Geotechnical Earthquake Engineering Colloquium

Final Report
July 2009

DHS Science and Technology Directorate
Infrastructure and Geophysical Division
and University Programs

Homeland Security
Science and Technology

Rensselaer

Cover Images:

Upper Left: Niigata-ken Chūetsu, Japan, Earthquake of October 23, 2004
Photo Credit: http://www3.imperial.ac.uk/geotechnics/people/researchers/davidtaborda12

Lower Left: Liquefaction Damage to Ports in Kobe, Japan from 1995 Kobe earthquake
Photo Credit: Ross W. Boulanger, University of California, Davis
http://cee.engr.ucdavis.edu/faculty/boulanger/geo_photo_album/GeoPhoto.html

Upper Right: Port of Kobe Memorial Park following Kobe Earthquake. November 2007.
Photo Credit:
http://commons.wikimedia.org/wiki/File:Port_of_Kobe_Earthquake_Memorial_Park01ds3200.jpg

Lower Right: Aerial view of leaning apartment houses after 1964 Niigata earthquake in Japan.
Photo Credit: National Geophysical Data Center
http://www.ce.washington.edu/~liquefaction/html/what/what1.html

DIEM
A DHS Center of Excellence
Natural Disasters, Coastal Infrastructure & Emergency Management
Based at The University of North Carolina at Chapel Hill

Proceedings of the Geotechnical Earthquake Engineering Workshop

Rensselaer Polytechnic Institute
July 29, 2009

Department of Homeland Security
Science and Technology Directorate

PREFACE

The Geotechnical Earthquake Engineering Workshop, held on July 29, 2009, was one in a series of four natural hazards colloquia co-sponsored and funded by two Department of Homeland Security Science and Technology (DHS S&T) Directorate organizations: the Infrastructure and Geophysical Division (IGD) and the Office of University Programs (OUP). Other colloquia in this series addressed coastal hazards (December 2008), wildland urban interface fires (June 2009), and tsunamis (October 2009). Each hazards colloquium convened scientists, academics, and policy-makers to discuss the current state of research and identify knowledge gaps. Topics centered around the phenomenology and the impact of natural hazards on the built and natural environment. Outcomes of the colloquia were used to assemble proceedings reports describing the colloquium discussions and the research topics and knowledge gaps identified by participants.

The colloquia series involved the efforts of several individuals within DHS S&T and the research lead for the Center of Excellence (COE) for Natural Disasters, Coastal Infrastructure, and Emergency Management (DIEM).

DHS S&T: Chris Doyle, Director, IGD, and Matt Clark, Director, OUP developed the concept of the hazards colloquium series and authorized the necessary funding. Mary Ellen Hynes, Director of Research, IGD, and Heidi Whiteree, Program Manager, OUP, guided the DIEM COE throughout the colloquium planning process to ensure that DHS S&T's goals were fully understood and addressed.

DIEM COE: The University of North Carolina at Chapel Hill is the co-lead for research for the DIEM COE, under the direction of Executive Director Gavin Smith and Principal Investigator Rick Luettich. Rick Luettich and Dr. William (Al) Wallace of the Center for Infrastructure and Transportation Studies at the Rensselaer Polytechnic Institute spearheaded the Geotechnical Earthquake Engineering Workshop planning process and convened a group of leading authorities to lend their expertise and unique perspectives to the discussions of these critical research topics.

Colloquium Participants: The subject matter experts assembled for the Geotechnical Earthquake Engineering Workshop contributed their time and knowledge not only during the colloquium, but also throughout the proceedings composition process. This report relies on their combined input to convey the broad research agenda described. A complete list of colloquium participants appears in Appendix A.

TABLE OF CONTENTS

EXECUTIVE SUMMARY 1
1 INTRODUCTION 3
1.1 Background 3
1.2 Current state of geotechnical earthquake engineering practice 4
1.3 Experimental, theoretical, and instrumentation advances 6
2 THE CONTRIBUTION OF GEOTECHNICAL EARTHQUAKE ENGINEERING TO CRITICAL INFRASTRUCTURE PROTECTION 7
2.1 Dams and levees 8
2.2 Water distribution systems 9
2.3 Tunnels, bridges, and railroads 10
2.4 Airports 10
2.5 Waterfront and harbor facilities 10
2.6 Oil and gas facilities 11
2.7 Tailings and hazmat storage 11
3 TECHNICAL RESEARCH NEEDS 12
3.1 Validation of analytical procedures 12
3.2 Soil-water-structure interaction 15
3.3 Modeling of interfaces and discontinuities 16
3.4 Performance-based engineering for multi-hazards 16
3.5 Capturing field performance due to actual extreme events 16
3.6 Sensitivity evaluation of computational methods and guidance on their use 18
3.7 Innovative construction methods and the use of advanced and smart materials 18
3.8 Blast effects 18
3.9 Properly scaled laboratory testing 19
3.10 Novel ways to model field performance and underlying phenomena 19
3.11 Interdisciplinary investigations 19
3.12 Innovative ground characterization techniques 19
4 CONCLUSIONS AND RECOMMENDATIONS 22
APPENDIX A - List of Colloquium Attendees A-1
APPENDIX B - Biographies of Colloquium Attendees B-1

ACKNOWLEDGMENTS and DISCLAIMER

This document reflects the collective work of a group of dedicated scientists, engineers, policy-makers, and government officials who gathered at the colloquium hosted by the research lead for the Center of Excellence for the Study of Disasters, Coastal Infrastructure and Emergency Management (DIEM). DIEM staff would like to acknowledge the contribution of all the colloquium participants, each of whom brought a unique perspective to the event and played an important role in constructing the broader research agenda presented here. A complete list of colloquium attendees can be found in the appendix. In particular, we would like to acknowledge the work of Dr. Ricardo Dobry, professor of engineering at the Rensselaer Polytechnic Institute who led the colloquium effort and the development of the proceedings document. This document was first drafted by Dr. John T. Christian; subsequent drafts reflect the technical input of Drs. Jean M. E. Audibert, Jonathan D. Bray, Ricardo Dobry, Ahmed W. Elgamal, Robert L. Hall, Mary Ellen Hynes, Lelio H. Mejia, Jose M. Roesset, and William A. Wallace.

The views and opinions expressed herein are those of colloquium participants and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security.

This material is based upon work supported by the U.S. Department of Homeland Security under Award Number: 2008-ST-061-ND 0001.

Reference herein to any specific commercial products, processes, equipment, or services does not constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of Homeland Security (DHS), or any of its employees or contractors.

For more information about the DHS Center of Excellence–Disasters, Coastal Infrastructure and Emergency Management (DIEM) or to download this report, visit http://hazardscenter.unc.edu/diem

Homeland Security

Science and Technology

EXECUTIVE SUMMARY

There have been many major advances in geotechnical earthquake engineering since research was accelerated by the 1964 Alaska and Japan earthquakes, where much of the damage was caused by soil effects. However, in many respects the state of the art remains less than satisfactory. A number of questions with important safety and economic implications have never been answered, or even posed clearly. Recent advances in computer and information sciences, laboratory and field testing capabilities, and field observation of earthquake effects, all infused with a new generation of powerful sensing technologies, provide an opportunity for resolving many of these major problems. Specifically, analytical procedures for geotechnical analysis and design, including powerful computer simulations, show promise of providing an increasingly realistic virtual counterpart to the actual performance of soils and structures during earthquakes. They also make it possible to perform systematic quantitative observational and experimental validations of those procedures.

On July 29, 2009, a workshop (colloquium) was convened jointly by the Center for the Study of Natural Disasters, Coastal Infrastructure and Emergency Management of the University of North Carolina at Chapel Hill, and the Center for Infrastructure and Transportation Studies of Rensselaer Polytechnic Institute, to identify high priority research questions that may now be addressed with modern technological and analytical tools. The workshop was held at Rensselaer Polytechnic Institute in Troy, NY. The workshop participants are identified in Appendix A. The participants considered the range of successes and problems in the field, identified groups of facilities exposed to earthquake risk that are of concern to the Department of Homeland Security, and prepared a prioritized list of research areas that can improve the state of practice for these facilities.

The group identified an array of facilities whose performance during and after earthquakes is significantly affected by the state of practice of geotechnical earthquake engineering. Facilities were identified under the categories of dams and levees; water distribution systems; tunnels, bridges, and railroads; airports; waterfront and harbor facilities; oil and gas facilities; and tailings and hazmat storage.

The technical areas in which participants agreed that research should be focused apply across the range of facilities listed above. That is, an advance in one technical area will affect design and construction for several types of facilities. The five areas of research with the highest priority identified by the workshop are:

- validation of analytical procedures,
- soil-water-structure interaction,
- modeling of interfaces and discontinuities,
- performance-based engineering for multi-hazards, and
- capturing field performance due to actual extreme events.

The workshop also identified the following as being high priority areas of research:

- sensitivity evaluation of computational methods and guidance on their use,
- innovative construction methods and the use of advanced and smart materials,
- blast effects,
- properly scaled laboratory testing,
- novel ways to model field performance and underlying phenomena,
- interdisciplinary investigations, and
- innovative ground characterization techniques.

1 INTRODUCTION

1.1 Background

At the request of the Department of Homeland Security (DHS) Science and Technology Directorate (S&T), a workshop (colloquium) was convened at Rensselaer Polytechnic Institute, Troy, NY, on July 29, 2009. The purpose of the workshop was to identify areas in the field of geotechnical earthquake engineering in which additional research efforts are needed to understand better the fundamental phenomenology and key knowledge gaps, to inform design and decision making, and to mitigate the damaging effects of earthquakes on the Nation. The report was first drafted by Dr. John T. Christian; subsequent drafts reflect the technical input of Drs. Jean M. E. Audibert, Jonathan D. Bray, Ricardo Dobry, Ahmed W. Elgamal, Robert L. Hall, Mary Ellen Hynes, Lelio H. Mejia, Jose M. Roesset, and William Wallace. These are also the ten experts that attended the July 29, 2009 workshop. Affiliations and biographies of these workshop participants are provided in appendices A and B.

Geotechnical earthquake engineering is a sub-discipline of geotechnical engineering, which is itself part of the larger field of civil engineering. Geotechnical engineering deals with facilities constructed in or out of geological materials such as soils and rocks and represents the interface between civil engineering and geology. Geotechnical earthquake engineering focuses on understanding and evaluating the geotechnical effects of earthquakes. Improved understanding of the response and performance of soils and soil-structure-water interaction in the frequency range of typical earthquake loads helps advance fundamental understanding in other frequency domains of interest, such as lower frequency pavement loading and higher frequency high-speed rail and blast loading. Post-earthquake evaluation of the performance of soil and soil-water-structures also sheds light on the behavior of structures subjected to blast events. Improving the fundamental understanding of the range of interactions between the built environment and the geological substrata is needed for effective and affordable design approaches that can mitigate the effects of natural hazards.

Because geotechnical engineering borders several other disciplines, there is considerable interaction between the geotechnical engineer and those in other fields, such as structural engineers, coastal and harbor engineers, geologists, and seismologists. Therefore, research and design questions may involve more than one discipline. The disciplinary interfaces often correspond to situations in which different mechanical systems or materials interact and, thus, present particularly complex problems that require interdisciplinary cooperation in order to be fully understood. The interaction among the disciplines also presents opportunities for new ideas and synergies. The 21st century challenge here is to figure out how these assorted disciplines can work together most effectively, and this report identifies some of these cases as areas in which further research could be particularly productive.

The workshop did not address specific issues arising from either deterministic or probabilistic seismic hazard analysis for ground motions. The results of such analyses constitute an important part of the input to geotechnical engineering on many projects, but several issues, including the description of ground motion relations and the treatment of epistemic uncertainty, are not fully resolved. The results of seismic hazard analyses, including probabilistic seismic hazard analyses, are usually presented in the form of ground

motions or ground motion parameters that define some conservative boundary such as the 84th percentile exceedance level. As these seismic motions form the basis for further design decisions, there is an inherent conservatism that is seldom addressed in the rest of the design process. A more rational treatment of uncertainty in seismic loadings should be adopted. However, this is an area of research that has been traditionally dealt with by the seismological community and, thus, falls outside the scope of this workshop.

The workshop met in July 2009, and the draft of this report went through several drafts in the subsequent weeks and months. The report was essentially complete before the Port au Prince, Haiti, earthquake of January 13, 2010, occurred. At the time this final form of the report is being prepared, the information available from the earthquake is largely anecdotal, and there is little scientific or engineering analysis of the events in what was clearly a major humanitarian disaster. In the absence of hard data, the authors of this report have decided not to incorporate potentially relevant information from the Haiti earthquake. However, it is worth noting that one of the major bottlenecks in the relief process is the extensive damage to the airport and to port and harbor facilities at Port au Prince, with the damage to the seaport having a substantial geotechnical component. This illustrates again the criticality of those two types of infrastructure discussed in sections 2.4 and 2.5 of this report.

1.2 Current state of geotechnical earthquake engineering practice

The evolution of geotechnical earthquake engineering has been driven by several factors, including the efforts to harden nuclear missile silos in the 1950s, the design of nuclear power plants through the 1970s, and the impact of several major earthquakes. Although the decline in construction of new nuclear power plants in the late 1970s removed a major impetus for improvements in the practical use of instrumentation, laboratory measurements, analysis, and design to resist earthquakes for critical facilities, there have been substantial achievements in other areas. The 1977 National Earthquake Hazard Reduction Program, prompted by the 1971 San Fernando, CA earthquake, provided new impetus for geotechnical earthquake engineering research — largely channeled through the National Science Foundation and the U. S. Geological Survey — but initially research was mostly limited to buildings. In the process, research investment and efforts that were focused on the performance of structures other than conventional buildings became the purview of agencies such as the U. S. Bureau of Reclamation (USBR) and U. S. Army Corps of Engineers (USACE) for dams, and the Federal Highway Administration for bridges.

The 1989 Loma Prieta, 1992 Landers and 1994 Northridge earthquakes, all in California, and the 1995 Kobe (Japan), 1999 Kocaeli (Turkey), 1999 Chi-Chi (Taiwan), and 2002 Denali (Alaska) earthquakes, in addition to many other major damaging earthquakes over the past two decades, have led to important advances in the practice of geotechnical earthquake engineering. The Seismic Hazards Mapping Act in California has advanced significantly the level of practice both in and outside of California. Some of the probabilistic performance-based earthquake engineering methods, such as liquefaction triggering relations, have started to make their way into practice in California. Ground motion selection and ground motion effects including amplification by local soils are much better understood. Near-fault ground motion effects are recognized as driving design in many areas, and this recognition has entered engineering practice, most notably following the 1992 Landers earthquake in California.

In many cases, observations from recent earthquakes provided the case history data to confirm or expand existing theories and were needed to enable the state of the practice to advance. Many new problems were solved as they arose following these earthquakes. Probabilistic methods were available, but they were not

adequately understood or refined so that they could impact practice in the manner that they are influencing it today. Nevertheless, for the large majority of facilities, especially those not located on the west coast or not expected to be exposed to very large earthquakes, geotechnical engineering practice still reflects the state of the art in the 1980s, as illustrated by the following two examples.

The first is the treatment of dynamic soil-structure interaction. The current state of practice is to divide the analysis into several steps, including amplifying the input motion through the supporting soils in the free field, computing the response of the structure or embankment as a linear structure, using pseudo-static models to evaluate the factors of safety or yield accelerations for potential failure mechanisms, and using sliding block models to estimate displacements along possible failure surfaces. It is conventional to use an iterative linear approximation to estimate the dynamic nonlinear stress-strain soil properties and to assume that the iterative values obtained in the amplification phase of the analysis can be used in the remaining dynamic analyses.

Overturning of slender building on shallow foundation in Adapazari, Turkey during the 1999 Kocaeli Earthquake (Observation made at N40.7841 E30.3998 on 8/25/99 at 1240). Photo courtesy of National Science Foundation – Geo-Engineering Earthquake Reconnaissance.

Although a few engineers and designers of critical facilities have focused on comprehensive finite element or finite difference methodologies to capture all of these efforts into single complex models, use of such methodologies is not widespread. For large and critical dams, the USACE has used coupled or partially coupled codes incorporating various ways of dealing with excess pore water pressures within the soil induced by the earthquake shaking to estimate deformations of soils and rock fills. The simplified, non-coupled techniques were employed in preliminary analyses. If the structure passed the performance criteria in these simplified – and hopefully conservative – methods, engineers did not proceed to the more complicated ones. If retrofits were needed, much more sophisticated codes were used. A number of other codes were compared in the proceedings of the 1993 conference on Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems, including uncoupled, partially coupled, and fully coupled codes. These efforts showed that unacceptable levels of ground deformation could occur before pore water pressures rose to the level of the confining stresses, and that full liquefaction of water-saturated sands was not necessary to get unacceptable levels of deformation. For example, an increase in the excess pore pressure of approximately 20% can lead to a reduction in safety factor of about the same amount. The behavior of the pore water pressure as deformation occurs is therefore important, in many cases more so

than the inertial effects during the earthquake shaking. However, these findings are not yet fully incorporated in engineering practice.

The second example is the evaluation of the potential for liquefaction or lateral spreading of water-saturated sandy soils during and after an earthquake. Most of the methods in practical use rely on field tests such as the standard penetration test (SPT) or cone penetration test (CPT) to establish the resistance of the soil materials, and on relatively simple dynamic analyses to establish the loadings. The experimental support for these methods is poor. The procedures rely heavily on field observations on level or nearly level ground made in the aftermath of past earthquakes. Extrapolation to steeper slopes or to cases in which there is significant interaction with a structure, such as a retaining wall, has much less experimental validation than the procedures for level ground. The widely used cyclic triaxial test of a small soil specimen provides a poor representation of the state of stress, stress path, and strain path of actual soil elements in a full-scale soil or soil-structure system. The best way to incorporate the effects of overconsolidation, seismic stress history, adequate pore water saturation, confining stress, and initial shear stress in liquefaction evaluation remains controversial.

In both these examples, the currently employed methods are ingenious engineering approximations to a complicated reality, and they may well be the best that can be done to deal with the actual complexity of soils as they exist in the ground. However, it is also true that these methods have not been dramatically changed since they were first introduced decades ago, and the state of practice has not yet benefited significantly from recent advances in experimental and analytical capabilities.

1.3 Experimental, theoretical, and instrumentation advances

Although most design procedures have not changed dramatically in the last thirty years, there have been many advances in the state of seismological knowledge,, as well as in computational abilities, field measurements, and laboratory facilities. Some of these include:

a) The George E. Brown, Jr., Network of Earthquake Engineering Simulation (NEES). This program has created a network of modern field and laboratory experimental facilities, located at universities and research stations across the country. They include centrifuge modeling and large-scale laboratory and field facilities equipped with some of the most advanced testing and sensing technologies. It is now possible for earthquake engineering researchers to carry out experimental studies of earthquake phenomena at a scale and detail that could not be contemplated a decade ago.

b) Modern computational capacity. Engineers now have on their desks or in their briefcases greater computational power than existed on the main-frame computers in use at the time most of the current computational methods were developed. Programs like FLAC3D, PLAXIS, LSDYNA, ABAQUS, ANSYS, ADINA – particularly the first ones – are being used extensively in geotechnical engineering research and practice, although perhaps more for traditional geotechnical problems than for earthquake related ones. The impact of computers in engineering practice is not limited to the increased computational capabilities but also to the possibility of storing and manipulating large amounts of data in different forms and facilitating remote communications. Geotechnical earthquake engineers have not yet taken full advantage of the increase in computational power and availability. Several hurdles to be overcome include the sensitivity of complex computer results to

the details on how the particular codes are used, lack of guidance on the use of the codes, and insufficient validation for a variety of relevant engineering systems and earthquake loadings.

c) Modern satellite and airborne measurement techniques. The recent improvements in global positioning systems (GPS) and their integration with geographic information systems (GIS) have effected significant improvements in the technology for capturing field data. These have changed the post-earthquake investigation from an exercise using film cameras and notebooks into a procedure of capturing data electronically, relating it to times and places, and storing it in databases for later retrieval and processing. Furthermore, communications advances, wireless transmission of data, wireless sensors of all kinds, and "smart" materials have greatly enhanced the ability to instrument facilities on a permanent basis and to monitor their state of health continuously. GIS-based approaches and the 3-D data VIZ-rooms are providing powerful visualization tools that greatly improve the ability to use the data and to formulate geologic models. Advances in sensing technology and reductions in its cost will provide more actual data from multiple instrumented sites, which will in turn lead to better understanding of attenuation and amplification phenomena and site response at various distances from the source.

These are three examples of areas in which advances in technology have made it possible to investigate seismic phenomena in greater depth and detail than ever before.

2 THE CONTRIBUTION OF GEOTECHNICAL EARTHQUAKE ENGINEERING TO CRITICAL INFRASTRUCTURE PROTECTION

The mission of DHS includes protecting critically important infrastructure, which encompasses a broad range of facilities found in a wide variety of locations throughout the country.[1] Measures to protect key facilities and structures must deal not only with procedures for designing and building new facilities but also with methods of evaluating and retrofitting existing structures and monitoring their performance. A brief list of the types of facilities involving geotechnical engineering that might be considered critical includes: embankments (such as dams, levees, canals, railroads, and bridge abutment ramps); deep foundations (such as bridge piers, navigation locks, and reservoir control towers); pipelines and other types of buried lifelines; waterfront and harbor facilities; and almost all types of transportation facilities such as tunnels. In addition to the dynamic loading of infrastructure facilities, the effects of earthquakes can include fault offsets, landslides, and underwater slope failures that disrupt undersea cables or pipelines. The following sections provide a brief description of critical facilities and other infrastructure that fall in the domain of geotechnical earthquake engineering.

[1] See the DHS Critical Infrastructure and Key Resources web page at http://www.dhs.gov/xprevprot/programs/gc_1189168948944.shtm.

2.1 Dams and levees

Dams and levees are physically similar and are often only distinguished by function. Many water retention projects consist of main dams as well as ancillary levees, and it has been argued that, when levees are intended to protect the public from catastrophic flooding, the design criteria should be closer to those for dams.

Broadly speaking, water retaining dams can be divided into concrete dams and soil or rock fill dams. While the latter are obviously in the purview of geotechnical engineers, elements of the former should be as well. Although the body of a concrete dam is by definition concrete and designed by a structural engineer, the dam sits on and is supported by soil or rock. The design and behavior of foundations for concrete dams, especially arch dams, is a major geotechnical problem, including their response during and after earthquakes. Furthermore, dam systems usually include attendant secondary soil or rock fill embankments, and pile foundations for navigation locks and reservoir control towers.

Dam failures can cause extensive damage and loss of life. The failure of the South Fork Dam, PA, in 1889 (which led to what is known as the Johnstown Flood) killed approximately 2,200 people. The 1928 failure of the Saint Francis Dam, CA, due to distress in the foundations at both abutments, killed at least 450 people. The failure of Teton Dam, ID, in 1977 led to 11 deaths and the attendant economic losses have been estimated as high as $2 billion. As of this writing, there have been no comparable failures due to earthquakes. However, the damage to the Lower San Fernando Dam, CA, in the 1971 San Fernando earthquake, due to liquefaction of part of the embankment, came close to causing a full rupture of the dam. A few more seconds of shaking would have caused that rupture and released the impounded water. The danger of flooding of the San Fernando Valley downstream of the dam prompted the evacuation of approximately 80,000 people from their homes.

The 2006 FEMA 576 report "Dam Safety and Security in the United States"[2] states that there are approximately 79,500 dams in the National Inventory of Dams (NID). More recent figures have raised this number to over 80,000, and the current belief is that more that 83,000 dams ought to be in the NID. To be listed in the NID, a dam must be over 25 feet high or impound a reservoir with a capacity of 50 acre-feet or more, although there are exceptions to these criteria. The ownership and purpose of these dams is widely distributed. For example, the 2006 report states that 56.4% of the NID dams are privately owned and only 5.7% are federally owned. The type of owner for 11.6% of the dams is listed as "Undetermined." Although the USBR and the USACE built or were involved in some way with approximately 1,000 dams, the Natural Resources Conservation Service provided technical assistance for nearly 27,000 of the NID dams.

Responsibility for maintaining, inspecting, and regulating dams varies between federal, state, and local authorities. It should also be noted that there is probably an unknown number of dams in addition to those in the NID that have not yet been identified and listed. Although dams provide an important service to the communities they support, only a small subset of dams are "critical" from the perspective of the National Infrastructure Protection Plan.

[2] http://www.damsafety.org/media/Documents/PDF/fema576.pdf

Levees have been built throughout the Nation both to direct the flow of rivers and to contain overflows in case of floods or other natural catastrophes. Although the spectacular failure of levees in New Orleans, LA, during Hurricane Katrina in 2005 is well-known, the risk of levee failure also exists along most of the Nation's waterways. The causes of levee failures are still the subject of scientific controversy. Many of these waterways have small seismic exposure, but some of them flow through areas with significant seismic hazard in California as well as the New Madrid earthquake zone, located at the intersection of the states of Arkansas, Illinois, Kentucky, Missouri, and Tennessee.

The Sacramento Delta area in Northern California provides a classic example of a series of levees at risk. Many of the California levees were built to reclaim land for agricultural purposes, but much of the land has since been developed for residential and commercial uses. There is widespread belief that a combination of inadequate maintenance and subsidence has led to a serious risk that a major earthquake could cause failures of several levees with consequent losses of life and property.

Many levees and dams along navigational waterways may also be vulnerable to ship impact. Although not an earthquake problem, analysis of loading due to ship impacts can take advantage of earthquake engineering knowledge and tools. Like dams, pipelines, and other linear structures of great extent, levees are often exposed to surface fault rupture hazards. In view of the vulnerability of most structures to surface fault displacement, mitigation of surface fault rupture hazards is particularly challenging.

2.2 Water distribution systems

Dams and the reservoirs they retain are major components of water distribution systems, which include many other facilities such as pipelines, regional and local distribution centers, and pumping stations. All of these could be impacted by an earthquake. They generally have less visibility than large dams and as a result may receive less attention. There is a significant geotechnical aspect to their design, particularly when they must be built to pass through or over regions of weak soils or potential fault displacement.

It is difficult to exaggerate the significance of reliable water distribution systems for maintaining a modern urban society. In addition to the need for an adequate supply of safe drinking water, communities rely on the availability of water to put out the fires that often accompany earthquakes. In both 1906 and 1989, failure of the auxiliary fire-fighting water distribution systems in the city of San Francisco, CA, created great difficulty in containing the fires caused by these major earthquakes. These were not isolated cases restricted to San Francisco, as post-earthquake fires have occurred in many other cities. Hence, assuring water availability after the event is extremely important. Sewage treatment and disposal is another significant component of water supply and distribution. These systems are usually similarly situated and often have the same vulnerabilities.

A further complication in addressing the vulnerability of water distribution systems is that they are sometimes connected across large distances. Disruption of the systems in one area could affect the availability of water in other locations. The complexities of the California water distribution systems provide a case in point. Local failures may affect local conditions, but there are also canals and pipelines connecting different sections of the state.

2.3 Tunnels, bridges, and railroads

There are many transportation facilities whose disruption by an earthquake would have serious economic consequences, to say nothing of the difficulty of bringing relief supplies and reconstruction equipment into the affected area. In particular, geotechnical considerations for these facilities include bridge piers and abutment ramps, locks along waterways, tunnels of all sorts, and high-speed railroad embankments. All of these are potentially vulnerable to disruption by an earthquake. The tools for designing these facilities have not significantly changed for years, and in many cases the behavior of the complicated combinations of soils and structures that comprise these facilities is not well understood.

The disruptions caused by failures of bridges and elevated structures in California during major earthquakes since 1971 received wide publicity and have led to significant improvements in design procedures for highway structures. These failures also prompted extensive retrofitting efforts. In other parts of the country, where earthquakes do not occur frequently but still pose credible threats, destruction of tunnels and bridges would impair transportation networks over wide regions of the country. For example, a limited number of highway and railroad bridges span the Mississippi River, many of them located in or near the New Madrid seismic zone. Failure of several of these facilities would have serious economic consequences throughout the country.

At present there are limited high-speed railroad facilities in the United States, and the speeds attained by the systems are modest compared to those achieved in Europe and Japan. Nevertheless, it is reasonable to assume that future systems will be much more widely distributed and will operate at higher speeds. The higher speeds by themselves will impose greater demands on railroad embankments built with traditional methods, and the wider distribution will expose the systems to greater likelihood of earthquakes.

2.4 Airports

Airports present a special set of vulnerabilities. Although each airport is limited in area, loss of an airport can seriously impair the ability to move people and supplies in and out of an area affected by an earthquake. Both the structures, such as control towers, and the runways may be damaged by an earthquake. Airports also have extensive facilities for storing fuels and lubricants; failure of such facilities poses a hazard in itself and may also make it impossible to operate aircraft for lack of fuel. The 1989 Loma Prieta, CA earthquake put all three of the major airports in the San Francisco Bay area – Oakland, San Francisco, and San Jose – out of commission, each for a different reason. Advances in geotechnical engineering may lead to improved design and retrofit of airport structures and runways so that disruption to the local and national air transportation system may be reduced or eliminated.

2.5 Waterfront and harbor facilities

Waterfront and harbor facilities present a particularly difficult set of problems. They are often built in locations where the soils are weak and compressible, and competitive cost constraints often limit the amount of effort that can be devoted to earthquake protection. The almost total destruction of the port facilities at Kobe in the 1995 Hanshin-Awaji, Japan, earthquake demonstrated that even facilities that were thought to be well designed to modern standards may be at risk. In addition to the potential loss of life in such an event, the economic consequences of disrupting the commercial activity at a major port are enormous.

Many existing port facilities were built decades ago, and their design procedures may not conform to modern understanding of earthquake effects. Also, port facilities include several types of retaining structures in which structural systems such as sheet piles and tie-backs are expected to work in conjunction with the soil, and the dynamic behavior of these systems is notoriously difficult to analyze.

2.6 Oil and gas facilities

Major oil and gas facilities include onshore and offshore drilling and pumping platforms, pipelines and refineries. Because many facilities must be sited where the oil or gas is located and because economics often dictates that other facilities be built on marginal land that is weak, compressible, or liquefiable, the foundation conditions may be poor at best. This provides real challenges to the geotechnical engineers, and it also increases the vulnerability to earthquakes.

Most new oil and gas facilities are well designed ductile structures that are usually able to accommodate significant earthquake demands except for relatively large ground movement or at critical connections. On the other hand, older facilities and weak links in networks present potential risks that are not always well understood.

Pipeline networks exist throughout the Nation, including those offshore. Some of these carry hazardous or flammable substances, such as natural gas. Inevitably, the performance of pipelines involves their interaction with the soils into which they are built, so they become a concern of geotechnical earthquake engineering. Researchers in the field of lifeline earthquake engineering have studied the performance of pipelines for decades and have developed building codes to make them more resistant to earthquake effects. However, modern research techniques could probably improve these design standards, and not all hazardous conditions have been identified.

2.7 Tailings and hazmat storage

In addition to dams that retain water, there is a large class of dams built to retain the wastes from mining and chemical processing of minerals and ores. These facilities exist under a variety of names, but they generally fall under the rubrics of waste piles or tailings dams. Some can be very large; by one current estimate the second largest impoundment in the world, after the Three Gorges Dam in China, is the Syncrude tailings facility in Alberta, Canada. The materials impounded behind tailings dams can also be quite toxic, especially if they are the by-products of chemical processing. Well-known examples of catastrophic failures of these structures include the Buffalo Creek, WV, disaster of 1972, in which the failure of a dam impounding coal mining wastes killed 125 people and made some 4,000 people homeless; recent failure of coal waste impoundments at Tennessee Valley Authority sites; and the 1965 earthquake liquefaction failure of the El Cobre copper mining tailings dam in Chile that killed more than 200 people. Although many of these facilities are well designed and maintained, there is a tendency to view them as expensive waste disposal facilities whose costs must be kept to a minimum despite the often disastrous consequences of inadequate engineering.

3 TECHNICAL RESEARCH NEEDS

The workshop identified twelve areas of technical research needs. Advances in these areas are relevant to DHS facilities and would significantly improve the state of practice of geotechnical earthquake engineering, thus both reducing the likelihood of failure during future earthquakes and improving the ability to recover from them. The twelve areas of research are, in order of priority:

1) validation of analytical procedures,
2) soil-water-structure interaction,
3) modeling of interfaces and discontinuities,
4) performance-based engineering for multi-hazards,
5) capturing field performance due to actual extreme events,
6) sensitivity evaluation of computational methods and guidance on their use,
7) innovative construction methods and the use of advanced and smart materials,
8) blast effects,
9) properly scaled laboratory testing,
10) novel ways to model field performance and underlying phenomena,
11) interdisciplinary investigations, and
12) innovative ground characterization techniques.

The areas are described below in the priority order established by the workshop. The first five (sections 3.1-3.5) are considered especially critical.

3.1 Validation of analytical procedures

Understanding soil behavior and constitutive modeling of soils and rocks has been a major concern of geotechnical research since the beginning of the study of soil and rock mechanics. Initially these efforts dealt only with static loadings, but in the last few decades, the corresponding models have been extended and modified to include the cyclic and fast character of earthquake and other dynamic loadings. While there have been significant advances, much of this research has had little impact on the practice of earthquake engineering. At present the cyclic stress-strain nonlinearity in soil behavior is usually dealt with by using iterative models that relate shear modulus and damping ratio to a measure of the average shear strain incurred during cyclic loading. Even this result is itself a linear visco-elastic approximation to the actual nonlinear behavior, and it over-estimates damping at high frequencies and under-estimates it at low frequencies. Furthermore, iterative linear models perform best at moderate levels of soil strain and deformation, and do not represent the stronger nonlinearities often associated with the extreme earthquake loadings which may affect critical infrastructure. Indeed, current practice is that, once reasonable values of

shear strain and corresponding modulus and damping ratio have been estimated, further analyses are carried out only linearly using the iterated values. In addition, very often the soil-structure or soil-foundation analyses are also done linearly using the iterated values obtained in the free field far from the structure. This methodology will not detect local nonlinearities, concentrations of strain, or other discontinuities. Furthermore, the linear analyses based on iterated values cannot capture important sources of nonlinearity such as appearance of cracks and gapping within the soil, or friction and separation at interfaces between soil and structural elements. In fact, even use of state of the art fully nonlinear analyses with proper constitutive relations may fail to capture some of these effects that may be modeled more appropriately by discrete rather than continuum methods. Therefore, when local effects are expected to be significant, the current practice is essentially to use conservative designs and to ignore the nonlinearities in the analysis and design. This approach does not address the evolution of failure in complex situations.

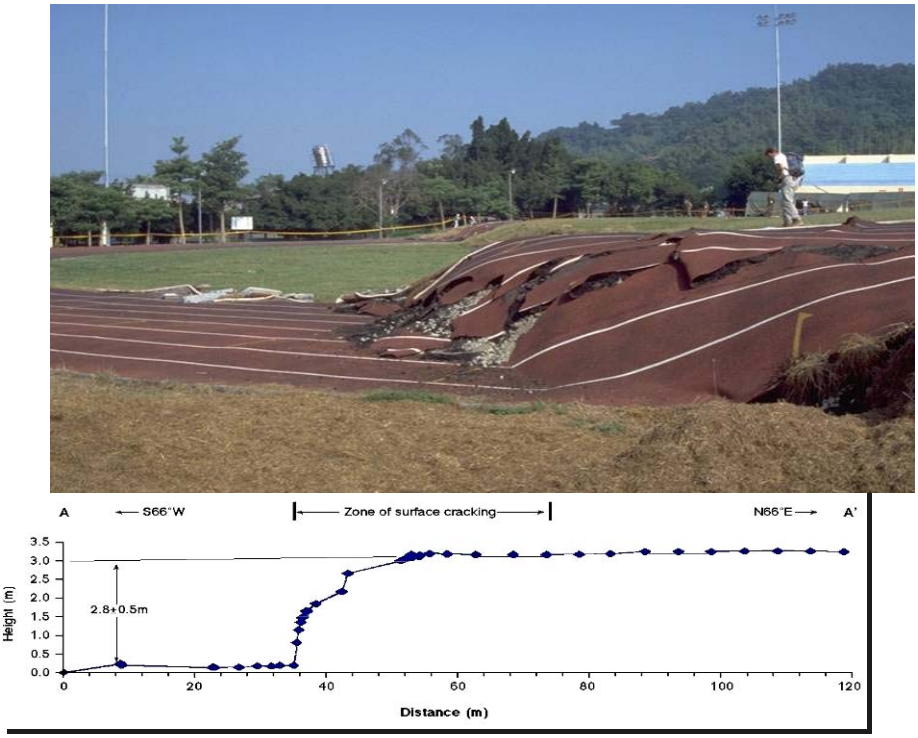
Current practice for local effects is conservative and ignores nonlinearities. This does not address the evolution of failure in complex situations.

Dynamic analysis presents many other difficulties, including proper consideration of boundary conditions to allow energy to be transmitted away from the problem site and the correct local computational details. These difficulties combine with the difficulties of constitutive continuum modeling to inhibit incorporating important details in dynamic analyses. The recent increases in computational capabilities should provide an opportunity to improve this situation. With the exception of the iterative models, which are really linearizations of the nonlinear problem, one of the few dynamic computer codes now widely used in geotechnical engineering which incorporate nonlinear formulations is the explicitly formulated finite difference program FLAC. Some finite element codes such as ABAQUS can deal with both dynamic capabilities and nonlinear materials, but they were not formulated for conditions that arise in the geotechnical environment and their use requires substantial compromise.

A further problem is that, although many constitutive models have been developed over the years, most of them are fully understood only by their developers and have found little wider application. The few models that have found application in static problems have not been widely used in dynamic analyses.

While the above considerations have been identified separately, they actually arise in combination. That is, one cannot address one of them without referring to the state of the art of the others. Thus, a challenge to geotechnical earthquake engineers is to incorporate important details like boundary conditions and changes in the computational model with time of shaking due to cracking, localization, and separation of soil from structural elements. The constitutive models, their implementation in computer codes, and the treatment of boundary conditions need to be seen together as a complex of analytical and theoretical factors that needs to be verified. They cannot be verified individually. This statement also applies to newly emerging non-continuum computer codes using techniques such as the Discrete Element Method that model the soil at the particle level, and to the combination of continuum and non-continuum formulations within the same code. The top priority identified by the workshop is the need for systematic validation. Modern advances in field and laboratory experimentation, large-scale testing, instrumentation, and centrifuge model testing now provide the capabilities that can be applied to such validation efforts.

Modern advances in experimentation, large-scale testing, instrumentation, and centrifuge modeling can be applied to validation efforts.



Detailed mapping of surface fault rupture from the 1999 Chi-Chi, Taiwan earthquake that shows 2.8 m of vertical offset over a 20 m wide zone of deformation. This information is being used to develop mitigation design strategies for engineered systems, such as buried pipelines, that must cross active faults. Credit: *NSF-sponsored paper by Kelson et al. (2001) "Fault-Related Surface Deformation,"* Chi-Chi, Taiwan, Earthquake of September 21, 1999 Reconnaissance Report, *in Earthquake Spectra Journal, Suppl. A to Vol. 17, EERI, 2001, pp. 19-36.*

Experimental validation of computational methods through well thought out baseline scaled experiments and associated research aimed at influencing the state of practice, and using the NEES facilities, is especially promising. Even with the available testing and sensor infrastructure, these tests are expensive. To be most useful, these tests should use advanced instrumentation and include a well defined free field, as well as the corresponding structural, foundation, or buried element(s). An associated computational effort is essential. Use of advanced sensors, state of practice field characterization of the soil such as penetration and shear wave velocity testing, and associated centrifuge research, as well as prediction exercises may help maximize the impact of the baseline tests. The advances need to be validated through baseline experiments explicitly aimed at influencing the state of practice. Whenever possible, field experiments are to be preferred, followed by large-scale tests in the laboratory and centrifuge testing. It should be noted that NEES has made significant improvements available in all these areas.

Centrifuge testing has made major contributions in many areas of geotechnical engineering including application to critical systems of interest to DHS, for example, the investigations into the failure of the levees in New Orleans, LA, during Hurricane Katrina in 2005. However, several technical issues remain unresolved. Reflections from boundaries often present difficulties when testing discrete volumes and dynamic loads, as they do for finite element or finite difference analysis. The basic assumption in centrifuge testing is that the continuum mechanics are unchanged by moving from the prototype to the experimental geometry, but this is not always true. Diffusion, as in the dissipation of excess pore water pressures, follows a different scaling law from the law that applies to the dynamic effects. Today this problem is often dealt with successfully by using a modified pore fluid, but the density and compressibility of the fluids must be

similar for the centrifuge model to be representative. In other words, centrifuge modeling requires attention to specialized details to be successful, and several matters remain to be studied.

3.2 Soil-water-structure interaction

Perhaps the most frustrating problems for analysis and design are those involving the dynamic interaction between soils and structures and water. When water is added to the already complex situation of soil-structure interaction, matters become truly complicated. The water can appear in two forms: water in the pores of the geotechnical materials, and free water in a reservoir, river or ocean that can interact with an embankment or pier. Some analytical approaches have been developed over the years, but the recent advances in computational and experimental capabilities present an opportunity for further development.

When water is added to the already complex situation of soil-structure interaction, matters become truly complicated.

Lateral earth pressures attracted the attention of both Coulomb in the 18th century and Rankine in the 19th, and modifications to their theories to account for dynamic loads date from the 1920s. Nevertheless, the analysis of lateral earth pressure under dynamic loadings remains challenging to this day. Understanding the effects of lateral earth pressure is important for the design of waterfront structures, dams, highway bridges, and other facilities where both soil and water push on a structural wall. This is one of the most common instances of soil-water-structure interaction.

Several phenomena are included within the liquefaction of water-saturated soils, but the usual one is the increase in pore water pressure in a loose, saturated, cohesionless sandy or gravelly soil due to cyclic loading, to the point that the effective confining stress is reduced to near zero and the soil does not have enough shear strength to withstand the load it is carrying. Catastrophic failures can occur as a result. As indicated already in Section 1.2, most of the practical ways of identifying potential zones of liquefaction involve using empirical relations between the SPT or CPT soil resistance, and estimates of the dynamic loading. These methods have been developed and tested primarily for conditions of level or mildly sloping ground, and their extension to other circumstances remains problematic. Much of the underpinning of this methodology is of questionable validity. For example, an actual earthquake time history imposes an erratic series of cyclic loads of varying amplitude, and it is assumed that the loads can be accounted for by using the cyclic summation techniques developed originally for fatigue analysis. This assumes implicitly that the order of the cycles makes no difference. The result is expressed as a "magnitude scaling factor," because larger amplitude earthquakes tend to last longer and have more cycles of loading. Unfortunately, the support for extending the cyclic loading methodology from fatigue analysis to liquefaction analysis is not well supported, and there is evidence that the order of the cycles is important. Although a consensus based on the accumulated empirical evidence has developed on practical ways to deal with liquefaction at sites with level or mildly sloping ground, enough unanswered questions remain for other conditions and confining stresses showing that more research is needed.

One concept that has arisen from research into liquefaction is that of the existence of a threshold strain, that is, a strain below which a phenomenon like liquefaction does not develop and above which it does. This approach should be explored for application to other situations, and blast effects present one such set of conditions.

3.3 Modeling of interfaces and discontinuities

Whenever the geotechnical engineer is confronted with discontinuities and interfaces with structural elements such as foundations, buried pipes, retaining walls, and earth embankment wrap around sections of concrete dams, the problem becomes especially difficult. Not only do different types of materials have different constitutive relations, but also the amplitudes of strain that they experience may be quite different. In some cases the soils must deform substantially before they can develop their full strength, and at that level of deformation structural materials have already passed their peak strengths. In addition, the discontinuities between soils and structures can become the places where strains concentrate and cracks open up allowing water to flow between them and cause a variety of effects, such as the undermining failure of the New Orleans, LA levee walls during Hurricane Katrina or erosion and piping after an earthquake damages an embankment dam or ruptures an underwater tunnel. Cracks in otherwise homogeneous materials, such as joints in rock, raise similar problems. Most current computational models cannot deal with this effectively, and it is a subject that requires much more study. It should be noted that dams and waterfront structures are classical examples of systems in which soils and structures are expected to work together.

Discontinuities between soils and structures, and joints in rock, may allow water to flow and failures to occur.

3.4 Performance-based engineering for multi-hazards

Risk and reliability have become major issues in geotechnical research and practice. These approaches extend the study of the effects of natural hazards from an evaluation of their consequences to incorporate the probability that a particular set of consequences will occur. Hacking (1975)[3] quotes Blaise Pascal as saying, "We ought to fear or hope for an event not only in proportion to the advantage or disadvantage but also with some consideration of the likelihood of the occurrence."

Probabilistic seismic hazard analysis has introduced some formal treatment of uncertainty into geotechnical earthquake engineering, but the extension to other aspects of the subject has been limited at best. Since the current way to deal with uncertainty is often simply to pile up conservatisms, unevaluated uncertainty can lead to some very expensive designs. Further research into risk and reliability in geotechnical earthquake engineering will address this issue. Reliability analysis can also address questions of multiple hazards, that is, situations in which several hazards present themselves.

Risk and reliability analysis can be used to address prioritization and identify where resources should be allocated.

Furthermore, it is not possible to prevent every eventuality. Prioritization of defense and security measures is essential. Risk and reliability analysis is one tool that can be used to address issues of prioritization and to identify where resources should be allocated. Performance-based earthquake engineering has been used increasingly in recent years to describe probabilistic and nonlinear performance of structures and should be a major part of a research program.

3.5 Capturing field performance due to actual extreme events

Most advances in earthquake engineering have arisen from observing the consequences of actual earthquakes and studying the observations in a controlled setting. This has been called "Learning from

[3] Hacking, Ian (1975) "The Emergency of Probability," Cambridge University Press.

Earthquakes." It is an important and critical area of research, but progress has been historically slow. To a large extent this progress depends on the occurrence of a significant earthquake that exhibits the phenomena needing investigation. It also depends on the availability of competent investigators to do the field studies, funds to support the field trip and the subsequent research, and technology to support data collection and processing. There has been recent progress in all these areas which should continue to be supported. For example, the Geo-engineering Extreme Events Reconnaissance Association has used emerging technologies, such as GPS, GIS, and remote sensing, to collect quantitative data on the geotechnical effects of earthquakes and other natural disasters. There are also new possibilities of in situ and scaled testing, especially using the NEES facilities.

Most advances in earthquake engineering have arisen from observing the consequences of actual earthquakes and studying the observations in a controlled setting.

Kobe port after 1995 Kobe earthquake in Japan. Photo credit: Ross Boulanger, http://cee.engr.ucdavis.edu/faculty/boulanger/geo_photo_album/Earthquake%20hazards/Liquefaction%20-%20%20Kobe/Kobe%20liquefaction%20P4.html

Learning effectively following earthquakes and other extreme events involves both early reconnaissance and follow-up research on issues identified by the reconnaissance. It is the very nature of such a program that the events triggering the study cannot be foreseen, and thus studies must be funded out of contingency funds. The value of results obtained from a well-conducted post-event reconnaissance program is large enough that funding agencies ought to be prepared to sponsor such studies. Many workshop participants felt that DHS might be especially helpful in funding reconnaissance efforts immediately after an important

event. Follow-up studies, continuing for a period of time after the earthquake for months or years, are particularly important and difficult to fund, and DHS may also be especially helpful in this respect.

A related area of research is the installation of instrumentation before an earthquake occurs at sites that are likely to be affected by an earthquake. This requires careful evaluation of the probability of occurrence of the critical event, but it has the potential for delivering especially well documented data by providing a full-scale experiment under actual earthquake conditions.

3.6 Sensitivity evaluation of computational methods and guidance on their use

There is often a disconnection between researchers and practitioners. After researchers have developed new insights and procedures for applying them, the practitioners need to know how to use the new knowledge and should understand the bases and assumptions that underlie the advances. The field of geotechnical earthquake engineering practice needs greater guidance in this area, especially as it relates to complex computer codes, and new developments need to be evaluated to establish their sensitivity to values of input parameters. The results of the validation research listed above in Section 3.1 should be used as much as possible to support and guide sensitivity evaluations and the writing of corresponding guidance documents for practitioners.

There is often a disconnection between researchers and practitioners.

3.7 Innovative construction methods and the use of advanced and smart materials

The purpose of civil engineering is not analysis but creation of practically useful facilities. The development of modern materials, especially synthetics and specialized fabrics, has had significant impact on geotechnical engineering design and construction. Geosynthetics and geotextiles are now major components of geotechnical engineering practice. They have been used to reinforce soils otherwise subject to excessive deformation, to accelerate drainage in compressible and impermeable soils, and to act as barriers to seepage. They also show great promise for mitigating the effects of earthquakes.

Modern materials show great promise for mitigating the effects of earthquakes.

The pace of recent advances in materials science and construction technology encourages further investment in research in this area.

3.8 Blast effects

Blast effects are important in themselves because the risk of destruction of infrastructure must include accidental or malicious explosions. Because of their obvious military significance, blast effects have been studied extensively by military researchers, and this research has indicated that explosives do pose significant dangers to geotechnical structures. Thus, they warrant further research.

In addition, explosives provide a mechanism for studying the effects of dynamic loading in scalable and controllable environments. Not only can researchers learn the effects of the blasts themselves, but they can also extrapolate the results to the larger energy levels of earthquakes.

Dynamic loadings causing soil strains below the threshold are nondestructive.

As mentioned before under Section 3.2, one concept developed in earthquake engineering, which may be useful to blasting analyses and evaluations, is that of a soil threshold strain. Dynamic loadings causing soil

strains below the threshold level are essentially nondestructive, causing neither excess pore water pressure nor permanent deformation of any kind. While conservative, the use of the threshold strain concept may play a useful role in both earthquakes and blasting in screening out the possibility of damaging effects for low intensity events or at a sufficient distance from the explosion or earthquake.

3.9 Properly scaled laboratory testing

Scaling experimental results up to the level of earthquake excitations is a large part of earthquake engineering research. Centrifuge testing is a particular example. Proper scaling of test results to prototype scale is often complicated by the fact that different phenomena have different scaling laws. For example, dynamic effects and seepage phenomena obey different scaling laws. Sometimes, the differences can be accommodated by changing the properties of some of the materials, but proper scaling is a subject that still requires further research.

Scale model tests, whether in centrifuges or at 1 g gravity, have been a major part of geotechnical engineering research. They have provided significant results. Theoretical analyses and laboratory scale tests must be validated by large or even full-scale testing in the laboratory or in the field.

3.10 Novel ways to model field performance and underlying phenomena

"Low probability but high yield" research should be encouraged by imaginative researchers.

Among the possibilities provided by advances in computer science, graphical modeling, global positioning systems, and information technology in general are improved ways to model geotechnical phenomena. The profession has already made some use of these developments, and the results are impressive. More research into this area should be encouraged, covering new possibilities conceived by imaginative researchers that may be classified under the label of "low probability but high yield" research ideas.

3.11 Interdisciplinary investigations

A characteristic of much modern scientific research is interdisciplinary cooperation. Fields such as medicine have benefited enormously from coordination among researchers who are adept in a variety of fields. Although there has been interdisciplinary cooperation in earthquake engineering – between geologists, seismologists, structural engineers, and geotechnical engineers, for example – much more could be done. Experience suggests that research sponsors can be effective in encouraging interdisciplinary work. The area of soil-water-structure interaction (listed above in Section 3.2) is a prime example where cooperation between geotechnical earthquake engineers and hydraulic and fluid mechanics scientists is essential.

In soil-water-structure interaction, cooperation between geotechnical earthquake engineers and hydraulic and fluid mechanics scientists is essential.

3.12 Innovative ground characterization techniques

The results of a sophisticated computer analysis can be no better than the quality of the input to the analysis. Improved ground characterization techniques are required to describe the state, in situ stress, and stress history of the earth materials underlying an engineering facility. The soil and rock materials used in the constructing of earth structures require improved characterization of their engineering properties.

Geologic details at a site can significantly impact the performance of engineered systems. A relatively thin layer of weak, sensitive clay produced numerous landslides in Anchorage during the 1964 Alaskan earthquake. Although more widespread use of tools such as the CPT with advanced sensors has helped engineers better assess the conditions of the ground, further advancements are required. For example, it is not generally recognized that almost everything known about the structure of the planet earth is the result of remote sensing. Prospecting for resources such as petroleum relies heavily on geophysical methods. Further research into innovative ground characterization methods using such techniques could do much to improve our Nation's resilience to earthquakes.

Improved ground characterization is required to describe the earth materials underlying a facility.

Vulnerability of Buildings and Infrastructure to Soil Liquefaction

The Problem

Extensive liquefaction damage to port facilities in 1995 Kobe, Japan, earthquake, due to tilting and displacement of quay walls, caused a US $10 billion loss (Iai, 1996).

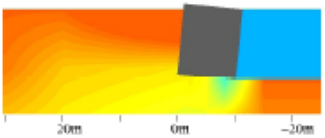
Liquefaction of wet sands causes much destruction in earthquakes. In San Francisco in 1906 and 1989 and in Alaska in 1964, it damaged buried pipes and buildings, crippled bridges, and destroyed waterfronts. The 1811-12 New Madrid earthquakes liquefied large areas from Tennessee to Missouri; a repeat today would have disastrous consequences. During liquefaction, the sand grains are suspended in the pore water, buildings sink into the soil, and the ground cracks, settles and moves laterally.

Structural failure and sinking of an apartment building in San Francisco Marina District, 1989 Loma Prieta earthquake (Nakata, USGS, 2002).

Research Tools and Accomplishments

The flow failure of the upstream slope of the Lower San Fernando Dam in 1971 nearly caused overtopping, which could have killed thousands. It has been reconstructed and analyzed by Seed, et al. (1975) to provide an understanding of the mechanics of flow failures and to develop engineering procedures to evaluate post-liquefaction soil shear strength.

Geotechnical centrifuges with in-flight shakers, such as the 9-meter radius unit at UC Davis, play a role in understanding and quantifying liquefaction effects.

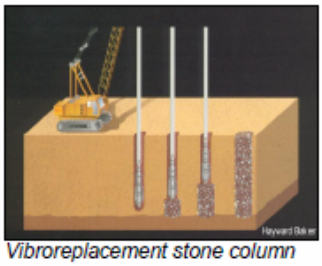


Visualization of data measured during shaking of waterfront structure centrifuge model, RPI, Troy, NY. (Colors: blue = ocean, black = quay wall, red = liquefied sand with high positive pore water pressure, yellow = sand with some positive pressure, green = sand with negative pore water pressure).

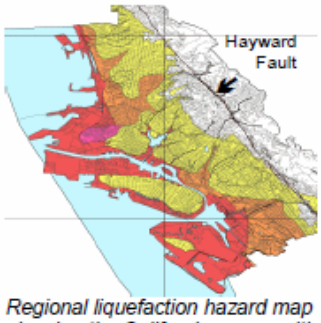
Research over several decades has clarified many aspects of liquefaction but progress in predicting its effects has been slow. This is due to the complex phenomena underlying liquefaction and ground deformation plus the uncertainty in determining the relevant properties of a natural soil mass. Observations in earthquakes, case studies, correlations with *in situ* soil measurements and environmental factors, field and laboratory soil investigations and measurements, centrifuge model tests, and computer simulations have been used as research tools.

Research Applications

Empirical and semi-empirical methods have been developed for mapping of areas at risk and prediction of liquefaction and ground deformation at specific sites. Engineering analyses and computational simulations calibrated by field or centrifuge observations are used to evaluate site and foundation liquefaction response. They are also used to develop new retrofitting and site remediation techniques, such as stone columns, compaction grouting and deep soil mixing.



Vibroreplacement stone column construction at Mormon Island Auxiliary Dam east of Sacramento, California (1993). Stone columns are one new method to improve the resistance to liquefaction. They work by densifying and reinforcing the sand, and by drainage of earthquake-induced pore water pressures.



Regional liquefaction hazard map showing the California communities between Berkeley and Oakland for a 7.1 magnitude earthquake. Blue areas represent water. 73% of the red area is predicted to show surface manifestations of liquefaction, Holzer, et al. (2002).

Credit: EERI (2003), "Securing Society Against Catastrophic Earthquake Losses: A Research and Outreach Plan in Earthquake Engineering," Earthquake Engineering Research Institute, EERI Publication No. RP-2003, Oakland, CA, June, 62 pages.

4 CONCLUSIONS AND RECOMMENDATIONS

There have been many major advances in geotechnical earthquake engineering, especially since the two major earthquakes in 1964. However, the state of the art in several areas remains less than satisfactory. Many questions have never been answered, or even posed clearly. Recent advances in computer and information sciences, laboratory and field testing capabilities, and field observation of earthquake effects provide opportunities for resolving many of these major problems. The workshop considered the range of successes and problems in the field.

The group identified an array of facilities whose performance during and after earthquakes is a concern of DHS and is affected by the state of practice of geotechnical earthquake engineering. Facilities were identified under the following categories:

1) dams and levees,
2) water distribution systems,
3) tunnels, bridges, and railroads,
4) airports,
5) waterfront and harbor facilities,
6) oil and gas facilities, and
7) tailings and hazmat storage.

The technical areas in which participants agreed that research should be focused apply across the range of facilities listed above. That is, an advance in one technical area will affect design and construction for several types of facilities. The five areas of research with the highest priority identified by the workshop are:

1) validation of analytical procedures,
2) soil-water-structure interaction,
3) modeling of interfaces and discontinuities,
4) performance-based engineering for multi-hazards, and
5) capturing field performance due to actual extreme events.

The workshop also identified the following as being high priority areas of research:

6) sensitivity evaluation of computational methods and guidance on their use,
7) innovative construction methods and the use of advanced and smart materials,

8) blast effects,

9) properly scaled laboratory testing,

10) novel ways to model field performance and underlying phenomena,

11) interdisciplinary investigations, and

12) innovative ground characterization techniques.

While all of these areas are important, it is recommended that DHS concentrate its efforts on the first five areas of research with the highest priority.

APPENDIX A - List of Colloquium Attendees

Jean M. E. Audibert	Consultant
Jonathan D. Bray	Professor, UC Berkeley
John T. Christian	Consultant
Ricardo Dobry	Professor, Rensselaer Polytechnic Institute
Ahmed W. Elgamal	Professor, UC San Diego
Robert L. Hall	Structural Engineer, ERDC
Mary Ellen Hynes	Geotechnical Engineer, DHS
Lelio H. Mejia	Principal and Vice President, URS Corporation
Jose M. Roesset	Professor, Texas A&M University
William A. Wallace	Professor, Rensselaer Polytechnic Institute

APPENDIX B - Biographies of Colloquium Attendees

Jean M. E. Audibert, **Ph.D., P.E.** is an independent Geotechnical Consultant with over 35 years of worldwide professional engineering experience both onshore and offshore, serving the power industry, petrochemical industry, oil and gas industry, and both the private and government sectors. He earned the B. Sc. Degree in engineering from the École Nationale Supérieure d'Arts et Métiers, Paris, France, and the Ph. D. degree in civil engineering from Duke University.

For over a decade, he held the position of Vice President/Manager of Engineering for Fugro-McClelland Marine Geosciences, in Houston, Texas, where he was responsible for the overall quality and schedule control for all the aspects of a wide range of offshore geotechnical projects. His responsibilities included the overall supervision and coordination of some 40 engineers, and the technical direction and management of numerous offshore geotechnical projects. He ensured that all tasks were carried out according to the client's specifications and that reporting deadlines were met in accordance with the contracts. He provided overall guidance and management of all field and office project teams, including mobilization, field surveys, laboratory testing, static foundation analysis and design, and earthquake engineering.

Offshore projects for which he was responsible have included foundation design, in situ testing, tool development, platform certification, pipeline routing and engineering, feasibility studies of deepwater platform concepts (guyed and buoyant towers, TLPs, SPARs, FPS and FPSOs), pile load tests, and research and development studies. He directed and participated in several R&D programs, including load tests on large instrumented driven piles and drilled and grouted piles, suction caissons, SEPLAs and torpedo piles. His extensive onshore project experience includes numerous geotechnical engineering studies for nuclear and fossil fired power plants, LNG terminals and re-gasification plants, dams, bridges, outfalls and intake pipes, earth and water retaining structures, lignite mines and petroleum product refining facilities. In addition, he has directed waste management projects, ranging from site investigations, remedial designs, remedial actions, and design of municipal and hazardous waste landfills.

Dr. Audibert is the author or co-author of over 70 technical papers. He received the Special Service Award from ASTM for organization of the 2nd International Symposium on the Pressuremeter and its Marine Applications. Dr. Audibert has received the J. James Croes Medal by the American Society of Civil Engineers, the Collingwood Prize from ASCE , an ASTM Special Service Award (1987), Fulbright Fellow (1968-1969), a Who's Who in Engineering (AAES) and Who's Who in Technology Today and Men of Achievement.

Jonathan D. Bray, Ph.D., P.E. is a Professor of Geotechnical Engineering in the Department of Civil and Environmental Engineering at the University of California, Berkeley, CA. Dr. Bray has been a registered professional professional civil engineer since 1985, and he has over two decades of experience in teaching and performing research in the areas of geotechnical engineering, earthquake engineering, environmental geotechnics, and numerical and physical modeling. He served as vice president of the Earthquake Engineering Research Institute, and he is a member of the Advisory Committee on Earthquake Hazards Reduction and an active member of ASCE. He has received several honors, including the Shamsher Prakash Research Award, ASCE Huber Research Prize, Packard Foundation Fellowship, and NSF Presidential Young

Investigator Award. He earned the degrees of B. S. from the United States Military Academy at West Point, M. S. from Stanford University, and Ph. D. from the University of California at Berkeley, all in civil engineering.

John T. Christian, Ph. D., P. E., has extensive experience in Geotechnical Engineering, Soil Dynamics, Earthquake Engineering, Geotechnical Reliability, Computer Applications, Finite Element Analysis, and Engineering Management. His expertise includes earthquake engineering, dynamic analysis, evaluation of soil liquefaction, amplification of seismic waves, stability of slopes, dynamic soil-structure interaction, and probabilistic seismic hazard assessments. His engineering work has included earth dam analysis and design, evaluation of flow through porous media and earth dams, nuclear power plants, solid waste landfills, foundation engineering, offshore facilities, mooring facilities, and pipelines. He has performed geotechnical analyses for on-site nuclear spent fuel storage facilities and for the stability of wastes at large mines. A pioneer in the use of computer methods, he co-authored the first general, user-friendly computer program for analysis of slope stability with circular and non-circular failure surfaces. He is the co-author and co-editor of a seminal book on Numerical Methods in Geotechnical Engineering, and co-author of a book on Productivity Tools for Geotechnical Engineers. His co-authored book on Reliability and Statistics in Geotechnical Engineering was published in 2003. He earned the B. S., M. S., and Ph. D. degrees in Civil Engineering from the Massachusetts Institute of Technology (MIT).

As Vice President of a major engineering firm, he was involved in the design, evaluation, and construction of a large number of nuclear power plants and other facilities for energy generation and distribution. He also had a variety of corporate management functions, including oversight of computer activities, corporate computer disaster recovery, and standards and qualification of software. He has managed an expert system development group. He has applied probabilistic concepts to geotechnical engineering, winning the ASCE Middlebrooks Prize in 1996 for a paper on the uses of reliability approaches to the design of embankments. In 2002-2003 he served as the Chairman of the National Academy of Engineering committee that reviewed the status of the $14.6 billion Boston Central Artery/Tunnel Project (the "Big Dig") and proposed management changes to expedite its completion. He is a member of the NAE Committee on New Orleans Regional Hurricane Projects and the committee to review the Louisiana Coastal Restoration Project. He was the chair of the NRC committee to review the Bureau of Reclamation's procedures for security of dams.

In addition to serving on the editorial boards of several professional journals, he has been the Editor-in-Chief of the ASCE Journal of Geotechnical and Geoenvironmental Engineering. He is the former Chairman of the Geotechnical Engineering Division of the ASCE and of the U.S. National Society of the International Society of Soil Mechanics and Foundation Engineering. He is the former Chairman of the Engineering Accreditation Commission, Accreditation Board for Engineering and Technology. He delivered the Terzaghi Lecture of the ASCE in 2003. He is an Honorary Member of the Boston Society of Civil Engineers Section of ASCE and a Distinguished Member of ASCE. He is a Member of the National Academy of Engineering.

Ricardo Dobry, Sc. D. is an Institute Professor of Engineering in the Department of Civil and Environmental Engineering at Rensselaer Polytechnic Institute. Dr. Dobry earned his B. S. from the University of Chile, his M. S. from the National University of Mexico, and his Sc. D. from the Massachusetts Institute of Technology (MIT), all in civil engineering. He has taught at MIT, the University of Chile, the

University of Texas at Austin, and since 1977 has been a member of the faculty at Rensselaer, where he has also served as Director of the Geotechnical Centrifuge Research Center since 1988.

Dr. Dobry's research interests include soil dynamics, geotechnical earthquake engineering and geotechnical dynamic centrifuge testing. He was a leading participant of the group that wrote the new seismic provisions on local site amplification in the 1990's now incorporated in U.S. building codes. He is one of the authors of the visionary 20-year research plan in earthquake engineering prepared in 2003 by the Earthquake Engineering Research Institute for the National Science Foundation (NSF). Since 2000 he has directed the Rensselaer geotechnical centrifuge experimental site of the Network for Earthquake Engineering Simulation (NEES), one of 15 interconnected experimental nodes funded by NSF to revolutionize earthquake engineering research in the U.S. He has written more than 200 technical papers and research reports and has directed 40 PhD and MS theses at Rensselaer.

Dr. Dobry has served as consultant and member of consulting boards of important and prestigious civil engineering projects, including offshore oil platforms in Venezuela and Australia, earth dams and dikes in California, Puerto Rico and South America, seismic retrofitting of several large bridges in New York City, seismic guidelines for design of new bridges in New York City, and design of the new Rion-Antirion bridge in Greece. Dobry has been an invited state-of-the-art and keynote speaker at international meetings in the U.S., Mexico, South America, Europe, Japan and Australia. He earned the J. James Croes Medal of the American Society of Civil Engineers in 1985, and was elected member of the National Academy of Engineering in 2004.

Ahmed W. Elgamal, Ph.D. is a Professor in the Department of Structural Engineering at the University of California, San Diego and the Equity Advisor for UCSD's Jacobs School of Engineering. Dr. Elgamal chaired the Department of Structural Engineering from 2003 to 2007. He earned the B. S. degree from Cairo University, Egypt, and the Ph.D. degree from Princeton University. He joined UCSD in 1997 as Professor after a post-doctoral appointment at the California Institute of Technology (1985-86), and faculty positions at Rensselaer Polytechnic Institute (1986-96) and Columbia University (1996-97). He served (2006-2007) as Principal Investigator of the Network for Earthquake Engineering IT project (http://it.nees.org) and as a Thrust Area Leader (2001-2007) of the Pacific Earthquake Engineering Research (PEER http://peer.berkeley.edu/) Center. His areas of research interest include large-scale soil-structure experimental and computational simulation of liquefaction and related mitigation approaches, Information Technology (IT) applications in Civil Engineering research and education, and interpretation of recorded seismic response through system-identification and data mining procedures. Incorporation of IT into structural engineering is currently among his main research areas, with emphasis on Health Monitoring of Structures and Earthquake Engineering. Internet applications include sensor networks for monitoring the civil infrastructure, with real-time condition assessment and decision-making algorithms (http://healthmonitoring.ucsd.edu). Integration of research and education with live web-accessible experiments is a main interest (http://webshaker.ucsd.edu). He is author and co-author of over 250 technical publications.

Robert L. Hall, Ph.D. is the Senior Technical Advisor for the Geotechnical and Structures Laboratory at the U.S. Army Engineer Research & Development Center. As such, he oversees research in numerous

disciplines: antiterrorism/force protection; earthquake engineering; structural mechanics; structural engineering; and survivability engineering. In addition, he assists the Defense Threat Reduction Agency, Department of Homeland Security (DHS) and the Corps of Engineers in formulating and guiding comprehensive long-range research programs in the areas of structural dynamics, computational structural mechanics and earthquake engineering. Dr. Hall leads the Corps' research programs in the area of seismic analysis of hydraulic structures and has supported the Corps in the seismic design/analysis of Olmsted Locks, Seven's Oaks Intake, and Folsom Dam. Dr. Hall has been responsible for the development of the Corps' guidance documents for the seismic design of concrete hydraulic structures. He has served as a technical advisor to BC Hydro in the seismic evaluation of Hugh Keenleyside, Seven Mile, and Strathcona Dams and outlet works; as an Advisory Board Member for BC Hydro on the seismic evaluations of La Joie, Blind Slough and Ruskin dams; as the chair of U.S./ Japan Panel's committee on the Seismic Design of Dams; and as the chair of the Structural Advisory Board supporting the Panama Canal Authority. In addition, he has worked several programs/projects with the Secret Service, Department of State, and Department of Homeland Defense. Dr. Hall earned his B. S. in Civil Engineering from Auburn University, his M. S. in Civil Engineering from Mississippi State University, and his Ph. D. in Civil Engineering from Oklahoma State University.

Dr. Hall has more than 100 technical publications in various journals and refereed papers in proceedings, international conferences, and symposiums. In addition to chairing sessions at various international and national conferences, he has been invited to give keynote addresses and speak at various national and international conferences. He also has given guest lectures on his research activities at various educational institutions. Other notable functions and experiences include: being a past member of ACI's technical committee on blast response of structures, a past member of ASCE's technical committee on Seismic Effects, a member of the Society of American Military Engineers, and a member of the Technical Program Committee for the 1993 National Earthquake Conference; serving on the Advisory Committee for the Engineering Research and Development Center Graduate Institute, serving as Chair of the ASCE's Government Engineers Section/Branch Involvement Committee; serving as an Adjunct Professor for Mississippi State University, Alcorn State University, University of Missouri at Columbia, and the University of Puerto Rico. His awards include the Achievement Medal for Civilian Service and the Director's Research and Development Award in 1996 and 2000, and the Meritorious Civilian Service Award in 2009.

Mary Ellen Hynes, Ph.D., P. E., is the Director of Research for the Infrastructure/Geophysical Division in the Science and Technology Directorate (S&T) at DHS. She comes to DHS/S&T after 30 years of research and development work at the US Army Engineer Research and Development Center headquartered in Vicksburg, MS. She obtained – with honors – her Bachelor's and Master's degrees in Civil Engineering from MIT and her Ph. D. in Civil Engineering at the University of California at Berkeley. Her past research areas focused on earthquake engineering for dams and probabilistic modeling, and included development of deformation procedures and acceptability criteria, now used all over the world. Dr. Hynes was also involved with the design and construction of the Richard B. Russell Dam and the Olmsted Locks and Dam, the seismic stability evaluation of the Panama Canal and over 600 large dam projects in the US.

At S&T, she has all the targets and all the threats for critical infrastructure protection and natural hazards. Additionally, Dr. Hynes is the DHS/S&T Co-Chair of the National Science and Technology Council Infrastructure Subcommittee, co-chaired with the Office of Science and Technology Policy, Executive Office of the President. She is a member of the U.S.-Japan Natural Resources Panel on Wind and Seismic Effects. Her technical affiliations include the American Society of Civil Engineers (past Chair of the Probabilistic and Risk Technical Committee and past Member of the Technical Advisory Council for the Geo-Institute; served on Geotechnical Journal editorial board), the Society of American Military Engineers, American Society for Testing and Materials (served on editorial board), International Society of Soil Mechanics and Foundation Engineers, and The Infrastructure Partnership (TISP). She chaired the National Science Foundation review panel for Geotechnical, Geomechanical, and Geoenvironmental Engineering for 5 years during the 1990's. She is the author or co-author of over 50 contributions to journals, books, proceedings and papers, and technical reports.

Lelio H. Mejia, Ph.D., P.E., G.E. is Vice President and Principal Engineer in the Oakland, California office of URS Corporation and is an Earthquake Engineering Practice Leader for URS. He is a registered civil and geotechnical engineer with over 25 years of professional experience. His main disciplines of practice are dam engineering, earthquake geotechnical engineering, and foundation engineering. He earned the Ph. D. degree in civil engineering from the University of California at Berkeley.

In his professional practice, Dr. Mejia has been involved with a broad range of engineering projects. He has directed numerous dynamic response analyses and seismic stability and design studies of dams, levees, and other earth structures. He has extensive experience in the evaluation of soil liquefaction and the use of ground treatment methods to mitigate the effects of liquefaction. He has conducted soil-structure interaction analyses of hydraulic structures, bridge foundations, power plant and harbor facilities, and buildings. He has also performed seismic risk analyses and engineering characterization of earthquake ground motions for dams, industrial facilities, bridges, and high-rise buildings.

While at the University of California he developed numerical techniques for the three-dimensional dynamic response analysis of rock and earthfill dams and applied those methods to study the dynamic behavior of dams in narrow canyons. He has recently conducted research on the applicability of fully nonlinear finite element methods to the dynamic response analysis of earth structures and dams. In addition, he has previously conducted research on the mechanisms of liquefaction failure during the 1989 Loma Prieta, CA earthquake.

He is a Secretarial Appointee to the Advisory Committee on Structural Safety of Department of Veterans Affairs Facilities and has been a Lecturer of Geotechnical Earthquake Engineering at the University of California at Davis, CA, an Extension Instructor in Geotechnical Engineering at the University of California at Berkeley, CA, and a member of the editorial board for the ASCE Journal of Geotechnical and Geo-environmental Engineering. He is a frequently invited lecturer at academic institutions and professional organization meetings, and has lectured at several continuing education courses on dam engineering, earthquake engineering, and liquefaction mitigation. He has served as a National Science Foundation Panelist for the CAREER Program and other NSF research programs in Geotechnical and Geohazards Systems, and has served on technical review boards for the US Bureau of Reclamation, the US Army Corps of Engineers, and the California Department of Water Resources on various dam projects, and for other owners on

foundation engineering projects. As a product of his research and project work, he has over 50 publications to his credit.

Jose M. Roesset, Sc.D., P. E., is the Associate Department Head and Cain Chair Professor of the Zachry Department of Civil Engineering at Texas A&M University. He received the degree of Sc D. in civil engineering from the Massachusetts Institute of Technlogy (MIT). As a faculty member in the Civil Engineering Department of MIT (1964-1978) Dr. Roesset conducted roughly half of his research on Nonlinear Structural Dynamics, with special emphasis on Earthquake Engineering, and the other half on what is known now as Geotechnical Earthquake Engineering. His structural work involved studies on inelastic response spectra, development of nonlinear structural models such as the fiber model, assessment of the validity of approximate procedures to derive equivalent inelastic single degree of freedom systems from incremental nonlinear static analyses of frames (later called the push-over method), and development of formulations in time and frequency domains. His work on geotechnical engineering involved first studies of the effect of local soil conditions on the characteristics of earthquake motions (soil amplification) for different types of seismic waves, then the determination of the dynamic stiffness of mat foundations and single piles, and finally the study of the effects of the soil/foundation flexibility on the seismic response of structures (soil structure interaction). Much of this work found applications in the seismic analysis and design of Nuclear Power Plants, a hot topic at that particular time, and Dr. Roesset served as a consultant in a number of plants.

At the University of Texas at Austin (1978-1997) Dr. Roesset continued to do some work on nonlinear structural dynamics and on dynamic stiffness of foundations (pile groups in particular) but he devoted most of his research effort to more fundamental wave propagation studies with special application to the nondestructive evaluation of soil deposits and pavement systems. This work was performed in collaboration with Dr. Kenneth H. Stokoe and involved on one hand the development of the formulation to interpret the data obtained with the Spectral Analysis of Surface Waves (SASW) method in order to backfigure the variation of soil properties with depth, and on the other the interpretation of the data obtained from Dynaflect and Falling Weight Deflectometer (FWD) tests to determine the elastic properties of pavement layers. The studies in this last case included the evaluation of the effects of the finite width of the pavement and the relative position of the FWD with respect to the edge, and the assessment of the importance of nonlinear soil behavior under large loads, particularly for flexible pavements.

From 1988, at the University of Texas first and at Texas A&M University since 1997, his research concentrated on the nonlinear dynamic response of deep water offshore platforms and fluidstructure interaction effects. This work was conducted for the Offshore Technology Research Center (OTRC), a joint venture between Texas A&M and the University of Texas at Austin with headquarters in College Station. Dr. Roesset was first the research coordinator for the center, then the Associate Director for the University of Texas at Austin, and finally the Director at Texas A&M.

Over the last five years Dr. Roesset has returned to the areas of Structural and Soil Dynamics with studies on the seismic response of base isolated bridges including soil-structure interaction effects, the dynamic response of pile foundations with large numbers of piles, and the in situ determination of nonlinear soil properties, work conducted in collaboration with Dr. Kenneth H. Stokoe in Austin and Dr. Giovanna Biscontin at Texas A&M University, under a NEES grant.

William (Al) Wallace, Ph. D. is Yamada Corporation Professor in the Decision Sciences and Engineering Systems Department, with joint appointments in the Civil and Environmental Engineering, and Cognitive Science Departments at Rensselaer Polytechnic Institute, and is presently Director of Rensselaer's Center for Infrastructure and Transportation Studies. He is a member of the National Research Council's Board on Infrastructure and the Built Environment and served on the National Research Council Committee on Social Science Research on Disasters. Professor Wallace received the International Emergency Management and Engineering Conference Award for Outstanding Long-Term Dedication to the Field of Emergency Management, The Institute of Electrical and Electronics Engineers (IEEE) Third Millennium Medal and is a Fellow of the IEEE, and received the 2004 INFORMS President's Award for work that advances the welfare of society. In addition, he was either Project Director or co-Project Director for research that resulted in the ITS-America "Best of ITS" award in the area of Research and Innovation and four project of the year awards from ITS-New York. He earned his Ph. D. from Rensselaer Polytechnic Institute (RPI).