ reinforcement is the use of micropiles, pin piles, or "root piles." These pile systems form a monolithic block of reinforced soil that extends below the critical failure surface (Figure 3.22). The principal differences between root piles and soil nailing are that root piles are usually longer, of larger diameter, and have a more three-dimensional geometric arrangement.

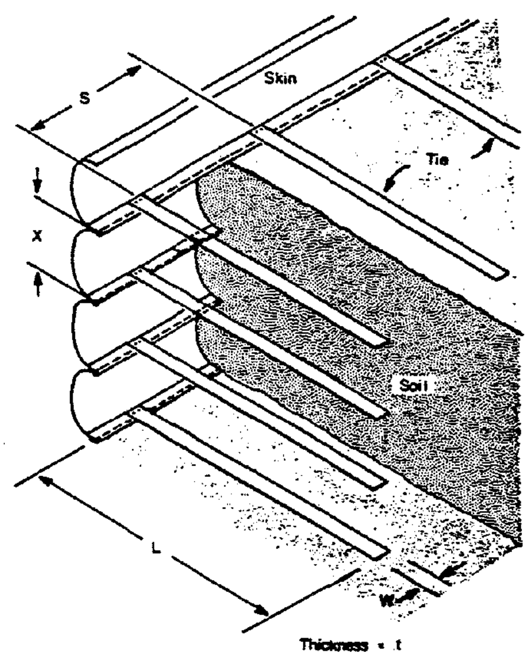
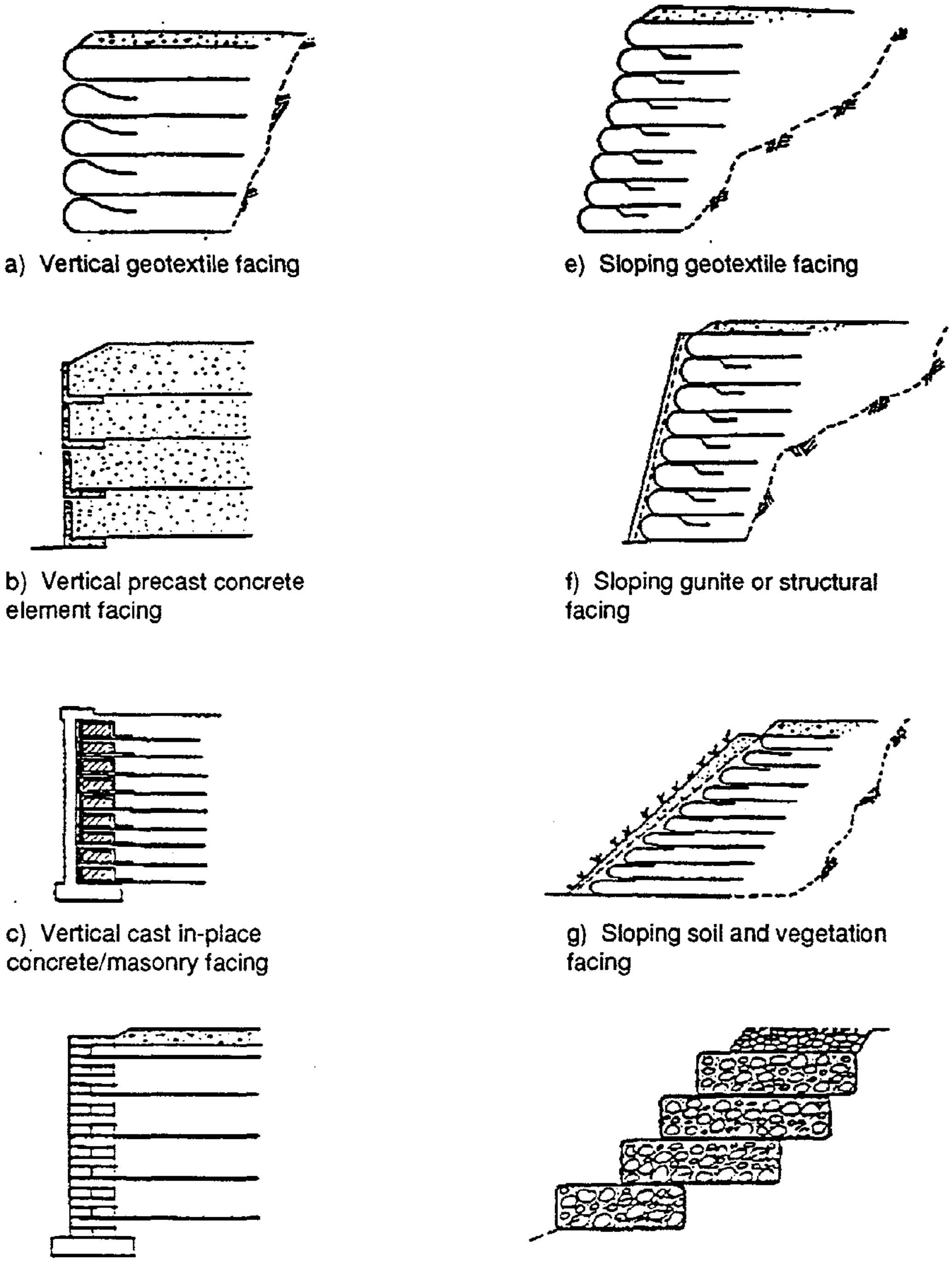


Figure 3.20. Component parts and key dimensions of reinforced earth wall (after Lee, Adams, and Vagneron, 1973)



a) Vertical geotextile facing

e) Sloping geotextile facing

b) Vertical precast concrete element facing

f) Sloping gunite or structural facing

c) Vertical cast in-place concrete/masonry facing

g) Sloping soil and vegetation facing

d) Vertical masonry facing

h) Geotextile gabion

Figure 3.21. Possible reinforced walls and slopes using geosynthetic reinforcement (after Mitchell and Villet, 1987)

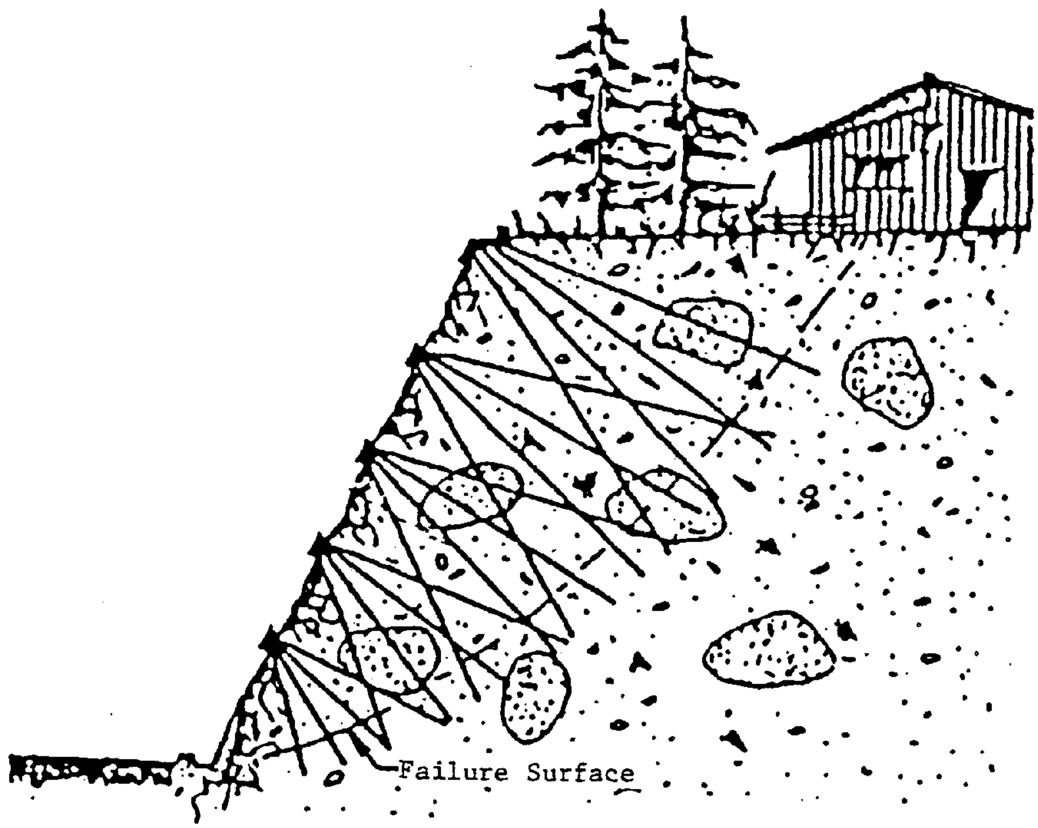


Figure 3.22. Schematic cross section illustrating the use of root pile for stabilization of a slope (after Lizzi, 1977)

Design of these systems requires an understanding of the composite pile-soil interaction, particularly the mechanism of load transfer from soil to piles as deformation takes place.

Stone Columns

Stone columns have three functions that enhance the seismic performance of a foundation during an earthquake: densification of the surrounding soil, drainage, and its own action as a stiffer component of the foundation soil system. Installation of stone columns and the functions of densification and drainage were discussed earlier in Sections 3.2 and 3.3. Stone columns also improve the ability of the soil to carry added structural loading with little reduced settlements. Because the primary benefit of stone columns in loose sands results from densification, the ability of the soil to carry added loading is rarely evaluated and considered. However, theory indicates that a reduction factor should be applied to cyclic stress ratios induced in the soil (Priebe, 1990). Because of this, the liquefaction resistance of soil-stone column systems should be enhanced.

3.5.2 The Practice of Soil Improvement Using Inclusions

3.5.2.1 Historical Use of Inclusions

Soil Nailing

According to Munfakh, et al. (1987), soil nailing was first developed in France and Germany in the early '70s. The method is an extension of the New Austrian Tunnelling Method, which utilizes a combination of rock bolts and lightly reinforced shotcrete as a support system for underground excavations. Application to the stabilization of excavated slopes is termed soil nailing. A number of well instrumented experimental full scale structures were constructed primarily in France and design rules established. In this country, Shen, et al. (1978) described a temporary support system for excavations which is the precursor of today's soil nailing systems. They also developed calculation procedures which have been widely used in the U.S.

Metal and Geosynthetic Reinforcement

Although very early examples of similar soil reinforcement systems can be found (Jones, 1985), the first modern developer and promoter of soil reinforced retaining systems was H. Vidal, who developed his system *terre armée* ("reinforced earth") in the mid 1960s (Vidal, 1969; Schlosser and Vidal, 1969; and Lee, et al., 1973). Since then, more than 16,000 reinforced soil structures have been successfully built throughout the world. The use of geosynthetics to reinforce the backfill behind retaining walls was developed independently in the U.S.A. by the U.S. Forest Service (Bell and Steward, 1977) and in Sweden (Holtz and Broms, 1977). Since then, geosynthetics have been used quite successfully to stabilize natural slopes (Margason and Bonaparte, 1985; Bonaparte et al., 1989), fill slopes, and for the construction of embankments on very soft and unstable foundations (Holtz, 1989; 1990).

Reinforcement Piles

The first use of piles as a soil improvement technique is rather obscure. Timber relief piles have been commonly used for at least 50 years and perhaps longer to stabilize embankments on soft foundations in Scandinavia. The outer rows of piles are driven battered, typically 1H:4V to 1H:10V, while the inner rows of piles are driven vertically (see Bjerrum, 1972). (The historical development of this stabilization technique is also discussed by Holtz, 1989). Under what conditions concrete and steel piles became a viable alternative to timber piles is not known; however, it must be a matter of economics and load carrying capacity. Long timber piles do not have very much lateral load capability, so steel piles and properly spliced precast concrete piles or drilled shafts would be more suitable in those situations.

"Reticulated Root Piles" were originally developed in the 1950s by F. Lizzi (1977) and were patented by the Italian construction firm Fondedile of Maples, which has installed the system all over the world, mainly for underpinning. It has only been in the past 20 years that root piles have been used for slope stabilization, and most root-pile slope-stabilization works have been constructed within the past 10 years.

According to Bruce (1992a), during the past 20 years, U.S. practice has developed using micropiles to a state quite different than the original European developments. He provides details from some 20 projects which illustrate recent developments of pinpile technology.

Stone Columns

Stone columns followed from the development of vibroflotation and vibroreplacement, in which instead of sand being added to the cavity, course crushed stone or gravel was utilized. According to DiMaggio (1978) this development occurred in Germany in the early 1950s.

3.5.2.2 Case Histories

Soil Nailing

According to Felio, et al. (1990), a number of soil-nailed structures were shaken during the Loma Prieta earthquake at acceleration levels around 0.1g and they performed very well. The structures were designed for an equivalent seismic load corresponding to horizontal acceleration coefficient $K_h = 0.159$ which was estimated as 1/3 of the expected peak acceleration of 0.45g. Similar satisfactory performance of tieback walls during the 1987 Whittier earthquake was observed by Ho, et al. (1990).

Reinforcement

Five steep slopes and walls reinforced with geogrids were all located within 100 km of the epicenter of the 1989 Loma Prieta earthquake. The slopes ranged in height from 3 m to 24.5 m; the 3 m high slope was within 11 km of the epicenter. Peak ground accelerations ranged up to 0.4g. According to Collin, et al. (1992), the performance of all five structures was satisfactory.

Reinforcement Piles

A number of case histories of the use of piles to stabilize landslides are given in Holtz and Schuster (1992), but in no case were piles specifically installed to enhance the seismic resistance of the slope.

However, piles are proposed as one of the remediation measures for Sardis Dam in Mississippi to control potential deformations induced by seismic liquefaction. During the design earthquake the saturated portion of the core and a part of the upstream slope are likely to liquefy. These, however, do not have a significant impact on stability. The prime factor resulting in excessive deformations is a layer in the foundation which could lose a large percentage of its strength during shaking. It is proposed to prevent sliding on this layer by driving 0.6 m square concrete piles through the layer to provide adequate restraint in the alluvial sands below. There are two major technical questions posed by the solution:

- how will the composite section behave?
- how should the piles be designed to resist both hard driving, cyclic loading, and the large static horizontal forces that develop after liquefaction?

A proposed replacement dock at the Georgia-Pacific facility in Bellingham, Washington, will be supported on piles driven through loose to medium dense sand and bearing in bedrock at depth. The upper 6 m behind the bulkhead line is loose, hydraulically-placed sand. Offshore soils along the slope are generally medium dense. The concern at the site is that lateral movement of liquefied onshore soils will cause excessive horizontal movement of the new dock. Using methods presented by Byrne (1991), 0.6 to 0.9 m of lateral soil movement was estimated. To reduce liquefaction potential and its effects on the new dock design, driving two rows of 15 m-long timber piles spaced at 0.9 m on-center along the bulkhead line was recommended. Lateral soil movement after the improvement was estimated to be about 30 cm during a moderate-sized earthquake. The timber piles will also be used to support the dead weight of the lightly-loaded bulkhead wall.

For case histories of pin piles for slope stabilization, see Bruce (1992b). An interesting case history on the use of pin piles to control slope movements was described by Pearlman, et al. (1992).

Stone Columns

Case histories on the use of stone columns to mitigate liquefaction potential have been reported by Dobson (1987), Hussin and Ali (1987) and Hayden and Welch (1991). Additional case histories on stone columns are reported by Watts and Charles (1991) and Mitchell and Wentz (1991); see also Section 3.2.2.2.

An interesting case of a failure of a stone-column-supported structure was reported by Mathis and Munson (1987). A reinforced earth bridge abutment constructed on a stone column foundation failed during construction. An investigation revealed the causes of failure included: (a) too rapid construction, (b) contamination of the columns, which lengthened the consolidation time, (c) weakening of the foundation soils by vibration and water jetting, and (d) an overestimation of the safety factor for short-term stability. A concentration factor (Barksdale and Bachus, 1983) of two was assumed in design; back analysis after the failure indicated this factor was only about one. Thus the load of the reinforced earth wall was not successfully transferred to the stone columns from the low-strength clays and silts in the foundation.

Egan, et al. (1992) report on the use of stone columns as a part of the seismic retrofit of a wharf at the Port of Oakland after the 1989 Loma Prieta earthquake (see also Section 3.6.2.2).

3.5.2.3 Observed Effectiveness

Soil Nails

From the reports by Felio, et al. (1990) and Ho, et al. (1990), nailed soil walls should perform relatively well during earthquakes because of their flexibility and ductility.

Metal and Geosynthetic Reinforcement

Performance of reinforced soil structures in seismic events has been very good. This was most recently demonstrated in the 1989 Loma Prieta earthquake. Several reinforced slopes and walls were subjected to this earthquake and performed very well (Collin, et al., 1992). One example is a 15 m high 1 to 1 slope, reinforced with HDPE geogrid, located on Highway 9 in San Lorenzo, about 26 km from the epicenter. Although the horizontal acceleration at the site was estimated to be about 0.4g, the slope showed no signs of distress after the event.

There is not much other direct evidence available as to the seismic stability of metal and geosynthetic reinforced slopes and walls. The rigid precast concrete facings of conventional reinforced earth and similar systems (e.g., VSL walls, Georgia stabilized earth walls, etc.), although they are relatively flexible, suggest that they may have some difficulty during a seismic event. The weak link in the system is the attachment of the reinforcement to the facing. Wrapped face geosynthetic reinforced structures, on the other hand, should not encounter this particular difficulty, although if their facings are protected by shotcrete or precast concrete panels, then similar difficulties may also arise with these types of walls.

Concrete and Steel Piles

Because no case histories of the performance of pile systems used for soil improvement and subsequently subjected to seismic events could be identified, there is no direct evidence available on their effectiveness. This is also true for root piles, although there are reports of several successful installations in seismically active areas of Italy.

Stone Columns

Comments on the effectiveness of stone columns during seismic shaking were given previously in Sections 3.2.2.3 and 3.3.2.3.

3.5.3 Issues in Use of Inclusions Techniques

Soil Nailing

There is currently no consensus as to how soil-nailed structures should be designed for both static and seismic conditions. Performance of facings during seismic events (in permanent installations) is not well understood. For permanent installations, the long term durability of the nails is subject to question, although experience with permanent tieback installations should provide considerable confidence in this respect.

Metal and Geosynthetic Reinforcement

Metallic reinforcement systems are quite well established in engineering practice, and design techniques for both static and seismic conditions appear to be well accepted. Questions concerning long-term durability under adverse geochemical conditions still remain, although the research by Elias (1990) and Allen (1991) has shed considerable light on this subject. Connections between the reinforcement strips, bars, etc. and precast concrete facings are the weak link in reinforcing systems subject to seismic shaking.

Design procedures for geosynthetic reinforcement are less well established, although considerable progress has been made (Allen and Holtz, 1991; Christopher and Leshchinsky, 1991). Limited work has been done on seismic design of slopes and embankments with geosynthetics (Bonaparte, et al., 1986; Yamanouchi, et al., 1986). Long-term durability is a serious impediment to the future use of geosynthetics reinforcement in permanent construction (Allen, 1991), and the FHWA now has a major study underway on this subject.

Reinforcement Piles

The lateral stability of these foundation elements during seismic loading, and their connections, either pile splices or connections to footings and pilecaps, are the most serious questions remaining .

Stone Columns

The primary issue remaining in the use of stone columns as foundation reinforcement is their actual performance under seismic shaking. Aside from the Loma Prieta case histories presented by Mitchell and Wentz (1991), no direct evidence of stone column performance during earthquakes is available.

3.5.4 Summary

In this section, the use of inclusions (soil nails, metal and geosynthetic reinforcement, piles, and stone columns) to reinforce and strengthen foundations and slopes against seismic loading has been discussed. Metallic reinforcement and piling systems appear to be the best understood, especially with regard to their performance during earthquakes. On the other hand, we have so little experience with soil nailed walls, geosynthetic reinforced walls, and stone columns during earthquakes that their performance during seismic loading remains difficult to predict.

3.6 Foundation Remediation Techniques

This category includes those remediation techniques that are not directed toward modification of the properties of the foundation soils and thus are not classed as inclusions. Consequently, except for the case of removal and replacement of unsuitable soils, which needs little attention here, these techniques are implemented by means of structural elements — piles, walls, footings, etc. — that form the interfaces between structures and foundation soils (or rocks).

While issues of characterization and verification are spread across the whole matrix of hazards and remediation, the use of structural elements has an inherent advantage in that the engineer generally has a high degree of confidence in what actually has been put in place in the ground. On the other hand, surveying damage to structural elements due to earthquakes or environmental deterioration can be very difficult or expensive, because these elements are normally not visible or easily accessible.

Remediation may consist either of the treatment of unsuitable soil or site conditions during the original construction, or the retrofitting of existing structures, either to correct later-discovered deficiencies or to repair damage. The applicability of various remediation techniques will depend on which of the two situations we are dealing with. For example, removal and replacement of unsuitable soils may in some cases be the method of choice in original construction, but would no longer be an available option once the structure is in place.

3.6.1 Description of Foundation Remediation Techniques

From a structural point of view, the action of structural elements in connection with foundation remediation include providing lateral support and stiffness, increasing the overall stiffness of the foundation, transferring seismic loads to stronger bearing layers, changing the resonant frequency or increasing the damping of the foundation, etc.

When considering the use of foundation remediation techniques to control or modify seismic response of a structure, the response characteristics of primary interest are the acceleration, velocity, and displacement of the structural system. Foundation remediation systems include various types of piles, sheet piles, and related structural members. Although base isolation is not addressed in this report, it offers significant benefits in controlling motions in a structure. Research in the area of base isolation, however, is considered a structural design issue.

Structural elements and systems for foundation remediation are usually selected to improve static performance, rather than to improve seismic response. The unsatisfactory static performance most often involves prediction of excessive settlement or inadequate bearing or lateral capacity. As design proceeds, the foundation system will often be modified to satisfy seismic loading requirements. However, as long as the foundation is able to meet shear and bending moment requirements from the structural loading, little effort is normally made to modify the foundation characteristics (stiffness, damping, mass) to control accelerations, velocities, or displacements in the structure. Rather the structure is designed to handle those motions.

On the other hand, it has been suggested that modification of the structural characteristics of the foundation offers potential benefits for "tuning" the soil-structure system to avoid excessive ground motion amplification. The amplification potentially results from coincidence of the natural frequencies of the soil-structure system and the seismic motion. The structural modification could include changes in the mass, stiffness, damping, and effective depth of the foundation. Because such changes are conventionally used to improve the performance of machine foundations, in principle there is no reason why similar methods could not be applied to seismic loading.

Strengthening of earthquake deficient foundations involves either additions or replacements. In all cases, the design should consider the effect of the new structural elements on remaining foundations and changes in the overall structural response.

Appropriate foundation remediation techniques may involve deeper foundations to bypass a troublesome soil layer that can not be more economically replaced or improved. Various types of piles, drilled piers, and underpinning walls are examples. These additions must be designed considering both inertial forces and ground motions.

For shallow foundations, if the deficiency is related to inadequate bearing capacity, increasing the foundation area could solve the problem provided load eccentricity and stiffness factors are properly considered.

3.6.2 The Practice of Foundation Remediation

3.6.2.1 Historical Use of Foundation Remediation Techniques

Foundation remediation systems such as piles offer a means of improving seismic response, particularly in the case of bridges and buildings that must be upgraded to meet higher seismic load requirements. The controlling need for these upgrades will likely be a reduction in the potential for yield of the soil under higher structural loading. On the other hand, economic studies may indicate that modification of mass, stiffness, damping, or effective depth of the foundation system may be less expensive than designing individual components of the structure to accommodate higher accelerations, velocities, or displacements. Fundamental to effective remediation is the elimination of all hazards such as a large displacement landslide or a foundation bearing capacity failure that would cause collapse of the structure or otherwise endanger public safety.

Foundation remediation techniques applied to liquefaction susceptible sites typically consist of structural systems designed to resist lateral and vertical loads occurring during the earthquake event. The system must mitigate loss of bearing capacity and the effects of ground settlement, and it must be adequately designed for compressive and uplift, downdrag, and lateral loads. Lateral loads from lateral spreading of liquefied soil may exceed the capacity of deep foundations. Stiffened mats or other heavily reinforced shallow systems may be required in such cases.

Systems that can be used at liquefaction sites include bored and driven piling, sheet piles, diaphragm walls (e.g., slurry and cylinder pile walls), encapsulation cells, and structural elements to increase foundation stiffness. Micro piles are not considered appropriate for this hazard due to the relatively small structural section compared to the applied loads causing bending.

Common practice in the design of bored and driven piling, diaphragm walls, and sheet piles is to ignore any lateral or vertical capacity of the liquefied soil mass. Thus the purpose of the remediation technique is to transfer load to underlying stable soil. The techniques used for determining lateral load capacity of pile systems are similar to the p-y analyses used for static load cases. These methods have not been developed nor fully verified for the dynamic case. Downdrag loads are often ignored in the liquefied zone in current designs, and uplift capacity is accounted for only below the liquefied zone.

Stiffness of pile groups in rotation and for axial loads are often accounted for by vertical and horizontal springs and by neglecting the liquefied soil mass. For bridges and marine structures, batter piles are often designed to resist lateral loads due to earthquakes. Their analysis neglects the effects of the vertical soil column above the piling and the effects of earthquake ground motions causing bending. No suitable means is available to estimate those loads for partial or full liquefaction, and the piling should be designed for bending.

In many cases settlement is accounted for indirectly by consideration of downdrag loads on the structural system. However, in the case of bridge abutments, area settlement may cause settlement of approach fills resulting in extreme vertical and lateral loads on piles. These forces need to be included in the stability analysis of the foundation system.

The techniques described above are generally applicable to liquefaction sites only if they are new sites. Retrofitting of existing structures by these methods is very difficult, for example, due to the typical size of piling and the location of diaphragm walls. Additionally, connecting the new system to existing pile caps or footings can be difficult and expensive. The question is how to make a positive connection that remains flexible and ductile.

It is important to recognize that mitigation of the effects of low probability events, such as earthquakes, does not require reduction of all associated potential damage. Accordingly, overdesign of foundation remediation measures should be avoided since such action could cause other adverse effects — e.g., stiffening the foundation could cause an increase in the inertial forces in the structure and its foundation.

3.6.2.2 Case Histories

Encapsulation cells have normally not been designed to mitigate liquefaction. However, a building with a sheetpile "skirt" wall survived the Niigata earthquake in Japan while adjacent buildings failed. This has led to the concept of using encapsulation cells to reduce the liquefaction potential of sites as well as to improve foundation stiffness. No methods are currently available to design this type of system or to estimate its effect on liquefaction potential of the confined soil.

The normally difficult problem of resisting strong ground motions for wharves can be greatly exacerbated by ground failure beneath the wharf. Some of the damage in the 1989 Loma Prieta earthquake at the Port of Oakland 7th Street Terminal was due to liquefaction failure of hydraulic fills at the wharf site (Egan, et al., 1992). The appropriate repair program for this wharf, designed by Ben C. Gerwick, Inc. and Geomatrix Consultants, involved use of vibro replacement stone columns to correct the liquefaction problem and ductile prestressed concrete piles to replace the damaged batter piles. Figure 3.23 shows the reconstructed wharf.

World War II era wharves at the Oakland Army Base were also damaged by the Loma Prieta earthquake. No soil failures were observed or suspected. Based on the results of non-linear soil structure interaction analyses for code level earthquakes, Earl and Wright designed a retrofit scheme for these seismically deficient wharves using large diameter steel pipe piles. Time histories of ground motion at various levels below the soil surface were required for these analyses.

3.6.2.3 Observed Effectiveness of Foundation Remediation Techniques

Because we have so little direct experience with the effectiveness of foundation remediation techniques, no definitive conclusions are possible at present with regard to their effectiveness.

3.6.4 Issues in the Use of Foundation Remediation Techniques

Very few retrofitted foundations have been tested by major earthquakes. Nevertheless, engineers can learn important lessons from case histories of successful and unsuccessful earthquake performance of foundation systems similar to the remediation scheme being considered. Examples range from the successful behavior of non-brittle pile foundations in major earthquakes such as San Francisco 1906 and Loma Prieta 1989 to the failure of some pile foundations due to uplift loads in Mexico City in 1985.

Analytical procedures for evaluating the effects of a foundation remediation system on seismic response of a structure seem to be well established. These include a variety of simple to highly complex numerical modelling methods. What seems to be uncertain is the accuracy to which these procedures can be used to estimate soil-structure performance. Any uncertainty in the method of analysis results directly in uncertainty in the benefits of the remediation method for modifying response of the structure to ground shaking. Limitations in the existing state of knowledge in the area of analytical procedures are the result of uncertainties in material characterization, as well as the analytical modelling method. Although various efforts are underway within the profession to improve confidence in these analytical methods, this area is still a serious research need.

A related area of earthquake research involves verification and improvement of site response models for seismic analyses of structures on sloping ground.

3.6.5 Summary

This section has described foundation remediation techniques and issues that are implemented primarily by means of structural elements, including various types of piles, walls, footings, and related elements or systems. Even though their cost is often higher than other soil improvement techniques, certainty of execution is often an overriding consideration in their selection. Research issues are primarily related to retrofitted foundations, as very few have been tested by earthquake shaking. Analysis and design procedures are well established.§

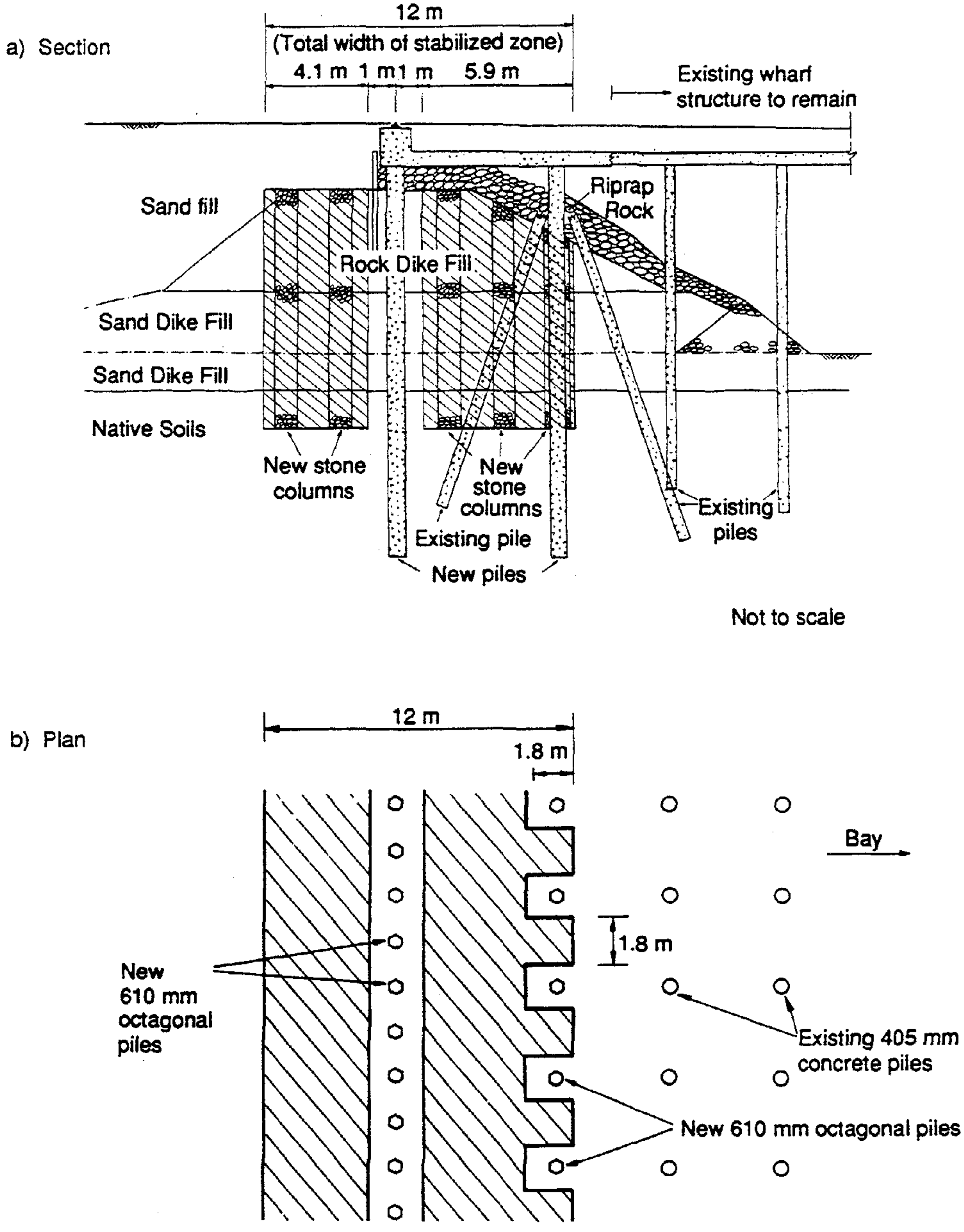


Figure 3.23. Stone columns and new piling installed to increase the seismic resistance of a wharf structure (Egan, et al., 1992)

4. Verification of Soil Improvement and Foundation Remediation

4.1 Introduction

All attempts at soil improvement and foundation remediation must be verified by some laboratory or field testing technique. In the absence of such verification, owners and engineers may not have confidence that any improvement has in fact occurred.

As discussed in previous chapters, the most common goal of soil improvement for foundation remediation is to increase the shearing resistance, or shear strength, of the soil. Therefore, verification of the effectiveness of measures intended to increase the strength of the soil would ideally measure the strength of the improved soil directly. However, increased soil strength is often accompanied by changes in other characteristics of the soil such as increased stiffness or increased density. It then becomes possible to infer improvement of soil strength by measurement of changes in one or more of these other soil properties.

Verification may be accomplished by laboratory or field testing techniques. While laboratory testing has historically been the most common means for verification of soil improvement, recent advances in field testing techniques have provided additional means for verification. Field testing techniques may be divided into in situ testing techniques and geophysical testing techniques. Ledbetter (1985) summarizes the common verification techniques.

4.2 Laboratory Testing Techniques

Verification of the effectiveness of soil improvement has commonly been performed using various laboratory tests. Laboratory testing techniques for verification purposes have a number of advantages over other methods of verification, but they also suffer from drawbacks that may, particularly for certain types of soil improvement, significantly limit their usefulness. Verification of foundation remediation involves evaluation of the response of the entire soil/foundation system, and is consequently not amenable to conventional, small-scale laboratory testing. Perhaps the most significant feature of laboratory testing techniques is the requirement of obtaining a sample of the improved soil. This requirement leads directly to many of the advantages of using laboratory testing techniques and also to many of the disadvantages.

4.2.1 Advantages

Obtaining a sample of improved soil allows visual inspection of the effects of improvement. For many soil improvement techniques, e.g., grouting, soil mixing, etc., the ability to inspect the treated soil provides direct and invaluable evidence of the pervasiveness and effectiveness of the treatment. Samples may be inspected in the field at the time of sampling or in the laboratory either before or after the performance of specific laboratory tests.

Testing of some soil properties, e.g., density, permeability, compressibility, etc., is easier to perform in the laboratory than in the field. In cases where these properties are important, considerable cost savings may be associated with verification using laboratory testing techniques.

Laboratory tests provide great flexibility in testing conditions. For example, samples of improved soil may be tested under stress conditions other than those that currently exist in situ. If the foundation soils beneath a planned embankment are improved by one or more techniques prior to construction of the embankment, the performance of the improved soil may be tested in the laboratory under stress conditions corresponding to end-of-construction conditions.

The stress conditions acting on a laboratory test specimen are generally much better known than those that exist in the field; in many tests the boundary stress conditions are directly controlled. Accurate knowledge of stress conditions is necessary for reliable interpretation of basic soil properties from test results.

The strain conditions in a laboratory test specimen are also better known and can be controlled with much more flexibility than those in field tests. As previously mentioned, most geotechnical hazards are mitigated by improving the strength of the soil. Since the strength is mobilized at relatively large strains, its measurement requires testing methods that can induce large strains. This can often be accomplished much more easily in the laboratory than in field tests.

4.2.2 Disadvantages

There are also a number of disadvantages associated with the use of laboratory testing methods for verification of soil improvement effectiveness. The disadvantages are generally associated with the necessity of sampling the soil to provide laboratory test specimens.

One of the most important considerations is evaluation of the influence of sample disturbance on test results. It is well known that some degree of sample disturbance is inevitable and that the results of many types of laboratory tests are sensitive to the effects of sample disturbance. The process of soil sampling, even with thin-walled, piston-type samplers, results in straining and remolding of the perimeter portion of the sample. This straining and remolding can change the structure and/or the density of the soil, and it can also obscure the influence of various physical and chemical processes that contribute to the in situ behavior of the soil. Since soil structure and density strongly influence properties such as strength, compressibility, stiffness, and permeability, sample disturbance can provide a misleading view of the effectiveness of soil improvement.

Many soil improvement projects involve loose, cohesionless soil deposits. The density changes associated with sampling of cohesionless soils treated by various densification techniques are particularly troublesome. Research (Marcuson, et al. 1977; Seko and Tobe, 1977; Singh, et al., 1979) has indicated that even thin-walled samplers can introduce significant volume changes in clean sands. Loose sands are densified and dense sands are loosened by the sampling process. Inaccurate evaluation of in situ density, either before or after soil improvement, can lead to considerable uncertainty in the evaluation of the effectiveness of the improvement, particularly when the effectiveness is interpreted using certain methods of liquefaction hazard evaluation (e.g., Kramer, 1989; Finn, 1991).

The process of drilling and sampling itself can be time-consuming and costly. Drilling rates can be quite slow in comparison with the rates of penetration that can be achieved with some in situ tests. Information on the effectiveness of soil improvement is not available until the laboratory tests have been completed. When faced with the need for field decisions on whether sufficient improvement has been obtained at a particular time in a soil improvement project, laboratory testing methods of verification are usually of limited use.

Another disadvantage of verification of soil improvement effectiveness using laboratory tests is the lack of geometric continuity of the information produced by a typical laboratory testing program. In a typical drilling and sampling operation, soil samples are obtained at discrete locations; continuous sampling is rarely used. As a result, measurements of soil parameters such as stiffness, strength, permeability, density, etc. are obtained at a discrete number of points and the variation of the parameters between those points must be estimated. For soil conditions in which properties can vary significantly over relatively small distances, the inferred properties may not reliably represent the properties of the entire soil mass. When soil improvement techniques are used to improve or eliminate localized zones or seams of weakness, verification by methods that require discrete sampling may be ineffective or inappropriate.

4.3 In Situ Testing Techniques

As suggested above, the disadvantages of conventional sampling and laboratory testing, especially in loose granular soils and other potentially unstable deposits, may be overcome by the use of in situ testing techniques. For this purpose, as well as in conventional geotechnical practice, the use of in situ tests has increased dramatically in the last 15 to 20 years. The traditional standard penetration test (SPT), Dutch cone penetration test (CPT), and plate load test (PLT) have been used extensively to investigate treated ground. In recent years, the pressuremeter test (PMT), piezocone penetrometer, screw plate compressometer, and the dilatometer have come into their own as in situ tests for ground improvement evaluation. Ledbetter (1985), Mitchell (1986b), and Welsh (1986) discuss in situ testing as applied specifically to foundation treatment methods, and they also present several case histories on the use of in situ tests to evaluate treated ground.

The CPT and especially the piezocone are particularly useful because they provide a continuous record with depth. Furthermore, these tests are rapid and cost effective, especially when used in sand and silt deposits. The results of penetration tests, however, must be interpreted carefully, since time-dependent increases in strength, stiffness, and penetration resistance have been observed after densification (Mitchell and Solymar, 1984; Mitchell, 1986a). Piezocone results are also especially useful at sites in which macrofabric and drainage boundaries are important, for example, when vertical geocomposite drains are used to accelerate the consolidation of soft soils.

The pressuremeter has been used extensively to determine the degree of improvement after dynamic compaction (Lukas, 1986). The PMT provides estimates of the lateral stress, modulus, and shear strength, but it is performed in pre-bored holes (unless the self-boring model is used) and it is relatively expensive, especially if a large number of separate tests are required.

In recent years, the dilatometer test has seen increasing use for determining the in situ stress and compressibility characteristics of loose sands and moderately soft clays. It is not very reliable for very soft clays and cannot be used if the soil contains gravel. In this case, relative density and improvement in soil properties after treatment must be derived from empirical correlations (Mitchell, 1986b).

Welsh (1986) notes that in situ testing techniques for establishing the degree of improvement of most grouting methods are still very primitive. Although conventional in situ testing can be used to evaluate some measure of the degree of improvement afforded by compaction grouting, care must be exercised in the interpretation of data. As described by Jamiolkowski and Pasqualini (1992), the penetration resistance of granular soils is not only influenced by relative density and depth (vertical effective stress) but very significantly by lateral stress. To the extent that improvement methods increase lateral stress, they will produce unconservative errors in the prediction of relative density based on commonly used methods, unless correction for the new stress state is considered. As for slurry grouting, fracture grouting and chemical grouting, in situ tests do not appear to hold as much promise as do geophysical methods.

4.4 Geophysical Testing Techniques

Several geophysical methods available today provide verification of the effectiveness of many ground improvement techniques. Other methods are being developed and tested for use in the near future.

4.4.1 Seismic Techniques

Most soil improvement techniques cause changes in subsurface conditions which are manifest in an increase in stiffness. Stiffness is directly related to soil modulus and modulus can be measured with seismic techniques. Furthermore, for soils treated by grouting, etc., there are empirical relationships between modulus and strength of the grouted soil.

Soil improvement techniques which result in increased modulus include compaction grouting, chemical grouting, jet grouting, soil mixing, dynamic compaction, vibrocompaction, blasting, drainage and dewatering, and stone columns. The effectiveness of all of these techniques can be verified with seismic techniques.

In most applications, it is best to perform seismic tests before and after soil treatment to measure improvement. In some instances, an increase in wave velocity is sufficient to prove improvement without absolute values of velocity. In other cases, it is sufficient to measure velocity after improvement because relationships between modulus (or wave velocity) and strength are available. The shear wave velocity (or shear modulus) is usually measured because it is not influenced by water in the soil; however where water is not present or not a factor, compression wave velocity (Young's modulus) may also be useful.

The most common seismic techniques for proof testing soil improvement are cross-hole and down-hole tests. Cross-hole testing may be superior because it integrates velocity along a wave path and represents a larger volume treated. However, a disadvantage is that the seismic wave tends to travel through the stiffest material and consequently, may not travel on a straight path from hole to hole. Byle, et al. (1991) describe the use of geophysical methods to evaluate a site treated by compaction grouting.

Seismic tests are nondestructive, but the cross-hole and down-hole test require boreholes. The recently developed spectral-analysis-of-surface-waves (SASW) method can be performed from any free surface (ground surface or inside of a tunnel wall for example), thus eliminating the need for boreholes. This makes the SASW method both nondestructive and nonintrusive (Gucunski and Woods, 1991).

SASW can be used to test any material from weak soil to rock and concrete. The procedure is the same; only the sensors, sources and spacing are different. For hard, strong materials, the spacing of sensors may be only 20 to 30 mm, while for weak soils, the spacing may be up to 30 m. This provides depths of penetration from a few millimeters to nearly 50 m.

Geotomography approaches are attractive to explore the improvement of soil in detail, but are very expensive at this time.

4.4.2 Ground Probing Radar

Ground probing radar (GPR) can identify the depth to strata of strong contrast. Ground improvement which causes sufficient change in properties should represent a reflector to electromagnetic waves and show up in GPR. This method, however, detects only boundaries and does not provide information on mechanical properties. It should probably be used with discretion and only in very specific cases for verification of soil improvement.

4.4.3 Resistivity/Conductivity

Some ground improvement techniques may produce a change in the electrical properties of the soil, and thereby cause changes in resistivity or conductivity. These methods need to be explored in more detail to determine their applicability.§

5. Research Needs

5.1 Introduction

The field of soil improvement has developed tremendously in the past two decades primarily because of three factors; (1) improved understanding of geotechnical hazards and the factors that control them; (2) the economic benefit of the development of sites with marginal to poor soil conditions; and (3) the use of innovative construction techniques developed primarily by specialty contractors. In contrast with many other aspects of geotechnical engineering, advances in soil improvement have occurred largely due to the initiative and imagination of contractors. A relatively small number of specialty contractors have developed many of the techniques now commonly used for soil and site improvement and, while many of these techniques have proven to be very effective, most have been developed by trial and error. Often, the mechanisms by which they work are not clearly understood by all practicing engineers, and thus their selection, design and utilization may not be the most efficient or economical for the soils or structure under consideration. Additional research is clearly required.

As one of the overall objectives of the workshop was to identify and evaluate current research needs in soil improvement and foundation remediation, the workshop participants devoted considerable effort to what is currently *not* known about the various techniques, especially when seismic hazards are considered. In this section, research needs as developed by the several techniques groups are described, and where possible, specific and detailed requirements are given.

5.2 Research Needs by Technique Group

In this chapter, the needs for research in soil improvement and foundation remediation are identified. These research needs were developed during meetings of the workshop discussion groups and in plenary session discussions. In keeping with the previous structure of the report and the workshop itself, they are presented in terms of the various classes of techniques. The research needs are then prioritized in a manner that reflects the general consensus of the workshop participants.

The workshop identified three major areas of research needs which are uniformly applicable across the entire spectrum of soil improvement and foundation remediation problems. These are:

1. A need for a well-documented data base of quantitative information from case histories of both failures and successes. This information is needed for validation of analytical methods, validation of field performance of remedial techniques, and verification of our conceptual understanding of the phenomena involved. Incorporation of Japanese and other foreign experience in the data base would be very useful;

2. A need for better methods of characterizing and describing the condition of soils and foundations in situ. This includes methods of nondestructive in situ testing of structural materials, soils, and rock, and methods of analysis which can account for complexity that is beyond our current ability to describe completely; and

3. A need for improved methods of verification of the effectiveness of the various soil improvement and foundation remediation techniques.

5.2.1 Densification Techniques

The densification techniques identified and discussed during the workshop have been developed primarily on a site-by-site basis by specialty contractors. As a result, existing design criteria lack the research backing required to fully understand the various densification processes.

Dynamic Compaction

Currently, no well-developed theoretical model exists for quantifying the dynamic compaction process. The basic mechanisms controlling the effectiveness of the method are not understood and, consequently, the method has probably not been optimized or "fine-tuned" to a variety of site improvement situations.

Current practice for estimating the effective depth of improvement is based on a simple empirical relationship that includes the energy per drop of the weight. Not only is this expression dimensionally incorrect, it fails to account for important factors such as the dimensions of the weight, the number of drops, level of groundwater, soil type, etc. Generally, weights used are often circular or octagonal with flat bottoms. No research has been conducted to determine the most efficient weight geometry to optimize of the transmitting stress waves into the underlying ground.

Although the dynamic compaction technique has been successfully used on both dry sites and sites with a high groundwater table, the mechanisms of densification must be different. At saturated sites several passes are used, causing local liquefaction around the impact point and subsequent reconsolidation. Although the method has been used mainly for sandy soils, it appears that it may be also applicable to silty and clayey soils, provided that effective drainage measures provide for dissipation of excess pore water pressures.

Large repeated high-energy impacts generate ground vibrations, often with low frequencies of between 5 to 25 Hz. Current threshold particle velocities and structural damage criterion are based on U.S. Bureau of Mines studies of blast vibrations with frequencies in the 10 to 60 Hz range. Some work is needed to better understand low-frequency vibrations and their attenuation with distance.

The measurement of deceleration of the weight upon impact could be used as a means of quality control and verification of improvement. This idea is analogous to the use of pile driver analyzers and high-strain measurements for evaluating pile capacities.

Dynamic compaction requires in situ testing before, during, and after improvement in order to verify the depth and extent of improvement at a particular site. While this has been previously accomplished using a variety of in situ devices (e.g., SPT, CPT, PMT, CPTU, DMT, NDE, seismic, and Becker probes), time effects now recognized in clean sands (Mitchell, 1986a; Mesri, et al., 1988; Schmertmann, 1989) have clouded the true degree of improvement. In situ tools which can effectively characterize unusual materials, such as landfills and waste materials, are also needed.

Vibro Techniques

Uncertainties in the application of vibro techniques still remain and should be the subject of further research. Items for which additional knowledge is needed include an evaluation of the increase in lateral stresses due to densification by horizontal expansion, evaluation of aging effects on probe penetration resistance, influence of soils that are believed to have potential for liquefaction, yet do not densify ("liquefy") by vibration, influence of the fines content, effect of vibrator frequency, comparison of wet vs. dry construction methods, quantification of drainage effects, and non-destructive and in situ evaluation of treated ground.

Compaction Grouting

Like many other soil improvement techniques, this technique was developed by specialty contractors without the necessary basic research. Specific research needs for compaction grouting include (1) improved understanding of the general mechanics of injecting a low slump, sanded grout into a soil and how the expanding element causes densification of soils, (2) development of a user's manual describing the theory and practice of compaction grouting for densification purposes, with an analytical procedure, typical design examples, and an updated bibliography, (3) determination of optimum spacing, pressure and mix design, and extension of the compaction grouting technique to the densification of more cohesive soils, in which a non-cementitious material is injected under continuing steady pressure.

5.2.2 Drainage Techniques

Although the design and construction aspects of most drainage techniques are quite well established, there still are several items that require improvement and thus can be considered to be research needs.

Interception

Research needs in this area include improved installation techniques, especially in controlling the alignment of subhorizontal and inclined drains. The durability and long term performance of interception drains is uncertain and requires attention.

Pore Pressure Control

A number of aspects of site characterization and soil properties, as well as post installation properties need further study.

In terms of liquefaction and settlement problems, the influence of grain size distribution and other properties such as permeability and compressibility, especially under seismic shaking, is not well understood. Conventional analyses of pore pressure control problems are at present unable to rationally consider site variability, nonlinearity of the coefficient volume compressibility m_v, its dependence on stress level and number of cycles of shaking, macro fabric of the deposit, three-dimensional and real earthquake time effects, and coupling of pore pressure and deformation.

Heretofore, only stone columns and coarse granular drainage blankets have been proposed to mitigate liquefaction effects in loose sand deposits through enhanced drainage. Research is needed on the rate of pore water pressure dissipation and rate of drainage required to prevent liquefaction. Investigation of the use of geocomposite drains for this purpose is an important research need, especially because of their advantages for rehabilitation applications in urban areas.

For evaluation and verification of pore pressure control techniques, research is needed on the durability and long term performance of these drainage systems and on evaluation of pore pressure dissipation, especially post liquefaction.

Dewatering

The primary research need in this area is in the development of improved hydrogeologic investigation models and analyses for site characterization and design properties.

As with other drainage techniques, durability and long term performance of dewatering systems, especially during and after earthquakes, needs research.

Accelerate Consolidation

Probably the most important consideration in site characterization and properties is a good understanding of especially the macrofabric of the deposit. Improved techniques and procedures for rapidly and effectively mapping the subsurface macrofabric are needed. Proper consideration of macrofabric, 3-D and real earthquake time effects in design analyses are also required.

Construction problems in this area are limited to appropriate determination of the amount and effect of smear during wick drain installation.

Wick drains are also subject to crimping and bending due to large settlements, and research is needed on how to properly consider these effects in evaluation of the effectiveness of the treatment technique.

Finally, research is needed in the long term performance and durability of the drains.

5.2.3 Physical and Chemical Modification Techniques

Grouting and Soil Mixing

Verification of the effectiveness of both physical and chemical soil improvement techniques is very important. The susceptibility of cohesionless and lightly cemented soils to disturbance during sampling makes laboratory testing less reliable. The relative weakness and brittleness of most chemically grouted sands results in samples that appear to be uncemented; hand-carved block samples are required to avoid the destructive affects of sample disturbance.

In situ testing for verification can be appropriate provided comparable preconstruction testing has been done. However, relatively minor variations in soil properties can complicate interpretation and diminish confidence in the results. Establishing appropriate techniques for evaluating the characteristics of improved soils is an important research need. Specifically, the following should be done: (1) guidelines for the potential strength improvement of fracture grouted soils as a function of soil characteristics, grout materials and application techniques should be developed, (2) the environmental impact of grouts and solidifying admixtures used in injection/mixing techniques should be evaluated, and (3) the effectiveness of deep soil mixing for improving the seismic performance of walls and foundations in various soil types should be determined.

Improved-Soil Cells or Grids

With regard to the use of improved-soil cells or grids, a better definition of the following are important research needs: (1) investigation of the effectiveness of improved-soil grids in reducing pore pressure generation in saturated granular soils during seismic events, (2) development of quantitative relationships between the thickness of liquefiable layers and the allowable spacing between improved-soil grid walls, (3) evaluation of the performance of stabilized zones in protecting structures from floating, sinking, lateral sliding or lateral spreading, and (4) evaluation of the loading induced on soil-improved grid walls constructed on slopes due to seismic degradation of retained soils (i.e., evaluation of residual strength) and potential flow of soils outside the cells.

Primary methods of study might include: (1) numerical modeling; (2) small-scale model tests using a dynamic centrifuge; and (3) larger scale model tests using a shaking table.

Improved Documentation

Improved documentation is required of projects where physical and chemical modification has been used to increase the seismic resistance of soil deposits, foundations, slopes or retaining structures.

5.2.4 Inclusions Techniques

Soil Nailing

No data is available on the performance of soil-nailed structures during shaking with peak accelerations greater than about 0.1g. Therefore, there is no check on the adequacy of current design practice under very strong shaking. The moderate to high shaking of the 1989 Loma Prieta earthquake provided no data to confirm the basic assumptions made in the seismic design of soil-nailed structures because no nails were instrumented and no walls suffered any apparent damage.

Designers are uncertain about the distribution of shear stresses and tension along the nail. The distribution of pressures that should be associated with the seismic force resulting from a Mononobe-Okabe analysis have not been established for these structures. The current practice is to use distributions determined from shaking table tests on rigid retaining walls. Selection of design horizontal and vertical pseudo-static earth pressure coefficients can significantly influence the cost of a soil nailed structure. These coefficients are currently selected in a rather arbitrary manner which, because of the implications for both safety and economy, should be verified by further research.

There are three procedures for developing suitable values of design horizontal and vertical pseudo-static earth pressure coefficients. First and foremost would be through the use of field data from instrumented walls. The infrequency of strong shaking and the difficulty in maintaining instrumentation over long time periods make it necessary to pursue other methods for clarifying seismic action of soil-nailed structures. Centrifuge tests offer the most effective procedure for determining seismic performance experimentally because effective stress levels in the field can be achieved in the centrifuge model. This is especially important because the response of the soil-structure and the action of the nails are controlled largely by the effective stress regime of the soil. Potentially useful for giving detailed insight into the behavior of soil-nailed structures is the application of finite element analyses. They do not appear to have been used very much so far to explore how the nails function or how the composite structure might behave under seismic loading conditions. If successful, this approach would be the most cost effective. The centrifuge tests could be used to verify the capability and results of finite element analyses.

Soil Reinforcement

Uncertainties in the values of dynamic earth pressure coefficients for design in a specific seismic environment have the same impact here as in soil-nailed structures. The basic design will be controlled by the earth pressure coefficients and research on their appropriate values is a high priority. Research on the general validity of the Mononobe-Okabe approach when applied to flexible reinforced soil structures is also needed.

Pull-out capacity is a key variable controlling the interaction between the soil and the reinforcement. The capacity under seismic loading requires verification. The strength and ductility of geosynthetics under seismic loading long after installation in the field requires verification.

Long term durability of geosynthetic reinforcement is an important research need, especially in terms of any synergistic effects of creep and subsequent seismic shaking.

Reinforcement Piles

The Sardis Dam problem (Section 3.5.2.2) has shown the need for research into the response of pile reinforced structures. For many similar applications, piles are a very attractive solution because of the ease of installation and the reliability of the properties of the inclusion. The latter is a major consideration in any situation involving significant issues of public safety.

Stone Columns

The feasibility of using stone columns to provide improved shearing resistance, stiffness, and lateral capacity requires attention.

5.2.5 Foundation Remediation Techniques

Foundations

The primary research needs for foundation remediation systems relates to the verification of analytical predictive methods. These verification efforts should involve: (1) review of foundation performance following seismic events, (2) instrumentation and monitoring of building and bridge foundations to obtain performance data, and (3) back analyses of performance information to calibrate analytical methods.

The potential economics and practicality of "tuning" foundation systems to reduce seismic ground motions and provide better seismic response should be investigated. There is a need for systems which can be easily added to existing foundations to change the mass, stiffness, or damping. This investigation must consider the potential variation in input motion characteristics (frequency and motion amplitude) as well as source motion directionality.

There is also a need for research on procedures which can be used to determine or confirm the dynamic characteristics (stiffness and damping) of existing foundations in order that retrofitting studies can be carried out with confidence.

To better understand the behavior and further develop the current techniques for dynamic design applications, research is required to improve our understanding of the behavior of soil and pile group interaction in a dynamic loading situation.

There is a need for techniques to retrofit existing pile foundations that are undersized.

Determination of the effectiveness of encapsulation systems to isolate and limit liquefaction, and to improve foundation stiffness needs to be made.

Improved methods need to be developed to analyze lateral load capacity of piling under seismic conditions.

Better methods are needed to determine the true residual strength of liquefied soils.

Known techniques currently considered for static stability in the remediation of slope and retaining structures, (examples: reinforced concrete retaining walls, slurry walls, bulkheads, tieback walls, rockbolting systems, buttress walls, and piling) may also be applied to seismic and dynamic design considerations.

There is a need for a better definition of seismic design loads on retaining walls. Analytical techniques should be improved to further understand and define the ground motion field around retaining walls. This would apply to reinforced concrete retaining walls, bulkheads, buttresses, and slurry walls. Design guidelines, equations, tables and charts would be helpful to practitioners.

Systematic procedures to determine the seismic design forces and to evaluate the performance of tieback anchors and rockbolting systems during earthquakes need to be established. Again, design guidelines, equations, tables and charts would be helpful to practitioners.

Effect of Code Changes

It is likely that forthcoming changes in building code seismic design requirements from working stress levels to limit state design along with the associated changes in structural ductility factors will prompt a reevaluation of existing foundations and result in increased foundation vertical and lateral forces for new structures. Research on the effects of these code changes on foundation design is timely.

Soil-Structure Interaction

Research is required on soil-structure interaction effects such as non-rigid foundation response. This work should establish the range of reduction in force levels and the associated displacements, and establish simplified analytical methods for soil-structure interaction.

Nondestructive Tests

Improvement in the methods used to evaluate the appropriate soil-foundation parameters for earthquake design is needed. Geophysical techniques that would be applicable to various types of piling warrant further experimentation. Related analytical studies are required, preferably based on results of well-documented case histories. Some high strain level and destructive tests should be performed to establish the limits of extrapolation of low strain test results to design earthquake levels.

5.3 Prioritization of Research Needs

The research needs identified and discussed in the previous section are listed in terms of the priority perceived by the workshop participants. On the basis of workshop discussions, the research needs were compared and divided into three categories: high priority, medium priority, and low priority. The order in which they are listed within these three categories is arbitrary.

5.3.1 High Priority Research Needs

General

- Development of well-documented data bases of successful and unsuccessful field performance
- Development of improved methods of determining in situ soil characteristics
- Development of improved methods for verification of effectiveness of soil improvement and foundation remediation techniques
- Enhancement of technology transfer and information exchange between USA and other countries, particularly Japan

Densification Techniques

- Development of theoretical models for understanding the mechanics of densification
- Investigation of time-dependent strength gain in densified ground
- Development of NDE methods for verifying densification effectiveness
- Further development of testing to evaluate the liquefaction potential of coarse-grained soils
- Investigation of the role of vibrator frequency and amplitude in the densification process

Drainage Techniques

- Improvement in the determination of soil properties required for drainage system design (horizontal and vertical permeability, compressibility, etc.), both before and after drain installation and before, during, and after a seismic event. Appropriate consideration should be given to nonlinearity and spatial variability of these properties
- Investigation of the suitability of gravel drains and prefabricated geocomposite drains that are installed without vibration to mitigate liquefaction potential in vibration sensitive environments
- Investigation of properties and performance of drains after large seismic events
- Development of methods for quantification of drainage effectiveness of stone columns

Physical and Chemical Modification

- Evaluation of long-term durability of grouts and cementing materials
- Investigation of the effectiveness of cells or grids of improved soil

- Investigation of the environmental effects of different types of grouts

- Identification and characterization of layered or stratified soils and evaluation of their effects on groutability

Inclusions

- Evaluation of appropriate dynamic earth pressure coefficients for nailed and reinforced structures

- Investigation of mechanics of reinforcement pile-soil systems

- Investigation of failure mechanisms for soil-nailed and reinforced soil structures

- Investigation of reinforcing effectiveness of stone columns

- Further development of physical modelling (shaking table and centrifuge) of nailed and reinforced structures

- Improvement of field instrumentation for nailed and reinforced structures

- Development of simplified numerical models for analysis of nailed and reinforced structures, and for piles and micro-piles

Foundation Remediation

- Improvement of instrumentation and monitoring of building and bridge foundations

- Calibration of analytical models by back-analyses of actual field performance

- Investigation of dynamic response of pile groups

- Investigation of methods for retrofitting undersized pile foundations

- Investigation of the effectiveness of encapsulation systems

- Evaluation of effects of building code changes on foundation design

- Development of simplified methods of analysis for soil-structure interaction

5.3.2 Medium Priority Research Needs

Densification

- Investigation of the role of residual lateral stress on the results of in situ tests

- Identification of soil types that can effectively be densified by explosives

- Investigation of the effects of shear, compression and Rayleigh waves on structural response to vibrations generated from dynamic compaction

- Evaluation of dynamic compaction efficiency at the surface by means of deceleration measurements

- Development of a manual describing the theory and practice of compaction grouting for densification purposes, with an analytical procedure, typical examples, and an updated bibliography

- Further development of the compaction grouting technique in which a non-cementitious element is injected under continuous steady pressure to improve cohesive soils

Drainage

- Rapid in situ determination of soil properties required for drain design

- Separation and quantification of the beneficial effects of densification and drainage with vibroreplacement and vibrocompaction techniques

- Investigation of long-term performance and durability of all types of drainage systems, including material durability and potential for physical, chemical, or biological clogging

- Development of means for simple verification of drainage system performance capability (i.e., that the drain is still functioning) many years after installation

Physical and Chemical Modification

- Verification of effectiveness of physical and chemical modification at the micro-level

- Investigation of the seismic performance of slurry walls and cutoff walls

- Development of grouting criteria — how much is enough?

Inclusions

- Investigation of mechanical reinforcement effects of stone columns

- Development of improved field instrumentation of piles, micro-piles and stone columns

- Development of simplified numerical models for stone columns

Foundation Remediation

- Investigation of the potential for "tuning" foundation systems to reduce dynamic response

- Development of methods for evaluation of dynamic characteristics of existing foundations

- Development of improved methods for evaluation of residual strength of liquefied soils

- Development of improved definition of seismic design loads on retaining walls

- Development of improved procedures for seismic design of tieback and rockbolting systems

- Development of improved methods for seismic analysis of retaining walls

5.3.3 Low Priority Research Needs

Densification

- Development of improved verification by geophysical methods

- Optimization of dimensions and shape of the DC tamper weight

- Investigation of liquefiable soils not liquefying by vibration techniques

- Investigation of wet versus dry installation of stone columns

- Investigation of the effectiveness of explosives

- Investigation of the range of material types for which vibrorod compaction is most suitable

- Investigation of the role of gas generation by explosives on laboratory and in situ test results

Drainage

- Development of biodegradable slurries for drain installation in loose deposits

- Investigation of bent, crimped and smeared prefabricated vertical drains

- Improvement of hydrogeological investigations, models, and analysis for dewatering systems

Inclusions

- Improvement of physical models for piles, micropiles and stone columns

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6. Future Directions for Research on Soil Improvement and Foundation Remediation

6.1 Introduction

When considering future directions for research on soil improvement and foundation remediation, it is important to keep its history in mind. Soil improvement and foundation remediation techniques have developed largely through the initiative and imagination of speciality contractors. While many of these techniques have proven to be quite effective, their use and applicability is mostly governed by empirical, heuristic rules and procedures developed through practical experience of the contractors. As a result, the actual mechanisms by which these techniques work are not always well understood, and thus their use may be more restricted than necessary and not be as efficient or economical as it could be. Both fundamental and applied research is necessary to improve their efficiency and effectiveness; such research will result in significant progress toward attaining the goals of the National Earthquake Hazard Mitigation Program.

The following sections discuss possible directions for future research on soil improvement and foundation remediation techniques.

6.2 Small-scale Testing

Small-scale testing, including laboratory testing and physical model testing, has historically been used with great success in soil mechanics. Small-scale testing offers the opportunity to evaluate the behavior of geomaterials under carefully controlled environmental and stress conditions.

Small-scale testing has proven useful in developing understanding of the physical processes involved in, for example, densification of soils. During the past 25 years, the laboratory testing that has been directed toward investigation of liquefaction and the seismic response of granular soils has greatly increased our understanding of the mechanics of densification, including identification of many of the factors that influence densification. Many of the important issues in densification, however, relate to the loading imposed on the soil by various densification techniques, as well as to the influence of boundary conditions. These factors are not easily modeled in small-scale laboratory tests.

The effectiveness of drainage techniques are less easily evaluated in small-scale tests. The important influence of boundary conditions, and the often dominant importance of material heterogeneity, render such

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tests generally less useful for investigation of the effectiveness of drainage techniques than many other soil improvement and foundation remediation techniques.

In the area of grouting and admixture stabilization, significant work has been done using small- or bench-scale testing on laboratory prepared specimens of typical field materials, which has greatly increased our understanding of the mechanics of permeation and chemical grouting. In addition, this work has permitted an evaluation of the likely improvement of waste materials and a determination of the influence of the in situ environment on stabilized materials and the concurrent influence of these materials on the environment. This latter factor is being recognized as of increasing importance. Issues relating to the influence of material heterogeneity and discontinuities on physical and chemical modification techniques, however, are still very difficult to address in small-scale tests.

The use of inclusions and foundation remediation techniques involves interaction between structural elements and the soil in which they are in contact. Such interaction problems are generally difficult to investigate by small-scale testing.

Small-scale testing does have an important place in soil improvement research. In many if not most cases, however, its applicability is limited and must be supplemented by other methods more capable of realistically representing the environmental conditions, stress conditions, and boundary conditions that are present in the field. Centrifuge model testing can play an important role in such research by allowing many of these conditions to be more accurately modeled in small-scale tests, and more tests can be conducted more economically.

6.3 Large-scale Testing

Large-scale testing can include both prototype-scale tests conducted in the laboratory as well as full-scale field tests. The former are especially practical when symmetry requires only a portion of a field problem to be modeled. Although almost always less than fully realistic, the large-scale laboratory testing affords a control of variables not often possible in the field. Full-scale field testing, though expensive and site specific, can produce extremely valuable information on the effectiveness of all soil improvement and foundation remediation techniques.

Research on soil improvement and foundation remediation using large-scale testing can be divided into two main categories: research directed toward improved understanding the mechanics of the improvement or remediation technique, and research directed toward a verification of the effectiveness of the technique. When the opportunity for large-scale testing presents itself, the research plan should consider both of these categories.

Proper instrumentation of large-scale field tests is particularly important as such tests are frequently expensive and may be impossible to repeat. Instrumentation and field measurements must be extensive, reliable and properly placed. In order to fully benefit from the large-scale tests, often extensive prior small-scale testing and analytical work may be useful. Instrumentation of improved and unimproved sites and structures in seismically active areas can be expected to yield very useful information on soil improvement and foundation remediation techniques, and programs to properly document such sites are strongly encouraged.

6.4 University-Industry Cooperation

The area of soil improvement and foundation remediation is a particularly fertile realm for interdisciplinary and cooperative University-Industry research programs. This is because so much of the development and practical application of the common soil improvement and remediation techniques has preceded the research necessary to explain how or by what mechanism improvement is obtained. As is true of most geotechnical engineering activities, the process of construction of the soil improvement technique significantly influences the characteristics of the end product. Because the practitioners and contractors have the actual experience of success and failure in field applications, their participation in research programs in this area, from planning through to execution and interpretation, can be very beneficial to the overall success of the research.

The failure of the U.S. construction industry to invest in research and development, particularly in comparison with their European and Japanese counterparts, has long been lamented. While many soil improvement specialty contractors, in spite of their relatively small size, are well above the national average in investment in research and development, most technological advances in this area still appear to be coming from overseas. One of the big reasons for this appears to be due to a difference in expenditures for research and development overseas in comparison with the U.S. Both government and the construction industry are equally responsible for the current situation.

For the situation to improve, incentives must be provided to encourage U.S. contractors to actively participate in research and development of existing and new soil improvement techniques. The potential payoffs from this cooperative participation are tremendous. Construction in all aspects is a very large portion of the overall national GNP. The return to society of expenditures on construction is almost instantaneous. Therefore, increases in productivity and efficiency in any aspect of construction has an almost immediate benefit to the local and national economy. Furthermore, there is a marvellous synergistic effect when the construction industry and university researchers work together. The research becomes more practical and immediately usable, the experience is good for student engineers working on such projects, and contractors benefit from an immediate improved understanding of the principles and processes involved and in improved credibility in later marketing of soil improvement services. These benefits to specialty contractors are real and thus are worth a significant financial and in-kind services contribution to the cost of the research project.

We believe that a significant opportunity for the future development of soil improvement and foundation remediation techniques lies in the use of interdisciplinary teams of university researchers and practitioners, particularly specialty contractors, to study and solve the problems described in this report.

6.5 National Test Sites Program

The development of a system of multiple-user test sites in the United States would be of great benefit to geotechnical engineering practice. Access to well-characterized field sites and to a central data repository would help develop, evaluate, improve and better understand laboratory and in situ tests, field instrumentation, predictive capabilities, soil improvement and foundation remediation techniques, design and construction methods, earthquake response, and geoenvironmental problems. The use of such sites for research would also lead to more cost-effective utilization of available research funds and would promote greater cooperation and exchange of information between public agencies, universities, and the private sector. Such sites have been used to great advantage in a number of other countries, resulting in significant economic benefits to geotechnical construction both internally and in the international market.

In order to discuss the establishment of a network of multiple-user geotechnical experimentation sites in the United States, the National Science Foundation (NSF) sponsored a workshop at the University of New Hampshire (Benoît and de Alba, 1988). About 50 distinguished geotechnical engineers and professors from the U.S. and abroad were invited to examine this problem. The participants were presented with the results of a pre-workshop survey of public agencies, universities and private firms in which the respondents had indicated the existence of 81 specific locations for which some level of data existed, and which potentially could be developed into multiple-user sites. One of the important conclusions of this meeting was that it was imperative to continue the process initiated by the workshop, and to establish a system of multiple-user sites, for which a central data repository should be created. This central repository would enable geotechnical researchers to select the most appropriate site for their needs. To oversee the establishment and maintenance of the data repository, identify promising sites, and encourage their use, a System Management Board (SMB) was established that would include representatives of different elements of the geotechnical community. The SMB would name a System Manager, who in turn would be charged with maintaining the central data base for the designated sites, promoting their use and helping to develop funding to support the entire program.

To preserve the momentum of the workshop and to put the process in motion, NSF provided the University of New Hampshire with funds to develop a summary catalog describing those sites that have already been proposed to be distributed to public agencies, universities, and interested private concerns. Further support was obtained for this effort through a contract with the Federal Highway Administration (FHWA) as part of the National Cooperative Highway Research Program, to establish a central data repository for all available national geotechnical experimentation sites. The scope of the work consists of developing a user-friendly system shell, with on-line computer search and data retrieval capabilities, to accommodate essential information about multiple-user test sites (generalized soil conditions, list of available test data, site logistics and limitations, published references, and any other pertinent site information). An electronic bulletin board will be provided as part of the system to permit rapid exchange of information about ongoing projects and notify experimenters of the existence of limited-access "event" sites. The data base will be continually updated as new information becomes available.

Another smaller workshop was convened in Orlando, Florida, in October, 1991, in order to develop detailed guidelines for (1) selecting the first few primary National Experimentation ("Class A") Sites and (2) selection, organization, and operation of the SMB and System Manager. Discussions were also started on the possible uses and local management of the initial Class A sites. Finally, persons who might be willing to serve on the SMB and as System Manager were proposed.

Since the Orlando meeting, the FHWA and the NSF have promised sufficient initial funds to establish the SMB, hire a System Manager, and to establish a few (3 to 4) designated geotechnical experimentation sites. It is envisioned that the sites will be characterized and the management system activated during the next two years. This initial activity will establish a system management strategy to ensure (a) maximum and appropriate utilization of each site, (b) maximum exchange of geotechnical information about each site among users, and (c) minimum costs to users.

The National Test Sites program is potentially of great value to soil improvement research. To date, field studies have often suffered from a lack of geotechnical data related to geologic and subsurface conditions both prior to and after improvement. The National Test Sites should provide excellent subsurface characterization in a variety of soil conditions. Furthermore, there is a reluctance to accept the results of small scale or even moderate scale laboratory testing on these techniques without some measure of field or prototype scale verification. Thus, the concept of National Geotechnical Test sites provides a framework for sharing of research costs and responsibilities as well as developing a cost effective mechanism for comparing the performance of various site investigation and verification techniques and soil improvement procedures.

6.6 Summary

In this chapter, the advantages and disadvantages of both traditional small-scale and large-scale or field testing used in geotechnical engineering research are discussed. The importance of increasing industry-university cooperative research is described, particularly in terms of the benefits to specialty contractors, university researchers, students, and even the local and national economies. The recent development of the National Test Sites program for geotechnical experimentation provides an excellent framework for sharing research costs and results, and it seems especially well-suited for research on soil improvement and foundation remediation techniques.§

7. Summary and Conclusions

7.1 Summary

On August 19-21, 1991 a workshop sponsored by the National Science Foundation on Soil Improvement and Foundation Remediation with Emphasis on Seismic Hazards was held at the University of Washington in Seattle.

The objective of the workshop was to provide a forum for the exchange of knowledge and experience among experts with a wide variety of viewpoints and perspectives on soil improvement and foundation remediation as well as geotechnical earthquake engineering. Invited participants included consulting geotechnical and structural engineers, specialty contractors, engineers representing all levels of government, and academic researchers. The workshop was one of the rare times that such a diverse group met for in depth discussions. The result was a real learning experience for the participants and a greatly increased appreciation for the problems and concerns each other faces in the solution of seismic hazard mitigation problems.

The specific goals of the workshop were (1) to summarize the current state of knowledge concerning soil improvement and its applicability to foundation remediation for various geotechnical hazards, especially those which are earthquake-induced; (2) to identify and evaluate current research needs and opportunities in these areas; and (3) to recommend future directions for research on soil and foundation remediation. This report is a written record of the workshop deliberations and its attempt to meet these goals.

After a brief introduction providing some background for and organizational details of the workshop, Chapter 2 presents an overview of the seismic hazards of liquefaction, ground shaking, and foundation, slope and retaining structure failures and their causes. It then discusses the general requirements of soil improvement and foundation remediation techniques for mitigation of these hazards.

Chapter 3 describes all the common soil improvement and foundation remediation techniques in terms of their current practice and illustrated by case histories, historical use, observed effectiveness, and current levels of confidence in their results. The chapter begins with a discussion of densification (dynamic compaction, vibro compaction and vibro replacement, compaction grouting, blasting, and compaction piles). Next the common drainage techniques (interception, pore pressure control, dewatering, and acceleration of consolidation) applicable to foundations, slopes and retaining structures are discussed. After physical and chemical modification techniques such as grouting and soil mixing, the chapter turns to inclusion techniques (soil nailing, metallic and geosynthetic reinforcement, piles, and stone columns) and ends with a discussion of structural foundation remediation techniques.

The issue of verification of the effectiveness of soil improvement and foundation

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remediation techniques is addressed in Chapter 4. Included are the traditional geotechnical laboratory and in situ tests, as well as a discussion of geophysical testing techniques which hold considerable promise in this area of verification.

As one of the workshop goals was the identification of research needs, these are described and prioritized in Chapter 5. Chapter 6 provides some general suggestions as to how future research in soil improvement and foundation remediation might be directed and improved. Included in this chapter is a summary of the state of development of National Test Sites for Geotechnical Experimentation, a program which holds promise for, among other things, industry-university cooperative research in soil improvement and foundation remediation techniques.

7.2 Conclusions

Although considerable progress has been made in the use of soil improvement and foundation remediation techniques, their empirical application and use indicates that much research is required for a fundamental understanding of their physical (and in some cases, chemical) mechanisms.

Probably the most important conclusion of the workshop is its development of a prioritized list of specific research needs that has been carefully considered by an interdisciplinary group of experts with a broad range of experience and perspective. The list addresses research needs for densification, drainage, physical and chemical modification, inclusions, and foundation remediation techniques. These research needs are given in Section 5.3.

There are tremendous benefits to increasing industry-university cooperative research on soil improvement and foundation remediation techniques, and such cooperation should be strongly encouraged. The developing National Test Sites program appears to provide an excellent framework for sharing research costs and results in this area.

The results of future research on soil improvement and foundation remediation techniques will lead to their more widespread acceptance, and to their more reliable economical use. As a result, research in this area will contribute to a realization of the goals of the National Earthquake Hazards Reduction Program.§

References

Allen, T.M. (1991) "Determination of Long-Term Tensile Strength of Geosynthetics: A State-of-the-Art Review," *Proceedings of the Geosynthetics '91 Conference*, Atlanta, Vol. 1, pp. 351-379.

Allen, T.M. and Holtz, R.D. (1991) "Design of Retaining Walls Reinforced with Geosynthetics," State-of-the-Art Review, Session 8A on Earth Reinforcing Systems, *Geotechnical Engineering Congress 1991*, Boulder, F. G. McLean, D. A. Campbell and D. W. Harris, editors; Geotechnical Special Publication No. 27, ASCE, Vol. II, pp. 970-987.

Ambraseys, N. and Sarma, S. (1969). "Liquefaction of Soils Induced by Earthquakes," *Bulletin of the Seismological Society of America*, Vol. 59, No. 2, pp. 651-664.

Babasaki, R., Suzuki, K., Saitoh, S., Suzuki, Y. and Tokitoh, K. (1991) "Construction and Testing of Deep Foundation Improvement Using the Deep Cement Mixing Method," *Deep Foundation Improvements: Design, Construction and Testing*, ASTM STP 1089, M. I. Esrig and R. C. Bachus, editors, ASTM, pp. 224-233.

Baker, W. H. (1982) "Planning and Performing Structural Chemical Grouting,"*Grouting in Geotechnical Engineering*, Proceedings of the conference, New Orleans, W. H. Baker, editor, ASCE, pp. 515-540.

Baker, W.H., Cording, E.J. and MacPherson, H.H. (1983) "Compaction Grouting to Control Ground Movements During Tunnelling," *Underground Space*, Vol. 7, pp. 205-212.

Barksdale, R.D. and Bachus, R.C. (1983) "Design and Construction of Stone Columns, Vol. I," Report No. FHWA/RD-83/026, Federal Highway Administration, 210 pp.

Bell, J.R. and Steward, J.E. (1977) "Construction and Observation of Fabric Retained Soil Walls," *Proceedings of the International Conference on the Use of Fabrics in Geotechnics*, Paris, Vol. I, pp. 123-128.

Benoit, J. and de Alba, P. editors (1988) *Designated Sites for Geotechnical Experimentation in the United States*, Proceedings of the NSF Workshop, University of New Hampshire, Durham, 165 pp.

Bjerrum, L. (1972) "Embankments on Soft Ground," *Proceedings of the ASCE Specialty Conference on Performance of Earth and Earth-Supported Structures*, West Lafayette, Vol. II, pp. 1-54.

Bolt, B.A. (1989) "The Nature of Earthquake Ground Motion," in *The Seismic Design Handbook*, F. Naeim, editor, Van Nostrand Reinhold.

Bonaparte, R., Holtz, R. D. and Giroud, J. P. (1987). "Soil Reinforcement Design Using Geotextiles and Geogrids," *Geotextile Testing and the Design Engineer*, ASTM STP 952, J. E. Fluet, Jr., editor, ASTM, pp. 69-116.

Bonaparte, R., Schmertmann, G. R., and Williams, N. (1986). "Seismic Design of Slopes Reinforced with Geogrids and Geotextiles," *Proceedings of the Third International Conference on Geotextiles*, Vienna, Vol. I, pp. 273-278.

Bonaparte, R., Schmertmann, G. R., Chu, D. and Chouery-Curtis, V. E. (1989). "Reinforced Soil Buttress to Stabilize a High Natural Slope," *Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering*, Rio de Janeiro, Vol. 2, p. 1227-1230.

Borden, R. H., Holtz, R. D. and Juran, I., editors, (1992) *Grouting, Geosynthetics, and Soil Improvement*, Proceedings of the conference, New Orleans, Geotechnical Special Publication No. 30, ASCE, Vols. 1 and 2, 1453 pp.

Broms, B. B. (1985) "Stabilization of Slopes and Deep Excavations with Lime and Cement Columns," *Soil Improvement Methods*, Proceedings of the Third International Geotechnical Seminar, Nanyang Technological Institute, Singapore, pp. 127-135.

Broms, B. B. and Boman, P. (1978) *Stabilization of Soil with Line Columns*, Design Handbook, 2nd Edition, Department of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm, 92 pp.

Broms, B. B. and Boman, P. (1979) "Lime Columns — A New Foundation Method," *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 105, No. GT4, pp. 539-556.

Broms, B.B and Wong, K.S. (1991) "Landslides," Chapter 11 in *Foundation Engineering Handbook*, 2nd Edition, H. Y. Fang, editor, Van Nostrand Reinhold, pp. 410-446.

Broomhead, D. and Jasperse, B. H. (1992) "Shallow Soil Mixing — A Case History," *Grouting, Soil Improvement and Geosynthetics*, Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 1, pp. 564-576.

Bruce, D. A. (1992a) "Progress and Development in Dam Rehabilitation by Grouting," *Grouting, Soil Improvement, and Geosynthetics*, Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 1, pp. 601-613.

Bruce, D. A. (1992b) "Recent Progress in American Pinpile Technology," *Grouting, Soil Improvement, and Geosynthetics*, Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 1, pp. 765-777.

Byle, M. J., Blakita, P. M. and Winter, E. (1991) "Seismic Testing Methods for Evaluation of Deep Foundation Improvement by Compaction Grouting," *Deep Foundation Improvements: Design, Construction and Testing*, ASTM STP 1089, M. I. Esrig and R. C. Bachus, editors, ASTM, pp. 224-233.

Byrne, P.M. (1991) "A Model for Predicting Liquefaction Induced Displacement" *Proceedings of the Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, St. Louis, Vol. II, pp. 1027-1035.

Byrne, R. J. (1992) "Soil Nailing: A Simplified Kinematic Analysis," *Grouting, Soil Improvement, and Geosynthetics*, Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 2, pp. 751-764.

Cedergren, H.R. (1989) *Seepage, Drainage, and Flow Nets*, 3rd Edition, Wiley.

Chaney, R. C. and Pamukcu, S., "Earthquake Effects on Soil-Foundation Systems, Part II," Chapter 16 in *Foundation Engineering Handbook*, 2nd Edition, H. Y. Fang, editor, Van Nostrand Reinhold, pp. 623-672.

Chang, F. K. and Krinitzsky, E. L. (1977) "Duration, Spectral Content, and Predominant Period of Strong Motion Earthquake Records from Western United States," U. S. Army Corps of Engineers, Waterways Experiment Station, Misc. Paper 5-73-1, Vicksburg.

Christopher, B. R., Gill, S.A., Giroud, J.P., Juran, I., Mitchell, J. K., Schlosser, F. and Dunnicliff, J. (1990) "Reinforced Soil Structures, Vol. 1: Design and Construction Guidelines," Report No. FHWA-RD-89-043, Federal Highway Administration, 285 p.

Christopher, B.R. and Leshchinsky, D. (1991) "Design of Geosynthetically Reinforced Slopes," State of the Art Review, Session 8A on Earth Reinforcing Systems, *Geotechnical Engineering Congress 1991*, Boulder, F. G. McLean, D. A. Campbell and D. W. Harris, editors, Geotechnical Special Publication No. 27, ASCE, Vol. II, pp. 988-1005.

Collin, J.G., Chouery-Curtis, V.E., and Berg, R.R. (1992) "Field Observations of Reinforced Soil Structures Under Seismic Loading," *Proceedings of the International Symposium on Earth Reinforcement Practice* (IS Kyushu '92) (submitted for publication).

DiMaggio, J.A. (1978) "Stone Columns for Highway Construction," Demonstration Project No. 46, Report No. FHWA-DP-46-1, Federal Highway Administration, 80 pp.

Dobry, R. and Vucetic, M. (1987) "Dynamic Properties and Seismic Response of Soft Clay Deposits," *Proceedings of the International Symposium on Geotechnical Engineering of Soft Soils*, Mexico City, Vol. 2, pp. 51-87.

Dobry, R. and Baziar, M. (1992) "Modelling of Lateral Spreads in Silty Sands by Sliding Blocks," *Stability and Performance of Slopes and Embankments — II*, Proceedings of the conference, Berkeley, R. B. Seed and R. W. Boulanger, editors; Geotechnical Special Publication No. 31, ASCE, Vol. 1, pp. 625-652.

Dobson, T. (1987) "Case Histories of the Vibro Systems to Minimize the Risk of Liquefaction," *Soil Improvement — A Ten Year Update*, Proceedings of a symposium, Atlantic City, J. P. Welsh, editor, Geotechnical Special Publication No. 12, ASCE, pp. 167-183.

Egan, J. A., Hayden, R. F., Scheibel, L. L., Otus, M. and Serventi, G. M. (1992) "Seismic Repair at Seventh Street Marine Terminal," *Grouting, Soil Improvement, and Geosynthetics*, Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 2, pp. 867-878.

Elias, V. (1990) "Durability/Corrosion of Soil Reinforced Structures," Report No. FHWA-RD-89-186, Federal Highway Administration, 173 pp.

Elias, V. and Juran, I. (1991) "Soil Nailing for Stabilization of Highway Slopes and Excavations," Report No. FHWA-RD-89-198, Federal Highway Administration, 221 pp.

Ergun, M. U. (1992) "Design and Performance of Two Port Silos on Improved Ground," in *Grouting, Soil Improvement, and Geosynthetics,* Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 2, pp. 842-854.

Faccioli, E. (1991). "Seismic Amplification in the Presence of Geologic and Topographic Irregularities," *Proceedings of the Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics,* St. Louis, Vol. II, pp. 1779-1797.

Felio, G., Vucetic, M., Hudson, M., Barar, P. and Chapman, R. (1990) "Performance of Soil Nailed Walls during the October 17, 1989 Loma Prieta Earthquake," *Proceedings of the 43rd Canadian Geotechnical Conference,* Quebec City, Vol. 1, pp. 165-173.

Finn, W.B.L. (1991) "Assessment of Liquefaction Potential and Post-Liquefaction Behavior of Earth Structures: Developments 1981-1991," State of the Art Paper, *Proceedings of the Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics,* St. Louis, Vol. II, pp. 1833-1850.

Gallavresi, F. (1992) "Grouting Improvement of Foundation Soils," *Grouting, Soil Improvement, and Geosynthetics,* Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 1, pp. 1-38.

Gazetas, G., Dakoulas, P., and Papageorgieu, A. (1990) "Local-soil and Source Mechanism Effects in the 1986 Kalamata (Greece) Earthquake," *Earthquake Engineering. and Structural Dynamics,* Vol. 19, pp. 431-456.

Gazetas, G., Fan, K., and Makris, N. (1992). "Analyses of Dynamic Response of Bridge Pile Foundations," Research report to Shimizu Company, State University of New York, Buffalo.

Gedney, D.S. and Weber, W.G. (1978) "Design and Construction of Soil Slopes" Chapter 8 in *Landslides: Analysis and Control,* Special Report 176, Transportation Research Board, pp. 172-191.

Graf, E.D. (1992a) "Compaction Grout, 1992" in *Grouting, Soil Improvement, and Geosynthetics,* Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 1, pp. 275-287.

Graf, E.D. (1992b) "Earthquake Support Grouting in Sands," *Grouting, Soil Improvement, and Geosynthetics,* Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 2, pp. 879-888.

Graf, E.D. and Zacher, E.G. (1979) "Sand to Sandstone: Foundation Strengthening with Chemical Grout" *Civil Engineering,* ASCE, January.

Gucunski, N. and Woods, R. D. (1991) "Instrumentation for SASW Testing," *Recent Advances in Instrumentation, Data Acquisition, and Testing in Soil Dynamics,* S. K. Bhatia and G. W. Blaney, editors, Geotechnical Special Publication No. 29, ASCE, pp. 1-16.

Handa, S.C. (1984) "Foundation Performance of Very Old Structures," *Proceedings of the International Conference on Case Histories on Geotechnical Engineering,* Rolla, Missouri, Vol. I, pp. 201-208.

Hannon, J.B. and Walsh, T.J. (1982) "Wick Drains, Membrane Reinforcement, and Lightweight Fill for Embankment Construction at Dumbarton," *Transportation Research Record* 897, pp. 37-42.

Harder, L.F., Hammond, W.D. and Ross, P.S. (1984) "Vibroflotation Compaction at Thermalito Afterbay," *Journal of Geotechnical Engineering*, ASCE, Vol. 110, No. 1, pp. 57-70.

Hausmann, M.R. (1990) *Engineering Principles of Ground Modification*, McGraw-Hill, 632 pp.

Hayden, R.F. and Welch, C.M. (1991) "Design and Installation of Stone Columns at Naval Air Station," *Deep Foundation Improvements: Design, Construction, and Testing*, ASTM STP 1089, M. I. Esrig and R. C. Bachus, editors, ASTM, pp. 172-184.

Ho, C. L., Denby, G.M. and Fragaszy, R.J. (1990). "Seismic Performance of Tied-Back Walls," *Design and Performance of Earth Retaining Structures*, Proceedings of a conference, Ithaca, P.C. Lambe and L.A. Hansen, editors, Geotechnical Special Publication No. 25, ASCE, pp. 843-853.

Holtz, R. D. and Kovacs, W. D. (1981) *An Introduction to Geotechnical Engineering*, Prentice-Hall, 753 pp.

Holtz, R.D. (1989) "Treatment of Problem Foundations for Highway Embankments," *Synthesis of Highway Practice 147*, National Cooperative Highway Research Program, Transportation Research Board, 72 pp.

Holtz, R.D. (1990) "Design and Construction of Geosynthetically Reinforced Embankments on Very Soft Soils," State-of-the-Art Paper, Session 5, *Performance of Reinforced Soil Structures*, Proceedings of the International Reinforced Soil Conference, Glasgow, British Geotechnical Society, pp. 391-402.

Holtz, R.D. and Broms, B.B. (1977) "Walls Reinforced by Fabrics — Results of Model Tests," *Proceedings of the International Conference on the Use of Fabrics in Geotechnics*, Paris, Vol. I, pp. 113-117.

Holtz, R.D. and Schuster, R.L. (1992) "Design and Stabilization of Soil Slopes," Chapter 17 in *Landslides: Investigation and Mitigation*, Transportation Research Board, (to be published).

Holtz, R.D., Jamiolkowski, M.B., Lancellotta, R. and Pedroni, R. (1991) *Prefabricated Vertical Drains: Design and Performance*, CIRIA Ground Engineering Report, Butterworth/Heinemann, Oxford, 131 pp.

Hoover, T. P. (1987) "CALTRANS Wick Drain Experiences," *Soil Improvement — A Ten Year Update*, Proceedings of a symposium, Atlantic City, J. P. Welsh, editor, Geotechnical Special Publication, No. 12, ASCE, pp. 184-196.

Houslby, A. C. (1982) "Cement Grouting for Dams," *Grouting in Geotechnical Engineering*, Proceedings of the conference, New Orleans, W. H. Baker, editor, ASCE, pp. 1-34.

Housner, G.W., et al. (1990). "Competing against Time," Report to the Governor, Governor's Board of Inquiry, State of California.

Hussin, J.D. and Ali, S. (1987) "Soil Improvement at the Trident Submarine Facility," *Soil Improvement — A Ten Year Update*, Proceedings of a symposium, Atlantic City, J. P. Welsh, editor, Geotechnical Special Publication No. 12, ASCE, pp. 215-231.

Iai, S. (1988) "Large Scale Model Tests and Analyses of Gravel Drains," *Report* of the Port and Harbor Research Institute of Japan, Vol. 27, No. 3.

Idriss, I. M. and Seed, H. B. (1968) "An Analysis of Ground Motions During the 1957 San Francisco Earthquake," *Bulletin of the Seismological Society of America*, Vol. 58, No. 6, pp. 2013-2032.

Idriss, I.M. (1985) "Evaluating Seismic Risk in Engineering Practice," *Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering*, San Francisco, Vol. 1, pp. 255-320.

Ingold, T.S. (1982) *Reinforced Earth*, Thomas Telford, 141 pp.

Jamiolkowski, M. and Pasqualini, E. (1992) "Compaction of Granular Soils — Remarks on Quality Control," *Grouting, Soil Improvement, and Geosynthetics*, Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 2, pp. 902-914.

Japan National Committee on Earthquake Engineering (1965), "Niigata Earthquake of 1964," *Proceedings of the Third World Conference on Earthquake Engineering*, Auckland and Wellington, New Zealand, Vol. 3, pp. S-78 - S-108.

Johnson, S.J. (1970) "Foundation Precompression with Vertical Sand Drains," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 96, No. 1, pp. 145-175. Also in *Placement and Improvement of Soil to Support Structures*, ASCE, pp. 9-39.

Jones, C.J.F.P. (1985) *Earth Reinforcement and Soil Structures*, Butterworths, 183 pp.

Karol, R. H. (1982) "Chemical Grouts and their Properties," *Grouting in Geotechnical Engineering*, Proceedings of the conference, New Orleans, W. H. Baker, editor, ASCE, pp. 359-377.

Kauschinger, J. L., Perry, E. B. and Hankour, R. (1992) "Jet Grouting — State-of-the-Practice" in *Grouting, Soil Improvement, and Geosynthetics*, Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 1, pp. 169-181.

Keller, T. O., Castro, G. and Rogers, J. H. (1987) "Steel Creek Dam Foundation Densification," *Soil Improvements — A Ten Year Update*, Proceedings of a symposium, Atlantic City, J. P. Welsh, editor, Geotechnical Special Publication No. 12, ASCE, pp. 136-166.

Koerner, R. M. (1990) *Designing with Geosynthetics*, 2nd Edition, 625 pp.

Kramer, S.L. (1989). "Uncertainty in Steady State Liquefaction Evaluation Procedures," *Journal of Geotechnical Engineering*, ASCE, Vol. 115, No. 10, pp. 1402-1419.

La Fosse, U. and von Rosenvinge, T. (1992) "Densification of Loose Sands by Deep Blasting," *Grouting, Soil Improvement, and Geosynthetics*, Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 2, pp. 954-968.

Lacy, H. S. and Gould, J. P. (1985) "Settlement from Pile Driving in Sands," *Vibration Problems in Geotechnical Engineering*, G. Gazetas and E. T. Selig, editors, ASCE, pp. 152-173.

Ledbetter, R. H. (1985) "Improvement of Liquefiable Foundation Conditions Beneath Existing Structures," Technical Report REMR-GT-2, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, 51 pp.

Lee, K.L., Adams, B.D. and Vagneron, J.M.J. (1973) "Reinforced Earth Retaining Walls," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 99, No. SM 10, pp. 745-764.

Leonards, G.A., Cutter, W.A. and Holtz, R.D. (1980) "Dynamic Compaction of Granular Soils," *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 106, No. GT1, pp. 35-44.

Lizzi, F. (1977) "Practical Engineering in Structurally Complex Formations (the In Situ Reinforced Earth)" *Proceedings of the International Symposium on the Geotechnics of Structurally Complex Formations*, Capri, Italy.

Lukas, R.G. (1986) "Dynamic Compaction for Highway Construction. Volume I: Design and Construction Guidelines," Report No. FHWA/RD-86/133, Federal Highway Administration, 241 pp.

Lyman, A. K. B. (1942) "Compaction of Cohesionless Foundation Soils by Explosives," *Transactions*, ASCE, Vol. 107, pp. 1330-1348.

Mansur, C.I. and Kaufman, R.I. (1962) "Dewatering," Chapter 3 in *Foundation Engineering*, G.A. Leonards, editor, McGraw-Hill, pp. 241-350.

Marcuson, W.F. III, Cooper, S.S., and Bieganousky, W.A. (1977). "Laboratory Sampling Study Conducted on Fine Sands," *Proceedings of Specialty Session 2*, Ninth International Conference on Soil Mechanics and Foundation Engineering, Tokyo, pp. 15-22.

Margason, E. and Bonaparte, R. (1984). "Landslide Repair in Orinda Claystone Utilizing Geogrid Reinforcement," *Proceedings of the Fourth International Symposium on Landslides*, Toronto.

Massarsch, K. R. (1991) "Deep Soil Compaction Using Vibratory Probes," *Deep Foundation Improvements: Design, Construction, and Testing*, ASTM STP 1089, M. I. Esrig and R. C. Bachus, editors, ASTM, pp. 297-319.

Mathis, H. and Munson, W.E. (1987) "Retaining Wall Failure at Northern Ditch," Report, Geotechnical Branch, Kentucky Department of Highways, Frankfort, 61 pp.

Menard, L. and Broise, Y. (1975) "Theoretical and Practical Aspects of Dynamic Consolidation," *Geotechnique*, Vol. XXV, No. 1, pp. 3-18.

Mesri, G., Feng, T.W., and Benak, J.M. (1990) "Postdensification Penetration Resistance of Clean Sands," *Journal of Geotechnical Engineering*, ASCE, Vol. 116, No. 7, pp. 1095-1115.

Mitchell, J.K. (1970) "In-Place Treatment of Foundation Soils," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 96, No. SM 1. Also in *Placement and Improvement of Soil to Support Structures*, ASCE, pp. 93-130.

Mitchell, J.K. (1981) "Soil Improvement — State-of-the-Art Report," Session 12, *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering*, Stockholm, Vol. 4, pp. 506-565.

Mitchell, J.K. (1986a) "Practical Problems from Surprising Soil Behavior" 20th Terzaghi Lecture, *Journal of Geotechnical Engineering*, ASCE, Vol. 112, No. 3, pp. 259-289.

Mitchell, J.K. (1986b) "Ground Improvement Evaluation by In-Situ Tests," *Use of In situ Tests in Geotechnical Engineering*, Proceedings of In Situ '86, Blacksburg, S.P. Clemence, editor, Geotechnical Special Publication No. 6, ASCE, pp. 221-236.

Mitchell, J.K. and Solymar, Z.V. (1984) "Time-Dependent Strength Gain in Freshly Deposited or Densified Sand," *Journal of Geotechnical Engineering*, ASCE, Vol. 110, No. GT11, pp. 1559-1576.

Mitchell, J.K. and Villet, W. C. B. (1987). "Reinforcement of Earth Slopes and Embankments," Report 290, National Cooperative Highway Research Program, Transportation Research Board, 323 p.

Mitchell, J.K. and Wentz, F. L. (1991). "Performance of Improved Ground during the Loma Prieta Earthquake," Report No. UCB/EERC-91/12, Earthquake Engineering Research Center, University of California, Berkeley.

Munfakh, G.A., Abramson, L.W., Barksdale, R.D., and Juran, I. (1987) "In-Situ Ground Reinforcement," in *Soil Improvement — A Ten Year Update,* Proceedings of a symposium, Atlantic City, J. P. Welsh, editor, Geotechnical Special Publication No. 12, ASCE, pp. 1-67.

National Research Council, Committee on Earthquake Engineering (1985). *Liquefaction of Soils During Earthquakes,* National Academy Press, Washington, D.C., p. 240.

Neely, W. J. and Leroy, D. A. (1991) "Densification of Sand Using a Variable Frequency Vibratory Probe," *Deep Foundations Improvements: Design, Construction and Testing,* ASTM STP 1089, M. I. Esrig and R. C. Bachus, editors, ASTM, pp. 320-332.

Newmark, N.M. (1965). "Effects of Earthquakes on Dams and Embankments," *Geotechnique,* Vol. 15, No. 2, pp. 139-160.

Noson, L.L., Qamar, A., and Thorsen, G.W. (1988). "Washington State Earthquake Hazards," *Information Circular 85,* Washington Division of Geology and Earth Resources, Olympia.

O'Rourke, T. D. and Jones, C. J. F. P. (1990) "Overview of Earth Retention Systems: 1970-1990," *Design and Performance of Earth Retaining Structures,* Proceedings of a conference, Ithaca, P. C. Lambe and L. A. Hanson, editors, Geotechnical Special Publication No. 25, ASCE, pp. 22-51.

Picornell, M. and del Monte, E. (1985) "Pile Driving Induced Settlement of a Pier Foundation," *Vibration Problems in Geotechnical Engineering,* G. Gazetas and E. T. Selig, editors, ASCE, pp. 174-186.

Porter, O. J. (1936) "Studies of Fill Construction over Mud Flats Including a Description of Experimental Construction Using Vertical Sand Drains to Hasten Stabilization," *Proceedings of the (First) International Conference on Soil Mechanics and Foundation Engineering,* Cambridge, Vol. I, pp. 229-235.

Powers, J.P., (1991), "Dewatering and Groundwater Control," Chapter 7 in *Foundation Engineering Handbook,* 2nd Edition, H. Y. Fang, editor, Van Nostrand Reinhold, pp. 236-248.

Priebe, H. J. (1990) "The Prevention of Liquefaction by Vibro Replacement," *Proceedings of the International Conference on Earthquake Resistant Construction and Design,* Berlin.

Richards, R. and Elms, D.G. (1979). "Seismic Behaviour of Gravity Retaining Walls," *Journal of Geotechnical Engineering,* ASCE, Vol. 105, No. 4, pp. 449-464.

Rixner, J.J., Kraemer, S.R. and Smith, A.D. (1986) "Prefabricated Vertical Drains, Volume I: Engineering Guidelines," Report FHWA/RD-86/168, Federal Highway Administration, 107 pp.

Ross, G. A., Seed, H. B., and Migliaccio, R. R. (1969). "Bridge Foundation Behavior in Alaska Earthquake," *Journal of the Soil Mechanics and Foundation Division,* ASCE, Vol. 95, No. SM 4, pp. 1007-1036.

Ryan, C. R. and Jasperse, B. H. (1989) "Deep Soil Mixing at the Jackson Lake Dam," *Foundation Engineering: Current Principles and Practices,* Proceedings of a congress, Evanston, F. H. Kulhawy, editor, Geotechnical Special Publication No. 22, ASCE, Vol. 1, pp. 354-367.

Salley, J. R., Foreman, B., Baker, W. H. and Henry, J. F. (1987) "Compaction Grouting Test Program — Pinopolis West Dam," *Soil Improvement — A Ten Year Update,* Proceedings of a symposium, Atlantic City, J. P. Welsh, editor, Geotechnical Special Publication No. 12, ASCE, pp. 245-269.

Sasaki, Y. and Taniguchi, E. (1982) "Shaking Table Tests on Gravel Drains to Prevent Liquefaction of Sand Deposits," *Soils and Foundations,* Vol. 22, No. 3, pp. 1-14.

Schlosser, F. and Vidal, H. (1969) "La Terre Armée," *Bulletin de Liaison des Laborotoires Routiers des Ponts et Chaussées,* Vol. 41, pp. 101-144.

Schlosser, F., Unterreiner, P. and Plumelle, C. (1992) "French Research Program CLOUTERE on Soil Nailing," *Grouting, Soil Improvement, and Geosynthetics,* Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 2, pp. 739-750.

Schmertmann, J., Baker, W., Gupta, R. and Kessler, K. (1986) "CPT/DMT QC of Ground Modification at a Power Plant," *Use of In Situ Tests in Geotechnical Engineering,* Proceedings of In-Situ '86, Blacksburg, S. P. Clemence, editor, Geotechnical Special Publication No. 6, ASCE, pp. 985-1001.

Schmertmann, J.H. (1991) "The Mechanical Aging of Soils," 25th Terzaghi Lecture, *Journal of Geotechnical Engineering,* ASCE, Vol. 117, No. 9, pp. 1288-1330.

Schuster, R.L. (1992) "Recent Advances in Slope Stabilization," Keynote Paper, Session G.3, Stabilization and Remedial Works, *Proceedings of the 6th International Symposium on Landslides,* Christchurch, New Zealand (to be published).

Scott, R. F. (1973). "Behavior of Soils during the Earthquake," *The Great Alaska Earthquake of 1964,* National Academy of Sciences, Washington, D.C., pp. 49-72.

Seed, H.B. (1968). "Landslides during Earthquakes due to Soil Liquefaction," *Journal of the Soil Mechanics and Foundations Division,* ASCE, Vol. 94, No. SM5, pp. 1053-1122.

Seed, H.B. (1970) "Soil Problems and Soil Behavior," Chapter 10 in *Earthquake Engineering,* R. L. Wiegel, editor, Prentice-Hall, pp. 227-251.

Seed, H.B. and Alonso, J. L. (1974) "Effects of Soil-Structure Interaction in the Caracas Earthquake of 1967," *Proceedings of the First Venezuelan Conference on Seismology and Earthquake Engineering.*

Seed, H.B. and Booker, J. R. (1976) "Stabilization of Potentially Liquefiable Sand Deposits using Gravel Drain Systems," Report No. EERC 76-10, Earthquake Engineering Research Center, University of California, Berkeley.

Seed, H.B. and Booker, J.R. (1977) "Stabilization of Potentially Liquefiable Sand Deposits Using Gravel Drains," *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 103, No. GT7, pp. 757-768.

Seed, H.B. and Idriss, I. M. (1967). "Analysis of Soil Liquefaction: Niigata Earthquake," *Journal of the Soil Mechanics and Foundation Division,* ASCE, Vol. 93, No. SM3, pp. 83-108.

Seed, H.B. and Idriss, I. M. (1970) "Analyses of Ground Motions at Union Bay, Seattle, During Earthquakes and Distant Nuclear Blasts," *Bulletin of the Seismological Society of America,* Vol. 60, pp. 125-136.

Seed, H.B. and Idriss, I. M. (1982). *Ground Motion and Liquefaction During Earthquakes,* Monograph series, Earthquake Engineering Research Institute, Berkeley.

Seed, H.B. and Wilson, S. D. (1967). "The Turnagain Heights Landslide, Anchorage, Alaska," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 93, No. SM4, pp. 325-353.

Seed. R.B., Boulanger, R.W., Bray, J.D., Dickarson, D.E., Kayen, R.E., Lysmer, J., Mitchell, J.K., Schmertmann, G.R., and Sitar, N. (1989) "The Loma Prieta Earthquake of October 1989: Geotechnical Considerations," Chapter 2 in *Preliminary Report on the Seismological and Engineering Aspects of the October 17, 1989 Santa Cruz (Loma Prieta) Earthquake*, Report No. UCB/EERC-89/14, Earthquake Engineering Research Center, University of California, Berkeley.

Seko, T. and Tobe, K. (1977). "An Experimental Investigation of Sand Sampling," *Proceedings of Specialty Session No. 2*, Ninth International Conference on Soil Mechanics and Foundation Engineering, Tokyo, pp. 37-42.

Shen, C.K., Bang, S., Herrmann, L.R. and Romstad, J.M. (1978) "A Reinforced Lateral Earth Support System," *Proceedings of the ASCE Symposium on Earth Reinforcement*, Pittsburgh, pp. 764-793.

Singh, S., Seed, H.B., and Chan, C.K. (1979). "Undisturbed Sampling and Cyclic Load Testing of Sands,"Report No. UCB/EERC-79/33, Earthquake Engineering Research Center, University of California, Berkeley, 142 pp.

Solymar, Z. V. and Reed, D. J. (1986) "A Comparison of Foundation Compaction Techniques," *Canadian Geotechnical Journal*, Vol. 23, No. 3, pp. 271-280.

Solymar, Z.V., Iloabachie, B.C., Gupta, R.C. and Williams, L.R. (1984) "Earth Foundation Treatment at Jebba Dam Site," *Journal of Geotechnical Engineering*, ASCE, Vol. 110, No. 10, pp. 1415-1430.

Sutton, J. and McAlexander, E. (1987) "Chemical Admixtures and Miscellaneous Methods," *Soil Improvement — A Ten Year Update*, Proceedings of a symposium, J.P. Welsh, editor, Atlantic City, Geotechnical Special Publication No. 12, ASCE, pp. 121-135.

Taki, D. and Yang, D. S. (1991) "Soil-Cement Mixed Wall Technique," *Geotechnical Engineering Congress 1991*, Boulder, F. G. McLean, D. A. Campbell and D. W. Harris, editors, Geotechnical Special Publication No. 27, ASCE, Vol. I, pp. 298-309.

Taki, O. and Yang, D. S. (1989) "Excavation Support and Groundwater Control Using Soil-Cement Mixing Wall for Subway Projects," *Proceedings of the Rapid Excavation and Tunneling Conference*, Los Angeles, pp. 156-175.

Tassios, T. P. (1987). "Failure of the Scaramaga Dry-Dock Tension Piles," Unpublished Report, Athens, Greece.

Tazoh, T., et al. (1988). "Seismic Observations and Analysis of Grouped Piles," Shimizu Co. Technical Research Bulletin No. 7, Japan.

Terzaghi, K. (1956) "Varieties of Submarine Slope Failures," *Proceedings of the Eighth Texas Conference on Soil Mechanics and Foundation Engineering*, pp. 1-41.

Terzaghi, K. and Peck, R.B. (1967) *Soil Mechanics in Engineering Practice*, 2nd Edition, Wiley, 729 pp.

Vidal, H. (1969) "The Principle of Reinforced Earth," *Highway Research Record 282*, pp. 1-16.

Warner, J. (1982) "Compaction Grouting — The First Thirty Years," *Grouting in Geotechnical Engineering*, Proceedings of the conference, New Orleans, W.H. Baker, editor, ASCE, pp. 694-707.

Warner, J., Schmidt, N., Reed, J., Shepardson, D., Lamb, R. and Wong, S. (1992) "Recent Advances in Compaction Grouting Technology," *Grouting, Soil Improvement, and Geosynthetics*, Proceedings of the conference, New Orleans, R. H. Borden, R. D. Holtz and I. Juran, editors; Geotechnical Special Publication No. 30, ASCE, Vol. 1, pp. 252-264.

Watts, K.S. and Charles, J.A. (1991) "The Use, Testing, and Performance of Vibrated Stone Columns in the United Kingdom," *Deep Foundation Improvements: Design, Construction, and Testing*, ASTM STP 1089, M. I. Esrig and R. C. Bachus, editors., ASTM, pp. 212-223.

Weaver, K. (1991) *Dam Foundation Grouting*, ASCE, 178 pp.

Welsh, J.P. (1986) "In Situ Testing for Ground Modification Techniques," *Use of In Situ Tests in Geotechnical Engineering*, Proceedings of In Situ '86, Blacksburg, S.P. Clemence, editor, Geotechnical Special Publication No. 6, ASCE, pp. 322-335.

Welsh, J.P., Anderson, R.D., Barksdale, R.D., Satyapriya, C.K., Tumay, M.T. and Wahls, H.E. (1987) "Densification," *Soil Improvement — A Ten Year Update*, Proceedings of a symposium, Atlantic City, J. P. Welsh, editor, Geotechnical Special Publication No. 12, ASCE, pp. 67-97.

Wood, H. O. (1908) "Distribution of Apparent Intensity in San Francisco," *The California Earthquake of April 18, 1906*, Report of the State Earthquake Investigation Commission, Carnegie Institute of Washington, Washington, DC, pp. 220-245.

Yamada, G. (1966). "Damage to Earth Structures and Foundations by the Niigata Earthquake, June 16, 1964," *Soils and Foundations*, Vol. 6, No. 1, pp. 1-13.

Yamanouchi, T., Fukuda, N. and Ikegami, M. (1986) "Design Techniques of Steep Reinforced Embankments without Edge Supports," *Proceedings of the Third International Conference on Geotextiles*, Vienna, Vol. I, pp. 199-204.

Yokomura, S. (1966). "The Damage to River Dykes and Related Structures Caused by the Niigata Earthquake," *Soils and Foundations*, Vol. 6, No. 1, pp. 38-53.

Yoshimi, Y. (1980) "Protection of Structures from Soil Liquefaction Hazards," *Geotechnical Engineering*, Vol. 11, No. 2, pp. 181-208.

Yoshimi, Y. and Tokimatsu, K. (1991) "Ductility Criterion for Evaluating Remedial Measures to Increase Liquefaction Resistance of Sands," *Soils and Foundations*, Vol. 31, No. 1, pp. 162-168.

Youd, T.L. and Perkins, D.M. (1987) "Mapping of Liquefaction Severity Index," *Journal of Geotechnical Engineering*, ASCE, Vol. 113, No. 11, pp. 1374-1392.

Zacher, E. G. and Graf, E.D. (1979). "Chemical Grouting of Sand for Earthquake Resistance," *Civil Engineering*, ASCE, January.

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